

The pyroclastic deposits and eruption history of Ascension Island: a palaeomagnetic and volcanological study

by
Kate Hobson



Thesis submitted to the
University of Oxford



for the degree of
Doctor of Philosophy



Department of Earth Sciences
and University College

Trinity Term 2001

The pyroclastic deposits and eruption history of Ascension Island: a palaeomagnetic and volcanological study

Kate Hobson

Department of Earth Sciences and University College, University of Oxford
Trinity Term 2001

Extended abstract

In this study, palaeomagnetic methods have been combined with field and volcanological techniques to identify, classify and correlate the pyroclastic deposits found on Ascension Island, South Atlantic, allowing them to be placed into a temporal and geographic framework. Pyroclastic material is abundant on the island and, in general, well-preserved, making Ascension an ideal site to study the nature and distribution of the pyroclastic products of this type of composite volcano or *stratovolcano*. A better understanding of the nature and distribution of the products of past pyroclastic eruptions on Ascension should enhance our ability to assess volcanic hazard around stratovolcanoes world-wide.

Field mapping and stratigraphic logging have revealed the presence of several major pyroclastic sequences on Ascension. These comprise extensive felsic (pumice) and mafic (scoria) lapilli deposits, two major and several minor exposures of welded material and numerous breccia deposits that exhibit great variation in juvenile/lithic content, matrix type and content and internal structure. Preliminary interpretations of the deposits were made in the field, based on features such as welding, grain shape and internal structures. However many of the deposits – particularly the breccia deposits – display ambiguous field characteristics that could be attributed to pyroclastic or epiclastic processes and their origins could not therefore be determined from field characteristics alone.

Samples were taken from ninety-seven individual units on Ascension, for palaeomagnetic analysis. Units were placed into one of three major categories according to their field characteristics: (proposed) airfall deposits, welded deposits and breccia deposits. The palaeomagnetic technique has provided emplacement temperatures for seventy-two of these units, allowing their origins to be clarified. Individual clasts from the units were categorised according to their remanence characteristics as: type 1 (*hot*), or type 2 (*cold*), with further subdivision according to the number of components they display: a = single component, b = two components and c = three components. Sixty-eight percent of the

units sampled display an emplacement temperature (T_e) of $>100^\circ\text{C}$ (the lower limit of the T_e technique), suggesting they were emplaced hot. Twenty-one percent have a T_e of 0°C , suggesting that they were emplaced cold, and for the remaining 11% T_e could not be determined.

Palaeomagnetic data for the proposed Ascension airfall deposits generally substantiate preliminary field interpretations. Lithic clasts typically display type 1 (b or c) remanence behaviour suggesting that the units were emplaced hot. Emplacement temperatures (T_e s) for the units sampled range from 175°C to 210°C for felsic airfalls, and from 273°C to $>580^\circ\text{C}$ for mafic airfalls. Juvenile clasts (pumice or scoria) typically display a type 1a remanence, which is interpreted as a chemical remanent magnetisation or CRM (Zlotnicki et al., 1984; McClelland and Druitt, 1989). Chemical alteration of the juvenile material (leading to CRM acquisition) is inferred to result from post-eruption resorption of water by the juvenile material (Sparks et al., 1999). Deviations from the expected behaviour in juvenile clasts from the Ascension airfalls is attributed to clast rotation during cooling, incomplete CRM overprinting or VRM (viscous remanent magnetisation) acquisition.

Five of the proposed airfall units (EFP1, MVA2, PC1, RP1 and RSP1) contain clasts that display type 2 remanence behaviour. In units RP1, PC1 and MVA2, this is interpreted as the result of post-depositional slumping caused by faulting, or contamination of the magnetic signal by CRM. However units EFP1 and RSP1 are re-interpreted as epiclastic deposits.

The airfall units sampled on Ascension are inferred to represent five *major* pumice airfall deposits (the Lower Pumice, Middle Pumice and Upper Pumice 1, 2 and 3), and three *major* mafic airfall deposits (unnamed). The major deposits can be distinguished on the basis of their geochemistry (whole rock major and trace element analysis) and the mean declination and inclination directions that they display (i.e. secular variation). The trace element characteristics of the Middle Pumice and Upper Pumice 1 are similar but contrast with the trace element characteristics of the Upper Pumice 2 and 3 suggesting that the Middle and Upper 1 pumices may have tapped a different magma source to that of the Upper Pumice 2 and 3.

Palaeomagnetic data from the Ascension welded deposits substantiate field interpretations as welded pyroclastic flow deposits and lavas. Most of the units sampled comprise type 1a clasts, suggesting that they were emplaced hot and moreover above the Curie temperatures (T_c s) of their magnetic minerals. The lowest T_c mineral contained in samples from the welded deposits/lavas is magnetite (T_c 580°C). Hence it can be surmised that all units were emplaced at temperature above 580°C . Some of the welded/lava units (e.g. BILL, NELL, SB2) contain samples that display more than one component of magnetism. In these clasts, low-temperature (low-T) components are

interpreted as CRMs, acquired a considerable time after deposition. Direction of CRM components in samples from NELL and SB2 not only differ from high-T directions, but deviate considerably from the expected GAD for Ascension. In these units, CRM directions are inferred to have been influenced by the internal magnetic field of the deposit, rather than the external (geomagnetic) field.

Of the lavas sampled, only the mafic lavas (BILL and NELL) display CRMs. These results suggest that mafic lavas may be more susceptible to alteration (and hence CRM acquisition) than felsic lavas, and are therefore less desirable for use in palaeomagnetic studies.

Palaeomagnetic analysis of clasts from the breccias sampled on Ascension has allowed the origins of most units to be clarified. Sixty-two percent of the breccia units sampled can be classified as type 1 units and are hence interpreted as having been emplaced hot. Emplacement temperatures for the units range from 186°C to >580°C and inferred origins include pyroclastic pumice and scoria flow deposits, a block-and-ash-flow deposit, pyroclastic surge deposits (ground or ash-cloud surge), pyroclastic lag breccias, and autobrecciated lava flows. Twenty-three percent of the breccia units sampled contain mostly type 2 clasts and are hence interpreted to have been emplaced at ambient temperature (i.e. cold). The majority of these contain one or more type 1c (three-component remanence) clast(s), implying that they have been reworked from previously hot pyroclastic material. Relict T_e s (i.e. estimates of the average T_e of the unit/s from which clasts were reworked) can be inferred from such clasts, and these range from 239°C to 427°C. In 15% of the breccia units sampled, palaeomagnetic analysis cannot clarify the origin of the unit, either because no low-T components can be resolved, or because no distinction can be made between TRM and VRM components. The palaeomagnetic emplacement temperature technique relies on low-temperature component being thermal in origin and hence where the origin of low-T components is unsure, no accurate T_e determination can be made.

A small thermal modelling study carried out on one of the hot breccia units (EFS1), suggests that thermal overprinting of the upper ~1m of the deposit may have occurred. This highlights the importance of combining palaeomagnetic data with field evidence (e.g. deposit thickness, surrounding stratigraphy, stratigraphic height of individual clasts) in the interpretation of pyroclastic deposits.

Analysis of magnetic polarity data (in combination with field data) has formed the basis of the proposed correlation for the pyroclastic deposits presented in this study. The data have revealed the presence of a reversal within the stratigraphy, which (from age relationships) is interpreted as the Brunhes–Matuyama boundary. This has allowed relative dating of the pyroclastic deposits, with all reversed polarity units interpreted as

older than 0.78Ma. The considerable age of the pyroclastic material highlights the fact that in arid environments, pyroclastic deposits may be relatively resistant to epiclastic processes.

Emplacement temperature data, field data and volcanological data (e.g. transport directions inferred from bomb-sags and ripples) from this study confirm previous suggestions (Nielson and Sibbett, 1996; Kar et al., 1998) that the pyroclastic deposits on Ascension had two major sources: the Central Felsic Complex – which comprises the Middletons eruptive centre and the Green Mountain eruptive centre – and the Eastern Felsic Complex. The presence of thick, widespread felsic airfall deposits and welded ignimbrite on Ascension suggest that the felsic complexes have played host to several violent eruptions. Dating of the products of these complexes is limited and their relative ages are hence unknown, but field evidence suggests that eruptions from the two sources were at least in part contemporaneous.

Felsic activity on Ascension began from the Central Felsic Complex, in the form of eruptions of lavas and pyroclastic deposits, from the Middletons eruptive centre. This included the eruption of felsic and mafic pyroclastic flow deposits, the Lower Pumice airfall deposit, and hydromagmatic eruptions that produced a sequence of pyroclastic flows and surges. A major Plinian-style eruption followed, which produced the widespread Middle Pumice, and is inferred to have culminated with major pyroclastic flow-forming eruption column collapse. Hydromagmatic eruptions continued from the Middletons area and the major build up of Green Mountain begun with the eruption of a major pumice-based scoria airfall deposit. Tapping of a compositionally zoned magma chamber (Sheppard and Harris, 1983; Nielson and Sibbett, 1996), or magma mixing is invoked to account for the dual composition of this deposit. Further eruptions from Green Mountain included a second Plinian-style event, which produced the Upper Pumice 1 airfall deposit and involved periodic minor eruption column collapse and two further Strombolian eruptions, which produced two further major scoria airfall deposits. Epiclastic activity also occurred, in the form of lahars or mudflows.

The Weather Post – Devils Cauldron area was the major source of the pyroclastic material of the Eastern Felsic Complex, although activity also occurred from Cricket Valley and possibly from a vent on the northeastern flanks of Green Mountain. Eruptions from these sources involved formation of pumice and scoria flows and two Plinian-style events that produced the Upper Pumice 2 and 3 airfall deposits. Thick pumiceous pyroclastic flow deposits overlie the Upper Pumice 3 and are inferred to reflect major column collapse at the climax of the Upper Pumice 3 eruption. Epiclastic activity occurred in the area, in the form of mudflows. Weather Post also sourced a sequence of pyroclastic deposits, exposed to the west of Cricket Valley, which include mafic lapilli breccia deposits, a phreatic or phreatomagmatic explosion breccia and extensive stratified ash deposits with interbedded

breccias. These deposits have a limited areal extent suggesting that they may have been deposited in a pre-existing caldera. The upper ash units display sedimentary-style bedforms, and may be pyroclastic (base-surge) or epiclastic (reworked, fluvial) in origin. An epiclastic origin for these units would have required the presence of a substantial volume of water. After the deposition of these units, a phreatic or phreatomagmatic explosion formed the crater of Cricket Valley.

Several large pyroclastic eruptions have occurred on Ascension. The most violent eruptions occurred from the felsic centres in the central and eastern parts of the island and produced large volumes of tephra (pumice and scoria lapilli and ash) and substantial pumiceous ignimbrite deposits. The largest eruptions are inferred to have been subplinian or Plinian in nature, and to have involved the deposition of more than 0.2km^3 of airfall material, from eruption columns of more than 10km in height. Recurrence of such explosive activity on Ascension would pose a major threat to the safety of the island's residents, as well as causing potential damage to property and rendering the island's runway (used frequently by the RAF and USAF) inoperative. Potentially more hazardous, though, is the eruption of pyroclastic flows and surges, both of which have occurred on Ascension. The deposits of such flows and surges sampled on Ascension typically display emplacement temperatures in excess of 300°C (and several in excess of 580°C), demonstrating that they have great destructive power. However, the most recent airfall activity on Ascension has been the eruption of minor localised deposits associated with the formation of scoria cones from satellite vents, particularly in the northwestern parts of the island. In addition, field mapping suggests that even the major pyroclastic flow deposits exposed on Ascension do not cover extensive areas and perhaps travelled only as far as a few km from source. Moreover, Nielson and Sibbett (1996) suggest that little surface hydrothermal alteration has occurred on Ascension and they find no evidence of hot spring or fumarolic activity, suggesting that the magma chamber that fed the felsic pyroclastic eruptions may no longer be active.

ACKNOWLEDGEMENTS

Many people have helped and supported me during my time at Oxford, and without filling up too many pages, I'd like to thank a few of them here.

Firstly, huge thanks to my supervisors: to Buffy McClelland, for her support, encouragement and advice in both scientific and personal matters (and for fun field trips), to Gary Wilson, for stepping in at short notice, to read so much so quickly, and for putting up with my arguments (and *occasionally* correcting my grammar), and to David Bell, for introducing me to Ascension Island in the first place and for highly civilised dinners with Stella and the World Service.

Thanks to Leon Bardot, for invaluable field assistance and for being a good companion down at the Volcano Club, and thanks also to Brian Daniels and Phil Jackson for their excellent running of the palaeomag lab (and for exciting high-speed trips to Wallingford).

Thanks to John Watson and Peter Webb at the Open University for their help with XRF analysis.

Funding for the project came initially from ROPA (grant ROPA/96/98 [GR3/R138]) and I am grateful for additional funding from NERC, the Burdett-Coutts fund and University College.

Thanks to all of the friends I have made during my time at Oxford, for making my time here fun (if a little prolonged). In particular, I would like to thank Chris, Chris and Keith, for silliness, excellent parties and courgettes, Conall and Liz, for many beers and good times and for looking after me and Leo, for saving me with many fine evenings and too many bottles of wine. Thanks also to Rick for his love, patience and generosity.

Finally, I would like to thank my family: Penny, Nick and James, for their love and support, without which I would never have been able to get to where I am now. This is for them.

CONTENTS

Abstract	i
Extended abstract	ii
Acknowledgements	vii
Contents	viii
CHAPTER 1: INTRODUCTION	1
1.1 THESIS AIMS	4
1.2 THESIS OUTLINE	5
1.3 ASCENSION ISLAND	5
1.3.1 INTRODUCTION AND GEOLOGICAL SETTING	5
1.3.2 GENERAL GEOLOGY AND ERUPTION HISTORY	8
1.3.2.1 DEFORMATION AND FAULTING	12
1.3.2.2 SUB-SURFACE GEOLOGY	12
1.4 VOLCANIC DEPOSITS	13
CHAPTER 2: PYROCLASTIC DEPOSITS AND FIELD GEOLOGY	17
2.1 PYROCLASTIC ERUPTIONS AND PRODUCTS	17
2.1.1 MECHANISMS OF EXPLOSIVE ERUPTION	17
2.1.2 PYROCLASTS	19
2.1.3 TYPES OF PYROCLASTIC ERUPTION	20
2.1.4 ORIGINS AND FIELD CHARACTERISTICS OF PYROCLASTIC ROCKS	23
2.1.4.1 AIRFALL DEPOSITS	24
Volcanic explosion breccias	26
2.1.4.2 PYROCLASTIC FLOW DEPOSITS	26
2.1.4.3 PYROCLASTIC SURGE DEPOSITS	29
2.1.4.4 EPICLASTIC DEPOSITS	31
Mud flows, debris flows and lahars	31
Rockslide and debris avalanche deposits	32
Fluvial and lacustrine (reworked) deposits	32
2.2 ASCENSION PYROCLASTIC DEPOSITS	33

2.2.1 AIRFALL DEPOSITS.....33

2.2.1.1 SCORIA CONES33

2.2.1.2 FELSIC AIRFALLS34

2.2.1.3 MAFIC AIRFALLS38

2.2.1.4 ASH FALLS41

2.2.2 WELDED DEPOSITS AND LAVAS.....41

2.2.2.1 WELDED DEPOSITS41

2.2.2.2 LAVAS44

2.2.3 BRECCIA DEPOSITS44

2.2.3.1 PUMICEOUS BRECCIAS45

2.2.3.2 SCORIACEOUS BRECCIAS47

2.2.3.3 LITHIC BRECCIAS47

2.2.3.4 LAVA BRECCIAS50

2.2.3.5 STRATIFIED BRECCIAS52

2.3 MAJOR PYROCLASTIC SEQUENCES57

2.3.1 NASA ROAD/PYROCLASTIC PLAIN57

2.3.2 MIDDLETONS RIDGE/VALLEY58

2.3.3 GREEN MOUNTAIN ROAD59

2.3.4 STREAKY BACON FORMATION60

2.3.5 NORTHERN GREEN MOUNTAIN60

2.3.6 WEST OF LITTLE ASCENSION FLOW60

2.3.7 EASTERN FELSIC SURGE DEPOSITS63

2.3.8 CRICKET VALLEY63

2.3.9 HUMMOCK POINT63

2.3.10 CRICKET VALLEY – WHITE HILL – SPIRE BEACH TRACK65

2.4 CONCLUSIONS65

CHAPTER 3: PALAEOMAGNETISM & PALAEOMAGNETIC CHARACTERISTICS OF PYROCLASTIC DEPOSITS.....67

3.1 GENERAL CONCEPTS67

3.1.1 MAGNETIC THEORY67

3.1.2 MAGNETIC SUSCEPTIBILITY AND FERROMAGNETISM69

3.1.3 REMANENT MAGNETISATION70

3.1.4 CURIE TEMPERATURE71

3.2 ACQUISITION OF MAGNETISATION71

3.2.1 RELAXATION TIME, SUPERPARAMAGNETISM AND BLOCKING TEMPERATURE73

3.3 METHODS OF REMANENCE ACQUISITION75

3.3.1 THERMOREMANENT MAGNETISATION75

3.3.1.1 pTRM ACQUISITION IN PYROCLASTIC ROCKS76

3.3.2 CHEMICAL REMANENT MAGNETISATION77

3.3.3 VISCOUS REMANENT MAGNETISATION78

3.3.4 ISOTHERMAL REMANENT MAGNETISATION78

3.4 DEMAGNETISATION TECHNIQUES79

3.4.1 THERMAL DEMAGNETISATION79

3.5 MAGNETIC MINERALS82

3.5.1	THE TITANOMAGNETITE SERIES	82
3.5.1.1	MAGHAEMATIZATION	83
3.5.2	THE TITANOHAEMATITE SERIES	84
3.5.3	OTHER MAGNETIC MINERALS	84
3.6	PALAEOMAGNETIC CHARACTERISTICS OF PYROCLASTIC DEPOSITS	85
3.6.1	REMANENCE CHARACTERISTICS	85
3.6.1.1	JUVENILE CLASTS	85
3.6.1.2	LITHIC CLASTS	86
3.6.1.3	REMOBILISATION (REWORKING) OF PYROCLASTIC DEPOSITS	89
3.6.1.4	SECONDARY NRM	90
3.6.2	EMPLACEMENT TEMPERATURE	92
3.6.3	MAGNETIC MINERALOGY	93
3.6.3.1	MAGNETIC MINERALOGY AND VRM	97
3.6.4	SECULAR VARIATION AND MAGNETIC POLARITY	98
3.7	NEW ZEALAND PILOT STUDY	99
3.7.1	RUAPEHU AND THE TAUPO VOLCANIC ZONE	100
3.7.2	ERUPTION HISTORY	101
3.7.3	GENERAL GEOLOGY	101
3.7.4	FIELDWORK	102
3.7.4.1	SAMPLING TECHNIQUE	102
3.7.4.2	FIELD OBSERVATIONS	103
3.7.4.3	PALAEOMAGNETIC OBSERVATIONS	104
3.7.4.4	DISCUSSION	114
3.7.5	CONCLUSIONS	115
CHAPTER 4: AIRFALL DEPOSITS		117
4.1	REMANENCE CHARACTERISTICS	117
4.1.1	JUVENILE CLASTS	118
4.1.2	LITHIC CLASTS	122
4.2	EMPLACEMENT TEMPERATURES	128
4.3	MAGNETIC MINERALOGY	129
4.3.1	FELSIC AIRFALLS	129
4.3.2	MAFIC AIRFALLS	131
4.3.3	MAGNETIC MINERALOGY AND VRM	132
4.4	SECULAR VARIATION	132
4.5	GEOCHEMISTRY	135
4.6	CONCLUSIONS	139
4.6.1	PALAEOMAGNETIC INTERPRETATIONS	139
4.6.1.1	ABILITY OF JUVENILE MATERIAL TO RECORD PALAEOMAGNETIC SIGNALS	140
4.6.2	EMPLACEMENT TEMPERATURES	140
4.6.3	MAGNETIC MINERALOGY	142
4.6.4	GEOCHEMISTRY, SECULAR VARIATION AND CORRELATION	142

CHAPTER 5: WELDED DEPOSITS AND LAVAS.....144

5.1 REMANENCE CHARACTERISTICS145

 5.1.1 LAVAS.....145

 5.1.2 WELDED DEPOSITS.....153

5.2 EMPLACEMENT TEMPERATURES156

5.3 MAGNETIC MINERALOGY156

 5.3.1 LAVAS.....157

 5.3.2 WELDED DEPOSITS.....157

 5.3.3 MAGNETIC MINERALOGY AND VRM158

5.4 SECULAR VARIATION158

5.5 CONCLUSIONS160

CHAPTER 6: BRECCIA DEPOSITS161

6.1 PUMICEOUS BRECCIAS161

 6.1.1 REMANENCE CHARACTERISTICS161

 6.1.1.1 CLAST-DOMINATED PUMICEOUS BRECCIAS162

 6.1.1.2 MATRIX-DOMINATED PUMICEOUS BRECCIAS164

 6.1.2 EMPLACEMENT TEMPERATURES171

 6.1.3 MAGNETIC MINERALOGY172

 6.1.4 SECULAR VARIATION175

 6.1.4.1 CLAST-DOMINATED PUMICEOUS BRECCIAS176

 6.1.4.2 MATRIX-DOMINATED PUMICEOUS BRECCIAS176

 6.1.5 CONCLUSIONS176

 6.1.5.1 CLAST-DOMINATED PUMICEOUS BRECCIAS177

 6.1.5.2 MATRIX-DOMINATED PUMICEOUS BRECCIAS179

6.2 SCORIACEOUS BRECCIAS180

 6.2.1 REMANENCE CHARACTERISTICS180

 6.2.2 EMPLACEMENT TEMPERATURES180

 6.2.3 MAGNETIC MINERALOGY181

 6.2.3.1 MAGNETIC MINERALOGY AND VRM182

 6.2.4 SECULAR VARIATION183

 6.2.5 CONCLUSIONS183

6.3 LITHIC BRECCIAS183

 6.3.1 REMANENCE CHARACTERISTICS183

 6.3.1.1 CLAST-DOMINATED LITHIC BRECCIAS183

 6.3.1.2 MATRIX-DOMINATED LITHIC BRECCIAS188

 6.3.2 EMPLACEMENT TEMPERATURES190

 6.3.3 MAGNETIC MINERALOGY191

 6.3.3.1 CLAST-DOMINATED LITHIC BRECCIAS193

 6.3.3.2 MATRIX-DOMINATED LITHIC BRECCIAS194

 6.3.4 SECULAR VARIATION195

 6.3.5 CONCLUSIONS196

 6.3.5.1 CLAST-DOMINATED LITHIC BRECCIAS197

 6.3.5.2 MATRIX-DOMINATED LITHIC BRECCIAS199

6.4 LAVA BRECCIAS200

6.4.1	REMANENCE CHARACTERISTICS	200
6.4.2	EMPLACEMENT TEMPERATURES	202
6.4.3	MAGNETIC MINERALOGY	203
6.4.3.1	MAGNETIC MINERALOGY AND VRM	204
6.4.4	SECULAR VARIATION	204
6.4.5	CONCLUSIONS	206
6.5	STRATIFIED BRECCIAS	206
6.5.1	REMANENCE CHARACTERISTICS	206
6.5.2	EMPLACEMENT TEMPERATURES	209
6.5.2.1	THERMAL STRATIFICATION STUDY	211
6.5.3	MAGNETIC MINERALOGY	213
6.5.4	SECULAR VARIATION	214
6.5.5	CONCLUSIONS	215
6.6	MAJOR CONCLUSIONS	217
 CHAPTER 7: CORRELATION AND ERUPTION HISTORY		219
7.1	REVERSAL STRATIGRAPHY	219
7.2	CORRELATION	220
7.2.1	GEOCHEMISTRY	222
7.3	SOURCE AREAS	226
7.3.1	PALAEOMAGNETIC DATA	226
7.3.2	VOLCANOLOGICAL DATA	227
7.3.3	ISOPACH AND ISOPLETH MAPS	229
7.4	ERUPTION HISTORY	234
7.4.1	THE CENTRAL FELSIC COMPLEX	235
7.4.2	THE EASTERN FELSIC COMPLEX	238
 CHAPTER 8: CONCLUSIONS		244
8.1	PALAEOMAGNETIC CONCLUSIONS	244
8.1.1	MAGNETIC POLARITY	244
8.1.2	EMPLACEMENT TEMPERATURES	245
8.1.3	MAGNETIC MINERALOGY	245
8.1.3.1	TITANOMAGNETITE AND CRM	245
8.1.4	CLAST TYPE AS A MEASURE OF RELIABILITY FOR USE IN T _e STUDIES	246
8.2	VOLCANOLOGICAL CONCLUSIONS	247
8.2.1	ERUPTION HISTORY AND SOURCE AREAS	247
8.2.2	PRESERVATION POTENTIAL OF PYROCLASTIC MATERIAL ON ASCENSION	248
8.2.3	PYROCLASTIC STRATIGRAPHY	249
8.2.3.1	AIRFALL DEPOSITS	249
8.2.3.2	WELDED DEPOSITS AND LAVAS.....	251
8.2.3.3	BRECCIA DEPOSITS	251
8.2.4	VOLCANIC HAZARDS	252

Bibliography 253

Appendices

APPENDIX A: SAMPLING SITE DESCRIPTIONS263

APPENDIX B: EXPERIMENTAL TECHNIQUES AND EQUIPMENT281

B.1 PALAEOMAGNETIC ANALYSIS281

 B.1.1 SAMPLING TECHNIQUE281

 B.1.2 SAMPLE PREPARATION282

 B.1.3 EQUIPMENT282

 B.1.3.1 FURNACES282

 B.1.3.2 MAGNETOMETERS283

 B.1.3.3 BULK SUSCEPTIBILITY284

 B.1.3.4 TEMPERATURE-DEPENDENT SUSCEPTIBILITY284

B.2 GEOCHEMICAL ANALYSIS285

 B.2.1 SAMPLING TECHNIQUE285

 B.2.2 SAMPLE PREPARATION285

 B.2.3 EQUIPMENT286

APPENDIX C: REPRESENTATION OF PALAEOMAGNETIC DATA AND STATISTICAL ANALYSIS287

C.1 REPRESENTATION OF DATA287

C.2 STATISTICAL ANALYSIS289

 C.2.1 FISHER STATISTICS289

 C.2.2 TESTS OF RANDOMNESS OF MAGNETIC DIRECTIONS290

APPENDIX D: PALAEOMAGNETIC DATA291

APPENDIX E: GEOCHEMICAL DATA297

Chapter 1

INTRODUCTION

Volcanoes are hazardous and pose a threat not only to their immediate surroundings and population, but also to the global environment. The eruption of effusive lavas, from volcanoes such as those of the Hawaiian chain, can cause extensive local damage. However, potentially much more dangerous are the eruptions of stratovolcanoes such as Mount St Helens, Vesuvius, Krakatau and Ruapehu, which tend to be highly explosive. These eruptions commonly produce hot, high-speed pyroclastic flows and surges, which can travel more than 100km from source (Cas and Wright, 1988), incinerating anything in their paths. Lahars may also be formed both during and after these eruptions, and in some cases repeatedly for several years after the initial event. These can have equally devastating effects – for example, during the four hundred year record of eruptions at Mayon volcano (Philippines), the most fatalities (1500) were caused by a lahar generated in 1875, three years after an eruption (Rodolfo, 2000). Large quantities of ash and cinders are also produced in stratovolcanic eruptions, and these are ejected high into the atmosphere, where they may be carried great distances to rain out over vast areas. The finest particles may circle the globe and remain in the atmosphere for years after the eruption. Pumice and ash falls can not only damage property, but also cause breathing difficulties, as well as contaminating water supplies. If an eruption involves the collapse of parts of the volcanic edifice, this can also cause destruction, in the form of landslides and possibly even tsunamis, where material slides into water.

In addition to these direct hazards, stratovolcanic eruptions can cause problems over a much longer timescale. Millions of tonnes of volcanic gases (such as carbon dioxide and sulphur dioxide) can be ejected into the atmosphere by these eruptions and these can greatly affect the local and global climate. The eruption of volcanic gases and ash, from

Tambora (Indonesia) in 1815 affected the global climate to such an extent that winter conditions prevailed in Europe and North America in the following year, even in the summer months (Mills, 2000).

The potential hazards associated with stratovolcanoes are clearly great. To be able to quantify these hazards, it is necessary to have an understanding of the styles and frequency of stratovolcanic eruptions as well as the types of material that they produce. Furthermore, for accurate hazard assessment, it is vital to be able to differentiate between different types of pyroclastic deposit in the field. Primary hot pyroclastic deposits and reworked deposits pose markedly different threats because of their different modes of formation. For example, the slow reworking of pyroclastic material through an area by rivers or streams is a small threat compared to the devastation that may be caused by the passing of a pyroclastic flow. In practice, it can be extremely difficult to distinguish *in situ*, primary (hot) material from that that has been reworked (cold) from the slopes of the volcano, as many of these deposits look texturally identical. An example of this is seen in Ui (1983), who describes the difficulty in discriminating between hot, dry volcanoclastic debris flows and cold debris flow deposits. In this study, palaeomagnetic methods have been used to identify and classify the pyroclastic deposits found on Ascension Island, South Atlantic, allowing them to be placed into a temporal and geographic framework. A better understanding of the nature and distribution of the products of past pyroclastic eruptions on Ascension should enhance our ability to assess volcanic hazard around stratovolcanoes world-wide.

Stratovolcanoes (or composite volcanoes) are the most commonly encountered type of large volcano found on the Earth's surface (Cas and Wright, 1988). They are constructed from repeated eruptions of pyroclastic material and lava – sometimes from more than one vent – and commonly have a complex stratigraphy and high relief. Epiclastic processes generally have a significant influence on the development of these volcanoes (although the extent of epiclastic activity is dependent on climate and the morphology and composition of the volcano). Pyroclastic material tends to be eroded soon after deposition due to its unconsolidated nature and this material is commonly redeposited to form a ring plain around the volcano within which, *in situ*, primary hot pyroclastic material is usually absent, or present only in minor amounts.

Little is currently known about accumulation rates of material at stratovolcanoes, for two major reasons. Firstly, direct observation of these volcanoes is difficult as well as highly dangerous, meaning that few large-scale pyroclastic eruptions have actually been observed. Those few explosive eruptions that have occurred in historical times (e.g. Mount St Helens, 1980, Mount Pinatubo, 1991) have greatly enhanced volcanologists' knowledge of the mechanisms involved in these events. In general, however, monitoring of these eruptive centres has not been undertaken over sufficiently long periods to

produce meaningful results. Secondly, the preservation of the primary pyroclastic deposits of stratovolcanoes tends to be relatively poor. This is not only because of epiclastic reworking, but also because of the fact that during explosive eruptions, much of the erupted material tends to be carried away. Construction of an eruptive history and stratigraphy for these volcanoes is consequently difficult.

The palaeomagnetic technique of emplacement temperature determination can greatly enhance the study of volcanoclastic deposits, as it allows discrimination between hot and cold material. This technique, (discussed in detail in Chapter 3), relies on the fact that on cooling from elevated temperatures in the presence of a magnetic field, the magnetisation of (magnetic) grains within a rock will become aligned with the external field. In this way, the direction (and intensity) of the Earth's magnetic field becomes 'locked' into igneous rocks on formation. Aramaki and Akimoto (1957) were the first workers to use magnetism as a method of distinguishing between hot and cold pyroclastic deposits. They used the presence in a deposit of an overall magnetic signal aligned with the Earth's field direction as evidence that the deposit was emplaced hot. No such alignment would be seen in cold deposits, because the rotation of clasts during transport would produce a random array of magnetic directions between clasts. A number of subsequent workers used this technique in similar studies to distinguish hot and cold deposits, such as Mullineaux and Crandell (1962); Chadwick (1971); Yamazaki et al. (1973) and Wright (1978).

The technique has since been extended to involve the thermal demagnetisation of lithic clasts from pyroclastic deposits (Hoblitt and Kellogg, 1979). This actually provides an emplacement temperature estimate for *each clast* and from these, an overall emplacement temperature for the deposit can be estimated. Thermal demagnetisation has been used in many subsequent studies, including Kent et al., 1981; Zlotnicki et al., 1984; Arguden and Rodolfo, 1990; McClelland and Druitt, 1989; Perez Torado et al., 1994; Bardot et al., 1996 and McClelland et al., 2000. Complications may arise where juvenile material is used in this technique (McClelland and Druitt, 1989) and the majority of modern work on emplacement temperature estimation therefore involves the demagnetisation of mainly lithic material. Recent work by Erwin (2001) has assessed the validity of the palaeomagnetic method, by comparing direct and palaeomagnetic measurements from pyroclastic deposits at Mount St Helens. This work suggests that the palaeomagnetic method can indeed provide accurate estimates of emplacement temperature.

Magnetostratigraphic techniques can also be useful in the study of volcanic terrains as they can enhance stratigraphic correlation and relative dating of deposits. An understanding of the volcanic stratigraphy and eruption chronology (including eruption frequency and recentness) is vital before the hazard potential of a volcano can be assessed.

Magnetostratigraphy relies on the fact that reversals in the Earth's magnetic field (EMF) have occurred throughout geological time. As igneous rocks will lock in the direction of the ambient field on formation, rocks of the same age, (even from different locations), should therefore have the same magnetic polarity (be it normal or reversed). A well-known example of this is seen in the rocks of the ocean floor, which have a similar age (and thus polarity) at equal distances either side of the mid-ocean ridge. The changes in the direction of the EMF can be traced back through the rock record and correlated with dated units, to produce a *geomagnetic polarity timescale*, which relates geological age to magnetic polarity.

If a sequence of deposits contains a magnetic reversal and the age of at least one unit is fixed, then the reversal can be dated and hence the sequence can be fitted to the magnetostratigraphic timescale. This not only allows units of different polarity within the sequence to be dated relative to the reversal, but also allows correlation of those units with similar polarities.

1.1 THESIS AIMS

The main aim of this study has been to examine the nature, distribution and temporal framework of the pyroclastic deposits on Ascension Island, to better understand the eruptive history of the island and thus the potential hazards associated with such stratovolcanic settings.

Within this framework, individual objectives have included:

- a) mapping and classification of the pyroclastic deposits on the island,
- b) determination of emplacement temperatures and hence origins for the pyroclastic deposits using palaeomagnetic techniques, and subsequent assessment of the ratio of primary to reworked material on the island, and
- c) use of palaeomagnetic polarity information to correlate and constrain the pyroclastic deposits within a temporal and areal framework.

Field observation, mapping, volcanological and geochemical techniques have all been employed in the project. However, in the thesis, a greater emphasis has been placed on palaeomagnetic and magnetostratigraphic information, as these techniques have provided the greatest insight into the nature of the pyroclastic deposits.

Ascension Island was chosen as the study area for this project, as pyroclastic material is abundant on the island and is relatively well preserved due to high levels of aridity. A comprehensive record of the volcano's eruptive history is therefore observable in the pyroclastic deposits, making the island an ideal site to study the nature and distribution of the pyroclastic products of this type of stratovolcano.

1.2 THESIS OUTLINE

This thesis comprises information on both field and palaeomagnetic characteristics of the pyroclastic rocks found on Ascension Island. The remainder of this chapter describes the basic geology and eruption history of Ascension, including a brief description of the pyroclastic deposits. Chapter 2 provides an introduction to pyroclastic eruptions and their products and discusses the field characteristics and proposed origins of the pyroclastic rocks identified on Ascension. Chapters 3 to 6 concentrate on the palaeomagnetic aspects of the project. Chapter 3 comprises an introduction to palaeomagnetism and the palaeomagnetic characteristics of pyroclastic rocks, including information on a palaeomagnetic pilot study carried out in New Zealand. Chapters 4 to 6 contain a discussion of the palaeomagnetic characteristics displayed by three major categories of pyroclastic deposits seen on Ascension Island; airfall (Chapter 4), welded (Chapter 5) and breccia deposits (Chapter 6). In Chapter 7, field, palaeomagnetic and geochemical data are combined to correlate the pyroclastic sequences and discuss possible source areas for the deposits and the eruption history of the island. Proposed stratigraphic correlations are presented in Enclosures 1 and 2. The conclusions of the thesis are presented in Chapter 8. Field descriptions for each unit sampled on Ascension for palaeomagnetic analysis are presented in Appendix A and the equipment and techniques used for palaeomagnetic and XRF analyses are documented in Appendix B. Appendix C discusses the representation and statistical analysis of palaeomagnetic data. Palaeomagnetic and geochemical data are displayed in Appendices D and E respectively.

1.3 ASCENSION ISLAND

1.3.1 Introduction and geological setting

Ascension Island is the exposed part of a dormant composite stratovolcano. The island is located in the South Atlantic Ocean at 7°56' S, 14°22' W, approximately 100km west of the median valley of the Mid-Atlantic Ridge and 50km south of the Ascension Fracture Zone (Figure 1.1). Ascension is one of a number of hot-spot related volcanoes in the South Atlantic and its nearest neighbour is St Helena, over 750 miles to the southeast (Figure 1.1). However, the heat source that formed Ascension is now thought to be located approximately 225km southeast of the island and is distinct from those that formed the other South Atlantic islands (Brozena, 1986). Two large seamounts, located to the northwest of the island are also likely to have been produced by the Ascension hotspot (Brozena, 1986). The single cone that makes up the volcano sits on magnetic anomaly 4, rising an estimated 3600m from the oceanic crust, which has a maximum age of 6-7Ma (Harris 1982; van Andel et al., 1973; Minshull and Brozena, 1997). Although the base of the volcanic edifice covers an area of over 2000km³ (Brozena, 1986), the island itself comprises only around 1% of the total volume of the volcanic cone (Harris, 1983), with an

area of 92km² and a peak (Green Mountain) of 859m (Figures 1.2, 1.3). However, it is likely that significant subsidence (possibly 1.5 to 2km) occurred during the formation of the island (Nielson and Stiger, 1996; Minshull and Brozena, 1997). A number of studies have investigated the oceanographic and tectonic characteristics of the seafloor around Ascension Island (Van Andel and Heath, 1970; Van Andel et al., 1973; Brozena, 1986; Minshull and Brozena, 1997). However, seafloor mapping in this area shows no evidence of significant debris or scar structures, suggesting that no major collapse of the edifice has occurred (Neil Mitchell, pers. comm.).

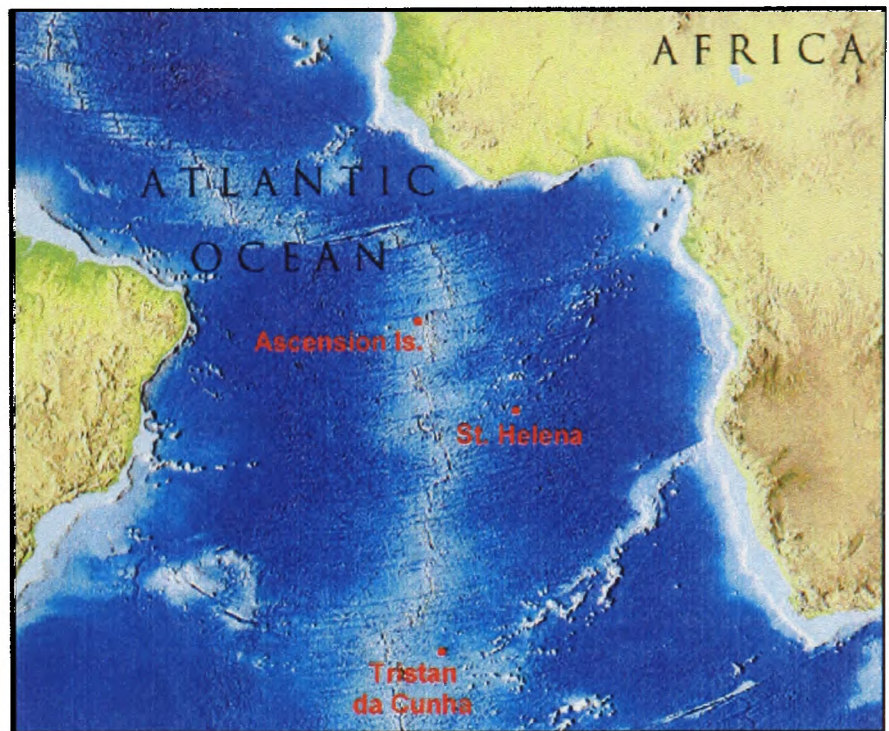


Figure 1.1: Map of the South Atlantic showing the location of Ascension Island (from Weaver, 2001).

Discovered in 1501 by the Portuguese explorer João de Nova, Ascension is now British owned with a population of around 1100. Both the British and US air forces maintain bases on the island and a NASA tracking station was also once in operation. In addition, the island is used by the BBC and Cable and Wireless as a relay station and communications point.

The climate on Ascension is sub-tropical, with consistent high temperatures and east-southeasterly trade winds. A 'rainy season' is experienced on the island between January

and April although showers occur throughout the year, especially in the southeastern parts of the island. Vegetation is sparse at sea-level, where the island is arid and desert-like, however, the amount of vegetation covering the island has increased significantly over the last few decades. Higher ground is



Figure 1.2: Green Mountain (photograph taken looking to southwest).

carpeted with lush vegetation and even tropical flora (such as the banana tree) are now seen on Green Mountain (Figure 1.2).

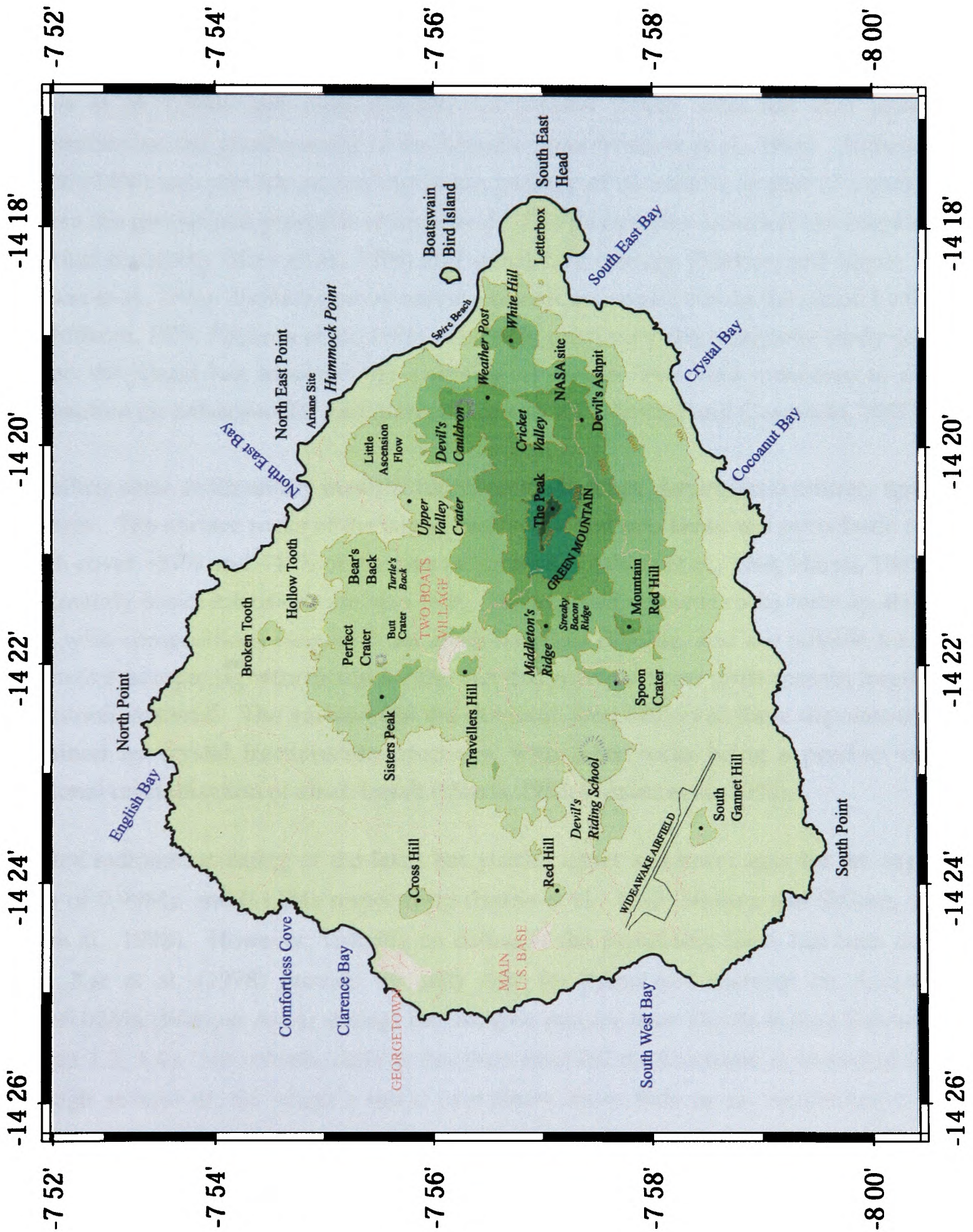


Figure 1.3: Topographic map of Ascension Island with place names. Shading represents contours of 500ft. Roads and settlements are shown in pink. Place names shown in italics are discussed later in the text.

1.3.2 General geology and eruption history

One of the first workers to make notes on the geology of Ascension was Charles Darwin, who made a study of the islands in the South Atlantic during the voyage of the *Beagle* in the 19th century (Darwin, 1876). Since that time, Ascension has attracted the interest of many workers, who have studied various different aspects of the island's geology. Geological mapping and descriptions of the geology have been carried out by Daly (1925), Atkins et al. (1964) and more recently by Weaver (2001), who has also provided information on the geochemistry of the island's lavas (Weaver et al., 1996). Nielson and Sibbett (1996) also provide an account of the geology of Ascension, as part of a project to explore the geothermal potential of the island. This project also included investigation of electrical resistivity (Ross et al., 1996) and subsurface geology (Nielson and Stiger, 1996; Hanson et al., 1996). Surface gravity surveys have been carried out on the island by (Dash and Milsom, 1973; Brozena et al., 1986). The only previous palaeomagnetic study carried out on the island has involved the sampling of certain lavas and intrusives to obtain information on palaeosecular variation on Ascension (Valentine and Czarnecki, 1997).

Excluding some sedimentary material found on the beaches, Ascension is entirely igneous in origin. The surface rocks of the island can be divided into lavas and pyroclastic rocks, which cover ~57% and ~43% of the area respectively (Atkins et al., 1964; Harris, 1983). A few (mainly basic) intrusions are also seen. The exposed volcanic rocks form an alkaline suite with compositions ranging from alkali-basalt to rhyolite, and are notable for their distinctive isotopic signatures and for the fact that many of these units contain fragments of plutonic material. The variation in the chemical composition of these deposits can be explained by crystal fractionation processes, with felsic rocks being a product of the fractional crystallisation of alkali-basalt (Harris, 1983; Weaver et al., 1996).

Limited radiometric dating of the lavas has yielded upper and lower ages for the exposed rocks of 0.99Ma¹ and 0.12Ma respectively (Harris et al., 1982; Nielson and Sibbett, 1996; Kar et al., 1998). However, virtually no dating of the pyroclastic rocks has been carried out. Kar et al. (1998) provide the only date for pyroclastic material on Ascension: 0.61±0.02Ma (feldspar Ar-Ar dating) for trachytic pumice from Devils Riding School (see Figures 1.3, 1.4). No volcanic activity has been recorded on Ascension in historical times, although several of the island's mafic lava flows show little or no weathering or soil development, suggesting that have been erupted in the last few hundred years (Atkins et al., 1964).

Many eruptions have taken place on Ascension and over 70 parasitic centres have been

¹ From Nielson and Sibbett (1996); Harris et al. (1992) quote 1.5Ma as the oldest age for the lavas sampled on Ascension.

identified aside from the main cone of Green Mountain (Harris, 1982). Volcanic activity can be broadly divided into an earlier felsic stage, and a later mafic stage and Figure 1.6 shows a simplified eruption chronology for the island. Harris (1982) and Nielson and Sibbett (1996) propose the tapping of a compositionally zoned magma chamber to explain the change from felsic to mafic volcanism on the island.

The felsic lavas and pyroclastics found on the island were sourced from two eruptive centres, the *Central Felsic Complex*, and the *Eastern Felsic Complex* (Nielson and Sibbett, 1996; Kar et al., 1998). The Central Felsic Complex (CFC) comprises the eruptive centres of Middletons Ridge and Green Mountain, and the Eastern Felsic Complex (EFC) encompasses the Weather Post – Cricket Valley area (Figure 1.3).

The Middletons Eruptive complex (MEC) played host to numerous eruptions and produced a series of pyroclastic deposits (including airfall and flow units) and interbedded rhyolite and trachyte flows, which can be seen exposed in the valleys to the south of Middletons Ridge (Figure 1.3). Units from the MEC are the most comprehensively dated of the felsic rocks on the island, with the oldest rhyolite flow of the sequence dated at $0.94 \pm 0.19 / 0.99 \pm 0.02$ Ma (Nielson and Sibbett, 1996). The majority of the sequence is cut by faults, one of which is host to a basaltic dyke that has been dated at 0.80 ± 0.03 Ma (Nielson and Sibbett, 1996). Dating and stratigraphic relationships suggest that the complex was probably built up over a period of around 0.4 Myrs (Nielson and Sibbett, 1996; Kar et al., 1998).

This eruptive centre probably also sourced the trachyte dome of the Devils Riding School (Figure 1.3). This remarkable feature was formed by the emplacement and subsequent subsidence of the trachyte beneath a pre-existing basalt flow (Daly, 1925). This formed a depression that was later filled by layers of pyroclastic airfall material, (probably also sourced from the MEC). Further subsidence and erosion produced the concentric outcrop pattern that is now seen at the surface (Figure 1.4).



Figure 1.4: The Devil's Riding School, taken looking southwest. Field of view is approximately 400m.

Green Mountain, played host to a number of eruptions that formed the main volcanic cone of the island between $\sim 0.7\text{Ma}$ and $\sim 0.5\text{Ma}$ (Kar et al., 1998). Eruptions from this centre included trachyte flows and domes, an extensive sequence of felsic pyroclastics, a number of mafic lava flows and a thick unit of basaltic cinders that cover most of the peak. Felsic pyroclastic deposits in this area include a substantial pyroclastic flow unit and two major trachytic airfalls as well as numerous smaller flows.

Eruptions from the eastern felsic complex are the most poorly constrained, but relative dating of deposits can be inferred from field relationships. Early eruptions produced most of the trachyte domes found in the area, as well as the Cricket Valley Pyroclastics (CVP). The localised extent of the CVP (Figure 1.8) has led some workers to suggest that they were deposited in a pre-existing caldera (Atkins et al., 1964; Nielson and Sibbett, 1996). The formation of a caldera on the island is consistent with the presence of welded ignimbrite that crops out on the northern flanks of Green Mountain.

Eruption of the large trachyte flow of Little Ascension (Figure 1.3) was the next major event in this area and following this, phreatic or phreatomagmatic explosions formed the volcanic depressions of Cricket Valley, Devils Cauldron and a small crater at Weather Post (Figure 1.5).

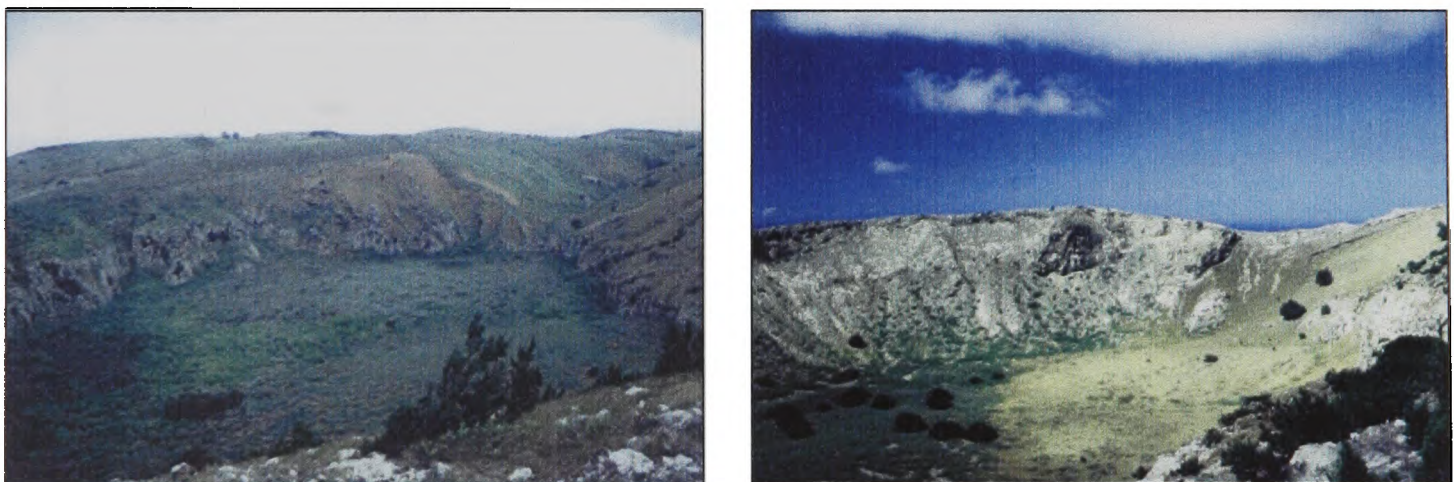


Figure 1.5: Two explosion features found in the eastern part of Ascension Island: Cricket Valley (left, field of view approximately 500m) and Devil's Cauldron (right, field of view approximately 300m).

One of these explosive events (probably the formation of Devils Cauldron) also produced a sequence of pyroclastic flows and surges that extend out onto Little Ascension flow and may be the youngest trachytic units on Ascension (Nielson and Sibbett, 1996).

The most recent activity to occur in this area has been the eruption of two small mafic flows from the side of Weather Post.

Eruptions from the island's felsic complexes may have been contemporaneous, however accurate correlation between these centres is difficult because of the lack of fixed radiometric dates.

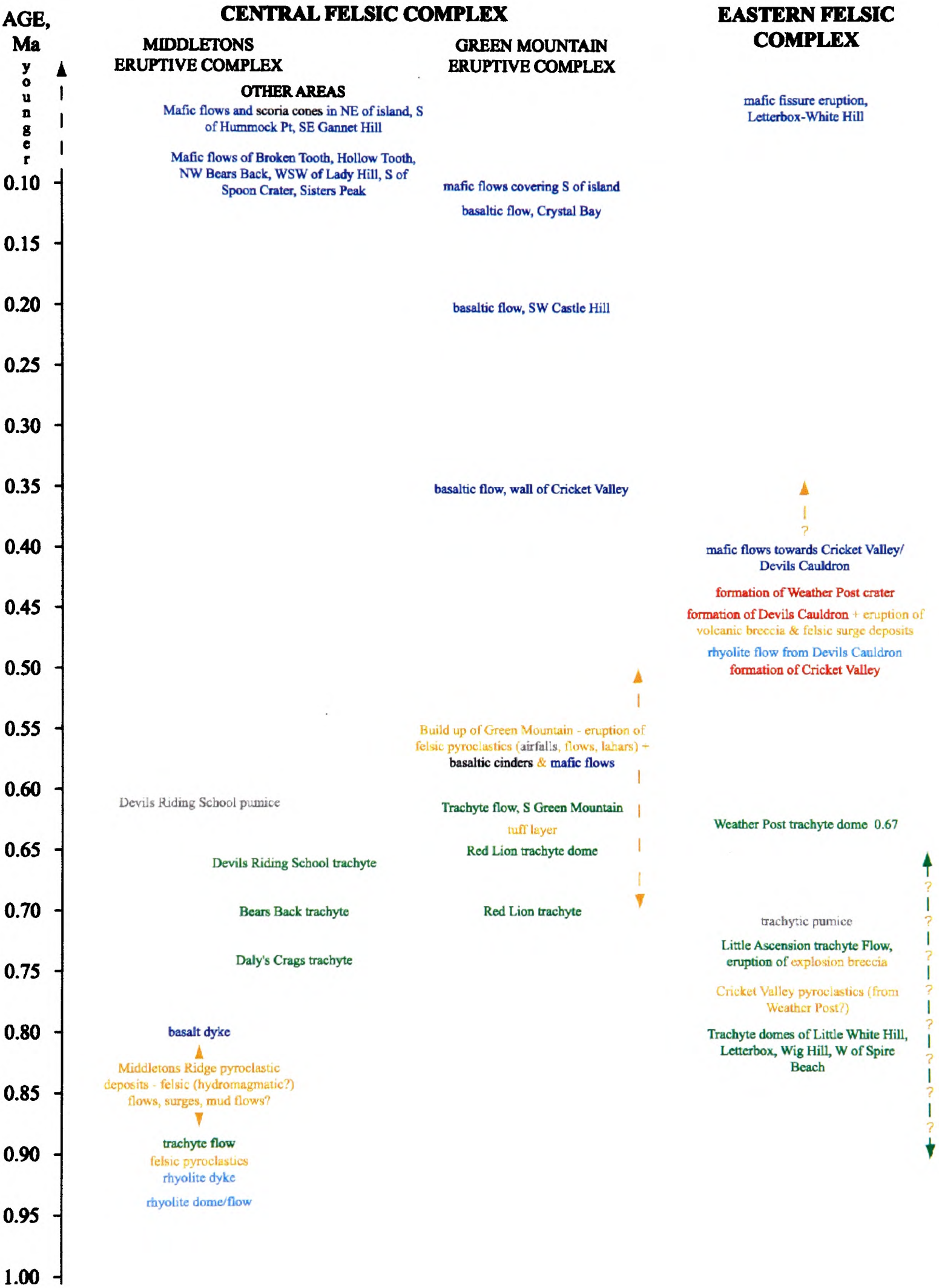


Figure 1.6: Basic eruption chronology for the exposed volcanic rocks of Ascension Island. Dates are from Harris et al., 1982; Nielson and Sibbett, 1996; Kar et al., 1998.

Mafic activity occurred later in the island's history and involved the eruption of extensive lava flows that cover most of the northwestern part of the island, as well as pyroclastic cone-forming episodes (Nielson and Sibbett, 1996). This is likely to have been some of the island's most recent activity and may have covered older felsic material that extended further north and west from the CFC.

1.3.2.1 Deformation and faulting

Four prominent fault trends have been mapped on the island, running northwest, northeast, north-south and east-west (Nielson and Sibbett, 1996). Faulting is most clearly seen on Green Mountain, where disruption of the pyroclastic sequence (by both northwest and north-south trending faults) has made correlation extremely difficult. Nielson & Sibbett (1996) suggest that much of the mafic lava and ash distributed to the south of the Mountain was erupted from northwest trending faults. East-northeast trending faults also run through the Middletons Ridge area and the western flanks of Green Mountain. East-west trending faults are found in the most eastern parts of the island, for example the fissure from which the benmoreite flow of the Devils Inkstain was erupted (Figure 1.7). According to Nielson and Sibbett (1996), all four fault trends have affected the eruptions of the most recent mafic flows, suggesting that they were recently active. They suggest that these radial fractures may have developed around the island, due to uplift as a result of melt intrusion beneath the island.

Deformation as a result of the intrusion of igneous material (typically felsic domes or flows) probably also accounts for the steeply dipping nature of some of the pyroclastic material seen on the island. An example of this is the basal stratified pumice units exposed in the Pyroclastic Plain, which dip at an angle of 41°.

1.3.2.2 Sub-surface geology

Information on the sub-surface geology of Ascension is available from a number of boreholes and a geothermal exploration well, drilled during the geothermal investigation of the island (Nielson and Stiger, 1989; Nielson and Stiger, 1996). The major conclusion to be drawn from these data is that the differentiation of a magmatic pulse to felsic compositions did not appear to occur until late in the volcano's history, possibly only since the island appeared above sea level (Nielson and Stiger, 1996).

The sub-surface data also reveal the presence of a similar series of felsic rocks to those exposed on Middletons Ridge and

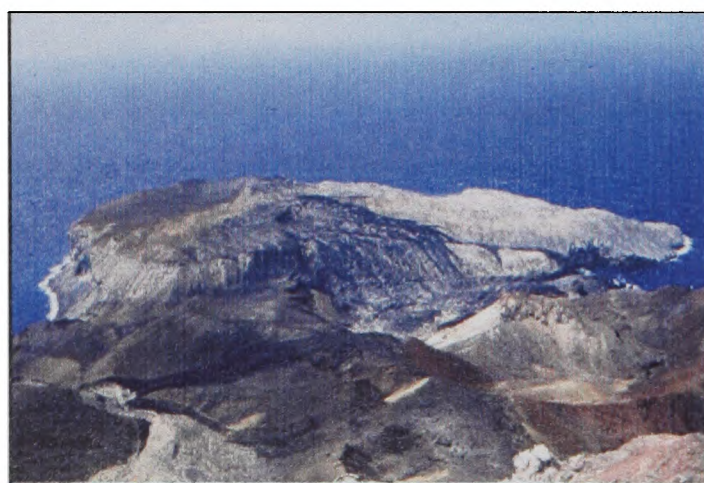


Figure 1.7: The Devils Inkstain benmoreite flow, erupted from fissure on south-east head. Field of view approximately 2km.

Green Mountain, (including a thick ignimbrite unit), in many of the sub-surface cores. However, surface and sub-surface units cannot be definitely correlated. In addition, the drilling of a borehole to the east of Cricket Valley provided the evidence of the limited areal extent of the Cricket Valley Pyroclastics that suggests that units were deposited in a pre-existing caldera. This borehole does not intersect the CVP units and thickest sub-surface accumulation of ignimbrite is found in this core.

Information on the interior of the volcano may also be gained from the examination of plutonic inclusions that are found within some of the lavas and pyroclastic units on the island. The compositions of these inclusions correlate with (and extend beyond the range of) those of the volcanic rocks, implying that the two are co-genetic (Harris 1983; Weis et al., 1987; Kar et al., 1998). The plutonic inclusions of Ascension have attracted particular attention as they contain rare minerals, and, like the lavas, are strongly peralkaline (Harris, 1983) and possess distinctive isotopic signatures. Many studies (in addition to those mentioned above) have incorporated work on the geochemical and isotopic characteristics of the plutonic fragments. These include work by the Oxford Group (e.g. Harris, 1982, 1986; Harris and Bell, 1982; Harris et al. (1982a); Sheppard and Harris, 1985) as well as Roedder and Coombs (1967), Weis (1983) and Kar et al. (1998). These studies have led some workers to invoke seawater-magma interactions as mechanisms for the eruptions of some of the material on the island (Sheppard and Harris, 1995; Kar et al., 1998). The minerals dalyite, eudialyte and vlasovite have also been identified in the plutonic blocks by van Tassel (1952), Harris et al. (1982b) and Fleet and Cann, (1967).

1.4 Volcanic deposits

Extensive mafic lava flows cover the majority of the north, western and southern parts of the island. Both ropy and blocky flows are seen and these surface features are well preserved in many flows. Most flows are associated with, (and often breach), scoria or spatter cones, erupted from central vents, although a fissure eruption (of benmoreite) is also seen on South East Head. Felsic lavas, which occur as large domes or flows, are found mainly in the central and eastern parts of the island and make up approximately 14% of the island's surface (Nielson and Sibbett, 1996). Trachyte is the predominant felsic lava type although some rhyolite is also found, which in some places is associated with obsidian. The largest trachyte flow (Little Ascension Flow) is approximately 2.5km in length (Figure 1.3).

The felsic rocks of the island display distinctive isotopic signatures that suggest that they have experienced interaction with seawater or seawater-derived hydrothermal fluids (Sheppard and Harris, 1985; Kar et al., 1998).

The island's lavas, like the plutonic inclusions, have formed the basis of many

geochemical and isotopic studies by workers including Gast (1969), O'Nions and Pankhurst (1974), Weis et al (1987) and Weaver et al. (1996).

Pyroclastic rocks are abundant on Ascension, however, in comparison to the lavas, these deposits have received relatively little attention in previous work. Where descriptions of the pyroclastics have been made in the past, these have tended to suggest that little in-situ pyroclastic material remains on the island and that the majority of deposits are reworked in origin (e.g. Atkins et al., 1964). In addition, the fresh nature of much of the pyroclastic material has prompted suggestions that any in-situ material must have been deposited recently, perhaps in the last few thousand years (David Bell, personal communication).

Recent work has included more in depth investigation of the pyroclastic deposits. For example, Nielson and Sibbett (1996) contains descriptions of the major pyroclastic sequences found on the island and makes suggestions as to the mechanisms of their eruption. Weaver et al. (1996) also sampled a number of the pyroclastic deposits for geochemical analysis. Work by Sheppard and Harris (1985) has also encompassed the pyroclastic deposits and concludes that magma-seawater interaction is likely to have been an important factor in their formation.

The pyroclastic deposits of Ascension are distributed mainly over the central and eastern parts of the island, in a number of major sequences (Figure 1.8). Most sequences are well-exposed, however in many places exposure is not continuous, making correlation problematic (see Chapter 7).

The distribution of recently erupted pyroclastic material has been affected by the prevailing trade winds from the east-southeast, however in general, there is a lack of pyroclastic material exposed in northwestern parts of the island (Figure 1.8). This may be explained if pyroclastic material was deposited in these areas and later eroded or covered by subsequent mafic lava flows. It must also be noted that wind direction may not have been constant over the last 1Myrs, meaning that earlier pyroclastic material may have been blown in other directions.

Many different types of pyroclastic unit are seen on Ascension, which range from mafic to felsic in composition. These include scoria cones, airfalls, welded and non-welded pyroclastic flow units, pyroclastic surges, explosion breccias, lahar deposits and reworked deposits.

Scoria cones have a wider distribution than other pyroclastic material and around 60 are found throughout the island. However, these typically represent discrete eruptions (both temporally and geographically) and are therefore not the focus of this study.

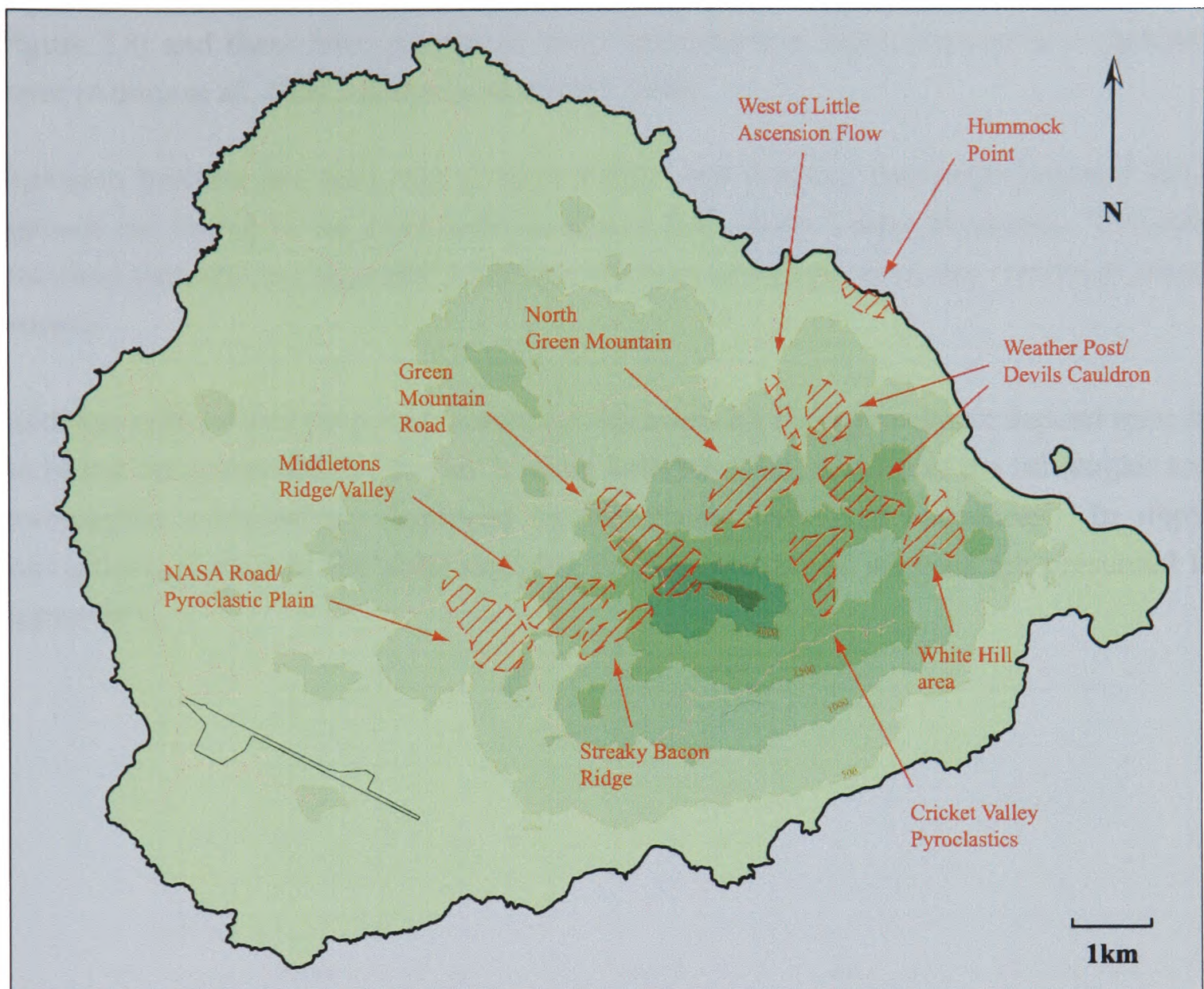


Figure 1.8: Topographic map of Ascension Island showing the locations of the major exposures of pyroclastic material (see Chapter 2 for descriptions). Shading represents contours of 500ft.

Airfall units are abundant in the central and eastern parts of the island and both mafic and felsic units are seen. Felsic airfalls are extensive and two major and several minor (mainly trachytic) units have been identified. Major units can be very thick where exposed on Green Mountain and around Middletons Ridge, reaching up to ~15m in thickness. However, these deposits may represent the products of more than one eruption. Significant scoriaceous airfalls are also present, with the majority of Green Mountain being covered by thick scoria lapilli.

Pyroclastic flow units are present in the form of ignimbrite, block and ash flows and possibly scoria flows. Major felsic pyroclastic flow units are exposed on the northern and western flanks of Green Mountain. This material ranges from welded to non-welded and the entire unit reaches a minimum of 15m thickness in places. Smaller flow units are also found on Green Mountain, on the NASA Road, and to the west of Little Ascension Flow.

Pyroclastic surge deposits, which show clear examples of sedimentary structures, are exposed to the west of Weather Post and on the surface of the Little Ascension trachyte flow. Proposed (base) surge units are also found within the Cricket Valley Pyroclastics

(Figure 1.8) and these have previously been interpreted as being deposited in standing water (Atkins et al., 1964; Nielson and Sibbett, 1996).

Explosion breccias are seen near Cricket Valley and Weather Post and proposed lahar deposits are found in the pyroclastic sequence that covers Green Mountain. Fluvially reworked deposits are typically located at the base of valleys or in dry riverbeds where present.

Field descriptions and proposed origins for the major types of pyroclastic deposit seen on the island are presented in Chapter 2, along with brief descriptions of the lithologies and stratigraphic relationships displayed by the major pyroclastic sequences. In depth descriptions of each of the units sampled for palaeomagnetic analysis are presented in Appendix C.

Chapter 2

PYROCLASTIC DEPOSITS AND FIELD GEOLOGY

This chapter comprises two sections: Section 2.1, which provides an introduction to pyroclastic eruptions and their products and Section 2.2, which discusses the field characteristics exhibited by the pyroclastic deposits on Ascension Island and the field relationships observed at some of the major exposures of pyroclastic material.

2.1 PYROCLASTIC ERUPTIONS AND PRODUCTS

Pyroclastic deposits are formed when fragmentation of magma and rock occurs during an explosive eruption. Explosive eruptions can take many different forms and produce a variety of pyroclastic deposits. The mechanisms involved in explosive eruptions, the pyroclastic material that they produce and the different types of eruption that occur in nature are described here.

2.1.1 Mechanisms of explosive eruption

To what extent a volcanic eruption will be explosive depends on a number of factors, including the presence or absence of water and the size and shape of the volcanic vent. However, the major factor governing explosivity is the composition and (more specifically) volatile content of the erupting magma. Deep in the crust, the pressure exerted on the magma (confining pressure) is high enough to keep these volatiles dissolved within the magma. However, as the magma rises to higher levels, the confining pressure decreases and the volatiles begin to exsolve. This exsolution may be intensified if formation of crystals from the magma occurs because this increases the concentration of dissolved volatiles in the magma and thus the vapour pressure. The exsolution of

volatiles (dominantly water) from the magma results in the nucleation and subsequent growth of gas bubbles, which eventually occupy so much volume that they disrupt the magma and *explosive fragmentation* occurs (Figure 2.1). If this takes place in an open vent, the vesiculating magma will rapidly ascend to the open air and erupt. However, if explosive fragmentation occurs in a restricted conduit or magma chamber, this can lead to failure of the overlying rock which may produce a large explosive event such as the caldera eruption of Lake Taupo (AD186).

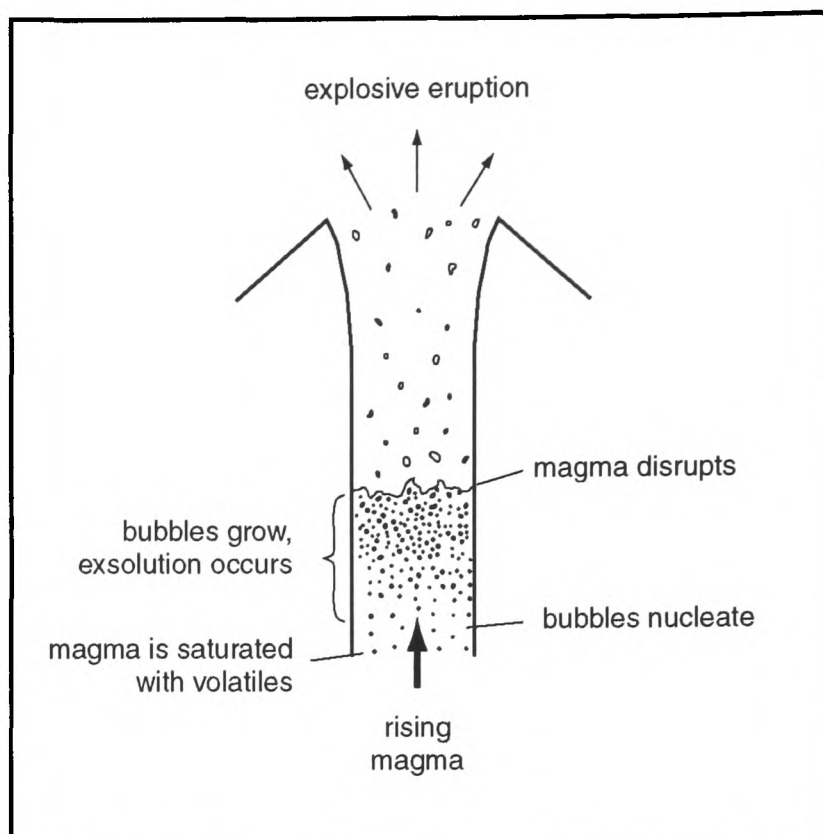


Figure 2.1: The sequence of magma saturation, bubble nucleation and growth, exsolution and magma disruption leading to eruption in an open vent. (After Sparks, 1978a, Cas and Wright, 1988).

The above eruption mechanisms can be further complicated if interaction between the magma and water occurs. This may come to pass in a number of situations, for example where the volcanic vent is beneath the sea or a crater lake or where the magma comes into contact with groundwater. In these situations, eruption is driven primarily by the explosive expansion of water to steam after it has been 'superheated' by contact with hot magma. The explosivity of such *phreatomagmatic* eruptions is dependent on the ratio of magma to water, and ranges from passive quenching, where little water:magma interaction occurs, to highly explosive eruptions, where the water:magma ratio is optimised (Morrissey et al., 2000). In the latter case, extreme magmatic fragmentation occurs (driven by both volatiles within the magma and the transfer of energy from the superheated water), and the products of the eruption are therefore typically highly fragmental (fine-grained) and widely dispersed. In some cases, little or no new magma is erupted and activity consists primarily of the explosive expansion of water to steam. Such steam eruptions can cause extreme fragmentation of the surrounding country rock and are termed *phreatic*.

An explosive eruption may also be triggered when two independently evolved magmas become mixed (Cas and Wright, 1988; Sparks et al, 1977, O'Hara & Matthews, 1981, Huppert et al, 1982a). Eruption may result from increased pressure within the magma chamber (with the intrusion of more magma) or from differences in temperature and volatile content of the two magmas. In the former case, the increase of pressure may be great enough to rupture the overlying rock, decreasing the confining pressure and possibly causing explosive fragmentation. Temperature differences can result in

explosion when felsic magma (e.g. rhyolite) is intruded by hotter, more basic magma (e.g. basalt). This will cause heating of the rhyolite, which will in turn increase the vapour pressure, possibly resulting in further exsolution. In addition, if the basaltic magma is intruded from below, lower parts of the rhyolitic magma will be heated and rise to higher levels (due to convection) where the confining pressure is lower. Heat transfer from the basalt to the rhyolite will also cause the basaltic magma to cool, which may induce crystallisation and thus exsolution. Volatile vapour pressure may also be increased if volatiles from the rising basaltic magma are able to transfer to the rhyolitic magma. Any of these actions may result eventually in explosive fragmentation.

Many pyroclastic eruptions will produce an *eruption column*, which comprises a buoyant plume of gas and pyroclasts that can reach heights of 50km. Whether or not an eruption column is formed will depend on the explosivity and style of eruption. Eruption columns have been described in detail by a number of authors, and Wilson and Sparks (1976) and Sparks (1986) divide the column into a lower *gas thrust* region and an upper *convection plume* and *umbrella region*. In the lower region, thrust is the dominant force due to the decompression of the explosively escaping gas and pyroclasts are ejected into the atmosphere. Once the column reaches a certain height however, the gas thrust wanes, buoyancy becomes the dominant force and the column billows out and upwards until its density is equal to that of the surrounding atmosphere. Here, the column spreads outwards further, forming an umbrella cloud that will rise until momentum is lost. As the column loses energy, material will fall out, producing an airfall deposit. If the column becomes too dense to sustain itself, it may collapse and in this way, pyroclastic flows and surges can be formed.

2.1.2 Pyroclasts

If any descriptions of pyroclastic deposits are to be made, it is first necessary to describe the different products or *pyroclasts* that may be generated in explosive eruptions. These can vary greatly in size and large fragments (over 64mm in diameter) are referred to as blocks or bombs, fragments between 64mm and 2mm as lapilli and fragments smaller than 2mm should be called ash. Table 2.1 provides a basic classification of the different clast types that make up pyroclastic deposits.

Juvenile is the term applied to rapidly cooled fragments of the erupting magma which may or may not contain crystals. These fragments are typically vesicular due to the explosive nature of the eruption, though vesicularity will vary depending on the composition of the magma. Dark juvenile fragments of basic to intermediate magma are called *scoria* and light, more silicic juvenile fragments are referred to as *pumice*. Scoria ranges in colour from black or brown in colour to red or orange, although the latter is typically a result of oxidation (typically of titanomagnetite or magnetite to maghaemite within the material).

Pumice is typically grey or white in colour depending on composition, however mixed pumice, which contain streaks of darker and lighter material, can be produced where magma mixing has occurred prior to eruption. Fragmentation of juvenile material produces much of the ash found on pyroclastic deposits. These ash-sized particles of juvenile material are referred to as shards and are essentially composed of the material that formed the walls of vesicles before they were shattered. *Lithic* fragments are the non-vesicular components of pyroclastic deposit. These may be *accessory* or *accidental*. Accessory lithics are parts of country rock that are exploded in the eruption but do not represent the erupting magma (for example parts of the pre-existing volcanic edifice). Accidental lithics are those that are incorporated into the deposit but were not formed by the eruption, for example fragments picked up locally from the ground over which a pyroclastic flow travels. Individual crystals may also be found in a pyroclastic deposit, especially if fragmentation has been extreme.

clast type	description
juvenile clast	Primary material erupted from the magma chamber: this may be <i>vesicular</i> , e.g. pumice, scoria, or <i>non-vesicular</i> , e.g. fragments of lava dome/spine (erupted in block & ash flows).
pseudo-pumice	Juvenile material (trachytic) found in Ascension lava breccias that varies in appearance from dense (non-vesicular) and lava-like to vesicular and pumice-like
accessory lithic	Non-vesiculated country rock (typically parts of the volcanic edifice), fragmented during an eruption and incorporated into a deposit; e.g. pre-existing lava
accidental lithic	Any non-intrinsic lithic material incorporated by a flow or surge during transport; e.g. peridotite xenoliths found in alkaline basaltic scoria deposits (Cas & Wright, 1988)

Table 2.1: Classification of clast types found in pyroclastic rocks.

2.1.3 Types of pyroclastic eruption

A number of different eruption styles have been detailed in the literature, each of which vary in terms of explosive power. Classification of these eruptions can be complicated, as the boundaries between different eruption styles are not always distinct. A common way of defining different eruption types is according to the degree to which the material that they produce is fragmented, and the area over which this material is distributed. Figure 2.2a shows different types of eruption in a plot (first produced by Walker, 1973b) of dispersal, D against fragmentation, F. Figure 2.2b shows different eruption styles in terms of eruption column height and explosiveness.

Hawaiian and Strombolian eruptions are some of the least powerful of explosive

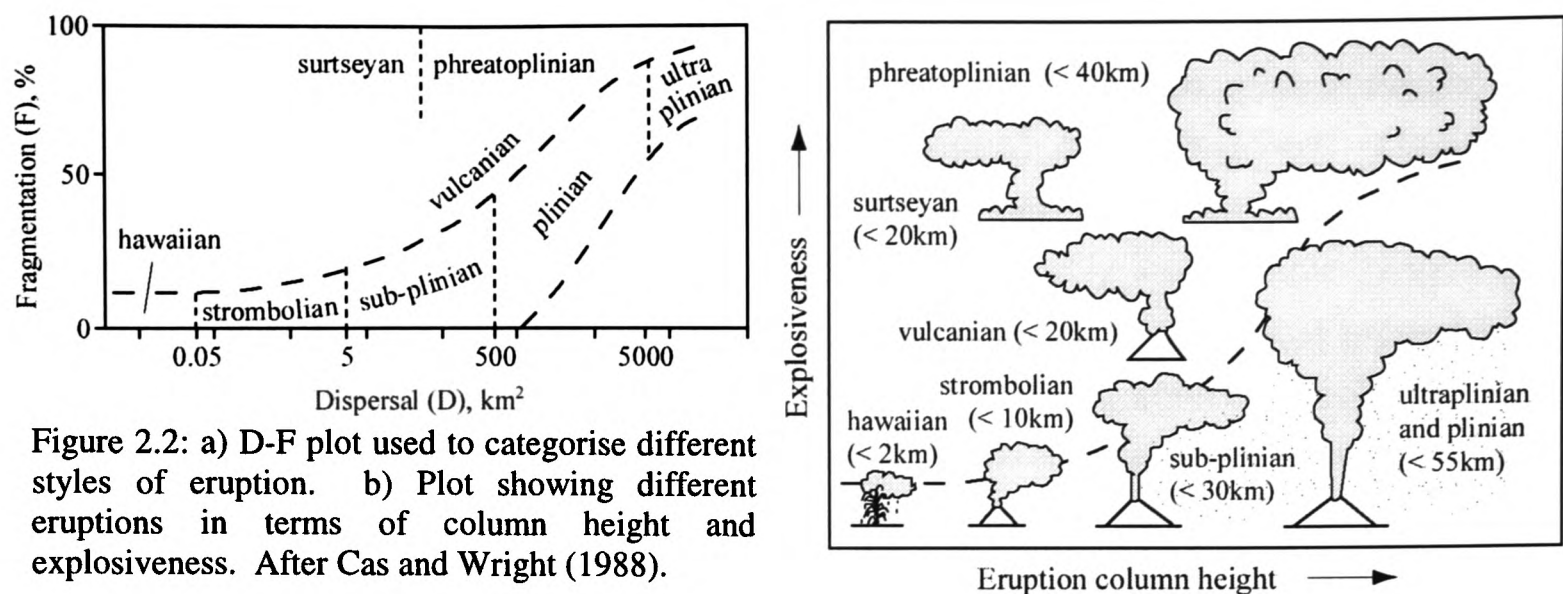


Figure 2.2: a) D-F plot used to categorise different styles of eruption. b) Plot showing different eruptions in terms of column height and explosiveness. After Cas and Wright (1988).

eruptions and are produced by basic (mainly basaltic) volcanoes such as those in the Hawaiian chain and Stromboli. Fragmentation and dispersal are relatively low in these eruptions. In Hawaiian eruptions, the disrupting fluid magma streams out of the vent as a fountain of material that can reach heights of up to 200m ('fire-fountaining'). Strombolian eruptions are characterised by short discreet explosions, caused by bubbles rising and expanding to burst the surface of a lava lake at the vent. If this occurs continuously, an eruption column may form which can reach up to 10km in height. Near vent, these eruptions produce coarse-grained scoria or spatter deposits, which build up into cones of lava 'spatter' (dominant in Hawaiian eruptions) or scoria (dominant in Strombolian eruptions) and may also produce lava flows. The majority of scoria cones represent single, relatively short-term eruptions (weeks or months) although in some cases numerous eruptions may be sourced from the same cone, e.g. Etna (Cas and Wright, 1988). Near vent deposits contain abundant bombs and may be welded (especially in deposits of Hawaiian eruptions). Deposits are typically poorly bedded and layering may be discontinuous where material has slid downslope. Further from the vent, these eruptions produce scoria fall deposits although these tend not to reach thicknesses much greater than 5m and may be restricted to areas around and downwind of the vent.

Plinian eruptions (named after Pliny the Younger who witnessed the Plinian eruption of Vesuvius in AD79) are far more powerful and the deposits of these eruptions can have an extremely wide dispersal. These eruptions tend to be associated with viscous magmas with more silicic compositions, from andesite to trachyte or rhyolite, and can last for more than a day in extreme cases (Cas and Wright, 1988). Well known examples of Plinian eruptions are the Minoan eruption of Santorini (1470 BC), Vesuvius (AD 79) and Mount St Helens (1980). Details of these eruptions can be found in Bond and Sparks, 1976; Lirer et al., 1973; Lipman and Mullineaux, 1981 (respectively) and a review of Plinian eruptions and their products in Walker, 1981b.

In Plinian eruptions, a mixture of explosively fragmenting magma and gas is ejected into the atmosphere through the volcanic conduit at high speeds. Gas velocities of up to

600ms^{-1} have been calculated for some eruptions (Wilson, 1976). Plinian eruptions produce significant eruption columns that are commonly greater than 20km in height, and from which far-reaching fall deposits (typically pumice) are sedimented. Pyroclastic flows may also be produced if the eruption column becomes too dense to support itself and collapses. Column collapse is a function of gas velocity and column height; gas velocity decreases as the eruption proceeds (as less volatile-rich magma is tapped from deeper levels in the magma chamber) but at the same time, column height tends to increase (as the vent becomes wider as it is eroded). This results in more material being carried up into the column, which becomes increasingly dense and unstable.

Fall deposits from Plinian eruptions are voluminous and can be extremely widely dispersed. These deposits are sheet-like, blanket topographic features and are typically well bedded. Units deposited close to the volcanic vent may be homogeneous, can be extremely thick (up to 25m) and are typically coarse grained (containing dm-sized lithic and pumice clasts), although larger pumice blocks tend to fragment on impact (Cas and Wright, 1988). Further from vent, the grain size and thickness of units decreases. In many units, internal grading or stratification is visible, defined by variations in grain size, or lithic, crystal or ash content. This is a result of variations in eruption column dynamics; for example, a decrease in the energy of the eruption column will be manifested within the deposit as fining upwards, as larger pyroclasts fall out of the column closer to the vent.

Sub-plinian and ultraplinian eruptions are essentially the same as Plinian eruptions, but occur on a smaller or larger scale (respectively). Sub-plinian activity is common although specific eruptions are not widely documented. In sub-plinian eruptions, deposits are less voluminous and have a smaller dispersion. Conversely, ultraplinian eruptions produce the most widely distributed deposits of all eruptions, with a high degree of fragmentation. One of the best known ultraplinian eruptions is the eruption of Taupo in AD 76, which may have produced an eruption column with a height of more than 50km (Walker, 1980).

Vulcanian eruptions commonly occur at andesitic (or basaltic-andesite) stratovolcanoes and involve individual blast-like explosions, separated by minute to hour intervals, each producing a small transient eruption column. Columns are short-lived and range in height from less than 5 to 10km (Cas and Wright, 1988). These explosions occur when gas pressure is built up by exsolution of magmatic volatiles or vaporising groundwater, in a conduit that is sealed by a cap rock (e.g. previously erupted, cooled lava). This eventually causes the cap rock to fracture, which in turn dramatically reduces the confining pressure, causing explosive fragmentation and eruption of the magma (Nairn and Self, 1978; Wilson, 1980a). Examples of Vulcanian activity are the 1888-90 eruptions of Vulcano (Aeolian Islands) and the eruptions of Ngauruhoe, New Zealand in 1974 and 1975 (Nairn and Self, 1978).

Deposits of Vulcanian eruptions are usually intermediate in composition and comprise stratified ash deposits that are widely dispersed, but voluminously small. Where column heights are greater (where explosions are more intense and sustained, e.g. Ngauruhoe 1974) coarser grained scoria fall may also be produced (Cas and Wright, 1988). Close to the vent, deposits contain larger blocks (that are transported ballistically rather than in the eruption column) but with increasing distance from vent, deposits are fine-grained, thin and are rarely preserved. Pyroclastic flows (scoria flows) are also commonly produced by these eruptions, where large amounts of material fall back around the vent (Cas and Wright, 1988), but these flows are relatively small in volume.

Surtseyan and phreatoplinian eruptions come under the category of hydrovolcanic or phreatomagmatic eruptions, occurring where there is interaction between magma and water from the sea, lakes or groundwater. This interaction produces some of the most highly fragmented pyroclastic deposits. Surtseyan is the term generally used for basic phreatomagmatic or hydrovolcanic eruptions. Examples are the basaltic eruption of Surtsey in 1963, where seawater inundated an open volcanic vent (Walker, 1973b), or the more intermediate eruption of Soufrière, St Vincent in 1979, which occurred through a crater lake (Shepherd and Sigurdsson, 1982). These eruptions are characterised by continuous hydrovolcanic explosions, which eject ash and pyroclasts in an eruption column. This type of activity produces fine-grained ash deposits, which are well-dispersed, typically show stratification (due to repeated explosions) and often contain accretionary lapilli (Cas and Wright, 1988). These pellets of ash (which are commonly internally concentric) are common features of material deposited in conditions where water is present, for example from rain flushing or steam within phreatomagmatic eruption columns (Moore and Peck, 1962; Self and Sparks, 1978). Base surge deposits may also be formed if column collapse occurs through condensation of steam (Cas and Wright, 1988). Eruption of repeated base surge deposits may build up maars, tuff-rings or tuff-cones around the vent. Phreatoplinian eruptions are the silicic equivalents of Surtseyan eruptions and tend to have higher eruption columns and produce more widely dispersed deposits than their basic counterparts (Cas and Wright, 1988, suggest that phreatoplinian columns may reach heights of around 40km). Phreatoplinian activity may be one of many different types of activity that occur during much larger rhyolitic eruptions, as was seen at Taupo, Vesuvius and Santorini (Cas and Wright, 1988). As with Surtseyan deposits, phreatoplinian deposits consist of fine-grained ash, which may be stratified and contain accretionary lapilli, and base surge deposits. With increasing distance from source, grain size and thickness of these deposits decreases.

2.1.4 Origins and field characteristics of pyroclastic rocks

Pyroclastic deposits can be placed into one of three basic groups, depending on the mechanisms that were involved in their transport and deposition. These groups are fall

deposits, flow deposits and surge deposits. Each type of deposit can be expected to display a distinctive set of field characteristics, resulting from its particular mode of formation. Hence, the spectrum of pyroclastic deposits that are seen in the field can generally be classified in crude terms as falls, flows or surges depending on their field characteristics. Some of the 'facies parameters' within which the different types of pyroclastic deposits can be discussed include: geometry, internal structure, sorting, lithic content and type, juvenile content, composition and vesicularity, clast roundness, matrix, colour and grain-size. Different processes of formation also give rise to distinct palaeomagnetic characteristics in each type of deposit and these are discussed in Chapter 3 (Section 3.6).

Here, the modes of formation and expected field characteristics of fall, flow and surge deposits are summarised. Further definitions and field descriptions of typical deposits can be found in many volcanology texts (e.g. Cas and Wright, 1988; Fisher & Schmincke, 1984). The field characteristics displayed by the pyroclastic deposits examined on Ascension Island are described later in the chapter.

2.1.4.1 Airfall deposits

Airfall deposits are formed by the fall-out of pyroclasts from an eruption column. Fall-out occurs at varying distance from the vent, depending on the size and density of the pyroclast. Larger, heavier particles will be released from the column closer to the vent, whilst the finest ash particles may be carried for several hundred kilometres before being deposited. Some pyroclasts are too heavy to be carried up into the column at all and these are ejected *ballistically*. Airfall deposits produced by silicic eruptions are likely to be more widespread than their basic equivalents, as silicic eruptions tend to be more energetic.

Three basic types of airfall deposit exist. These are *pumice* falls, *scoria* falls and *ash* falls. Pumice falls are produced by sub-plinian, Plinian or ultraplinian eruptions of highly viscous magma such as rhyolite or trachyte. Scoria falls are composed of basaltic to basaltic-andesite magma and are generally formed by Strombolian or Hawaiian type eruptions, where eruption columns are smaller and dispersal more limited. Ash falls may be deposited by a number of processes and may be a product of many different eruptive styles (e.g. phreatomagmatic or phreatic, Plinian, Strombolian or Vulcanian activity). Phreatomagmatic eruptions commonly produce ash due to the high degree of fragmentation that occurs in these eruptions, but any eruption producing fine particles may deposit ash. Ash falls may also be formed by the settling of fine material from the ash clouds that accompany pyroclastic flows ('co-ignimbrite ash-falls'). Ash is also deposited as the distal equivalent of pumice or scoria falls.

In general, airfalls form sheet-like deposits that mantle topography and maintain a constant thickness. However, the thickness and dispersal of airfall units are dependent on eruption style. Pumice falls can be very thick (up to ~25m near to the volcanic vent) and

can be extremely widespread. Scoria falls are typically less widespread and near to the volcanic vent ('near vent') form spatter or scoria cones (in Hawaiian and Strombolian activity). Further from the vent, deposits are finer grained (containing lapilli sized clasts) and are generally less than 5m in thickness. Distal ash deposits of pumice or scoria falls tend to thicken away from the vent, because fine material is carried far away from source by aeolian fractionation. Ash from phreatoplinian eruptions ranges in thickness from <1mm near vent, to up to >1m thick, more than 100km away from the vent (Cas and Wright, 1988).

Airfall deposits are typically moderately well-sorted as particles undergo aeolian fractionation during transport. However, near vent, scoria or pumice falls (or ash deposits produced by phreatic and Vulcanian eruptions) may contain ballistic blocks or bombs, which are unaffected by wind. Welding may also occur in near-vent deposits. Grain-size varies with distance from vent and is not therefore a defining characteristic for airfall deposits. Matrix is generally insignificant or absent in pumice or scoria falls, as finer material is carried further away (by aeolian processes) and deposited as ash-falls.

Airfall clasts tend to be more angular than in those seen in other pyroclastic deposits, as little abrasion takes place in the air. However, rounding of juvenile clasts does not preclude a deposit from being an airfall as abrasion may occur in the vent or eruption column. Juvenile type, colour and vesicularity are dependent on the composition of the magma being erupted. Pumice falls range from blue-grey to white and scoria falls from black to dark grey, however, many scoria deposits have a red or orange colour produced by the oxidation of iron oxides (e.g. titanomagnetite or magnetite to maghaemite). Vesicularity can vary within a single airfall unit and in some cases, pumice clasts take on a streaky appearance due to the stretching out of vesicles as material moves up the conduit, before eruption. Banded pumices may be formed if mixing of felsic and more basic magmas occurs prior to eruption.

Lithic type and content will vary between deposits, according to the composition of the magma and surrounding country rock, and depending on eruption dynamics (which will affect, for example, how much of the volcanic edifice is explosively ejected and incorporated into the eruption column). In the case of co-ignimbrite ash falls, the composition of the flow will determine that of the ash (i.e. an ash formed from a clast-rich pyroclastic flow is likely to be lithic-rich).

Internal stratification is relatively common in airfall deposits and is defined by variations in grain size (normal or reverse grading of juvenile or lithic clasts), variations in lithic content, or the presence of distinct layers of lithics, juveniles, or ash. These features are the result of changes in behaviour of the eruption column. Cross-stratification or truncation of internal layers are *not* typical features of airfall deposits. Exceptions may arise, however, where airfalls are deposited on steep slopes and slumping occurs, or

where instabilities of the incipiently collapsing eruption column produce flow-like structures within the deposits (seen for example at the tops of Plinian fall units; e.g. Cas and Wright, 1988). Other internal features that may be exhibited include accretionary lapilli, which may be formed in phreatomagmatic co-ignimbrite ash falls by rain flushing.

Volcanic explosion breccias

Explosion breccias are a common product of phreatic eruptions where magma interacts with water. In these eruptions, the ratio of water to magma is low and hence activity typically consists of steam explosions, which will fragment the surrounding country rock. The resulting lithic fragments will travel in a ballistic trajectory and fall back around the volcanic vent. Hence, they are categorised here as 'airfall' deposits, although no transport in the eruption column occurs.

Explosion breccias are deposited close to the volcanic vent due to the ballistic trajectory of pyroclasts. They are typically composed of unconsolidated, angular blocks of mainly accessory lithic material. Juvenile clasts are scarce (or absent), as little explosive fragmentation of the magma occurs in phreatic eruptions. Accidental lithics will not be significant, as the ejected material will not travel across the ground surface (as it would in a pyroclastic flow).

2.1.4.2 Pyroclastic flow deposits

Pyroclastic flow deposits are the products of concentrated high-velocity and (generally) high-temperature¹ flows of pyroclastic debris. These are a product of energetic eruptions (i.e. Plinian – Vulcanian – phreatomagmatic) and are generated by the collapse of an eruption column or a lava flow or dome. Three major types of pyroclastic flow have been identified (Cas and Wright, 1988) and these are block-and-ash-flows, scoria-flows and pumice-flows (also called ignimbrites). Lava dome or flow collapse tends to occur at andesitic to silicic volcanoes. Collapse may be simply gravitational, due to the unstable nature of the dome or flow (which is exacerbated at andesitic volcanoes, where slopes tend to be steep) or may be triggered by a landslide or explosion. Explosions occur for a number of reasons, for example due to a drop in pressure because of a landslide or sector collapse, because of the interaction of the dome or flow with groundwater, or because of a combination of factors. Examples of this type of activity are the eruptions of Mount Pelée, Martinique in 1902 and Mount St Helens in 1980 (Cas and Wright, 1988). These eruptions produce block-and-ash-flows (although these may also be produced by column collapse), which tend to be small-scale deposits with volumes typically <1km³ (Cas and Wright, 1988).

¹ Direct and palaeomagnetic measurements of pyroclastic flow deposits yield temperatures ranging from <100°C to >800°C (Cas and Wright, 1988). For example, Banks and Hoblitt (1981) record temperatures of 300-850°C for the 1981 Mount St Helens pumice flow deposits and McClelland et al. (2000) record temperatures of ~150°C to >500°C for the Taupo ignimbrite.

Scoria-flows and pumice-flows are generated by eruption column collapse. In some cases, flows may erupt directly from the vent with relatively little or no collapse occurring, while in other cases, collapse occurs due to the fall back of dense material from a small column produced by a short explosion. In large eruptive events, a higher, more maintained column may undergo partial or complete collapse when it becomes 'choked' with pyroclastic material. Scoria flows tend to be formed by smaller events, where eruptions are less energetic and thus column height is lower. The Vulcanian eruption of Ngauruhoe in 1975 produced scoria flows, as did the eruption of Cotopaxi in Ecuador (1877), where flows were reported to have 'bubbled over' the sides of the volcano (Cas and Wright, 1988). Pumice flows are likely to be formed by partial or full collapse of higher, maintained Plinian-type columns. These eruptions may be associated with the formation of a caldera, if the lithostatic pressure on the roof of the magma chamber exceeds the chamber pressure. Caldera collapse can result in very large eruption rates and to the ponding of thick ignimbrite deposits in the caldera depression.

Examples of eruptions during which ignimbrites were produced are Mount St Helens, 1980; Krakatau, 1883; Tambora, 1815 (Cas and Wright, 1988) and the Taupo eruption of AD 76 (Wilson, 1985). Sparks et al. (1978) suggests that ignimbrites are the products of the continual collapse of large Plinian columns and as such are deposited in a number of flow units. However this is not thought to be the sole mechanism responsible for their genesis, as some pumice flows (e.g. at Mount St Helens, 1980) are known to have formed from low columns (Cas and Wright, 1988).

The mechanisms by which pyroclastic flows are transported have been the subject of much study and some contention (see for example Smith, 1960a; Sparks, 1976; Fisher, 1966a, 1979; Sheridan, 1979; Wilson, 1980, 1984; Branney and Kokelaar, 1992). However, it is now generally accepted that they travel as high-particle-concentration flows that are partly fluidised by fine ash and gas. These flows can travel tens of kilometres, surmount extreme topographic barriers and are capable of transporting blocks tens of metres in diameter. Pyroclastic flows can be divided into a head, a body and a tail region (Wilson and Walker, 1982), although in some flows, the head may be poorly-developed (Cas and Wright, 1988). Erosion takes place at the flow-head, where large quantities of air may be ingested, resulting in highly fluidised and turbulent conditions (Wilson, 1980). Material deposited from this region is likely to be lithic and crystal rich and lacking in fine material ('fines-depleted'), as fine particles are carried out of the flow (elutriated) by the ingested air. Coarse pockets of fines-depleted pumice may also be formed by material 'bursting' from the pumiceous head of the flow due to the rapid expansion of the ingested air (Cas and Wright, 1988). The majority of deposition occurs from the body and tail of the flow. A more in-depth discussion of the mechanisms of transport and deposition in pyroclastic flows is beyond the scope of this thesis. However, further information can be found in work such as Sparks (1976), Wilson (1980), Wright and Walker (1977, 1981), Branney and

Kokelaar (1992) or in volcanology texts such as Fisher and Schmincke (1984) or Cas and Wright (1988).

Unlike airfall deposits, the distribution and thickness of pyroclastic flow deposits is topographically controlled, i.e. they will preferentially fill depressions or valleys. Sorting is typically poor (some flow deposits may contain lithic blocks tens of metres in diameter), and as a result, these deposits may be distinguished easily from (well-sorted) airfall deposits in most cases. Pyroclastic flow deposits typically comprise a mixture of juvenile material (which may be vesicular or non-vesicular), lithics (accessory and/or accidental), crystals and ash matrix. Grain size is not a characteristic feature, but in some deposits will decrease with distance from vent.

Many pyroclastic flow deposits are massive, however in some deposits, internal stratification is defined by grading of both juveniles and lithics (which may be normal or reversed, depending on gravitational settling, buoyancy and shear within the flow). Stratification may also be visible where a deposit is composed of a number of flow units. Flow units vary in thickness from tens of centimetres to more than 100m and in many cases also show internal grading. In addition, some ignimbrite units have been shown to display a vertical variation in composition, reflecting a change in magma composition as the eruption proceeds. This is seen in a flow unit from the Acatlan ignimbrite, where there is a change from rhyolitic (white) to andesitic (black) pumice (Wright and Walker 1977, 1981).

Many pyroclastic flow deposits exhibit a fine-grained basal layer beneath the main flow unit. These layers tend to be less than 1m (and may be just a few centimetres) in thickness and may show grading of larger juveniles and lithics (although these clasts are still fine in comparison to those within the main flow). Grading is typically reversed in the basal layer, however and a faint stratification may also be seen. Distinct field characteristics such as the presence of carbonised wood (where flows travel over vegetated areas), an orange or pink coloration (produced by thermal oxidation of iron), or welding may be seen in flows that are emplaced at elevated temperatures. Hot flows may also produce *gas segregation pipes* or pods, which are areas of relatively coarse crystals, lithic clasts or juvenile clasts formed by the removal of fine material by jets of gas escaping from the flow. Most importantly for the palaeomagnetist, hot deposits will also retain a thermal remanent magnetism.

Block-and-ash-flow deposits are principally composed of angular fragments of poorly (or non-) sorted poorly to non-vesicular juvenile material from the collapsed dome or flow. These deposits tend to be coarse grained (with blocks over 1m in diameter) and often show reverse grading of clasts. Large juvenile blocks may show radial cooling features. Basal layers are not commonly seen in these deposits.

Scoria flows and ignimbrites are poorly sorted and topographically controlled, although large ignimbrites may be so thick that they swamp the topography. Juvenile material is abundant in both and consists of basaltic to andesitic scoria lapilli and ropy surfaced clasts in scoria-flows (Cas and Wright, 1988) and pumice in ignimbrites. Pumice may be round due to abrasion during transport in the flow. Both deposits also contain ash in varying amounts. Ignimbrites are commonly massive, but reverse grading may be seen in larger clasts within scoria-flows. Either type of deposit may exhibit a fine-grained basal layer and/or overlying ash-cloud surge deposits (deposited from the ash-cloud accompanying the flow).

2.1.4.3 Surge deposits

Pyroclastic surges are low-density, turbulent pyroclastic flows. They are discussed separately here, as the mechanisms of their genesis and transport, and the characteristics of their deposits can differ from those of the high particle-concentration flows described above. However in practice, a spectrum of flow types exist and pyroclastic surges can be regarded as the low-density 'end-member' of this spectrum.

Pyroclastic surges result from either phreatic or phreatomagmatic eruptions, or can be produced in association with pyroclastic flows or falls. Unlike those flows described previously, pyroclastic surges travel as dilute, expanded turbulent masses. Three main types of surge can be distinguished which are base surges, ground surges and ash-cloud surges (Cas and Wright, 1988). Base surges are the product of phreatic or phreatomagmatic explosions or the collapse of a phreatic or phreatomagmatic eruption column (or both). The surge cloud rapidly expands radially from the vent in a blast that can travel at speeds of 100ms^{-1} (value from Moore, 1967, from the eruption of Taal volcano in the Philippines in 1965). As they are produced from eruptions in which water is involved, base surges are often wet and cold, but hot, dry surges can be produced where the water:magma ratio is low enough. The repeated eruption of base surges can build up volcanic forms known as *maars*, *tuff rings* or *tuff cones* around the vent. This type of activity is a common product of basaltic volcanoes, but eruptions of intermediate or more silicic compositions (e.g. andesite, rhyolite) may also produce base surges, especially where a crater lake is present (e.g. Ruapehu, 1975; Cas and Wright, 1988). Ground surges and ash-cloud surges are both formed in association with pyroclastic flows, although it is thought that ground surges may also be produced by minor column collapse without the generation of pyroclastic flows (Cas and Wright, 1988). Ground surges are dilute clouds that precede dense pyroclastic flows, and their deposits are typically found in association with the bases of pyroclastic flow units. These surges may be formed either by a directed blast from the vent (e.g. Mount St Helens, 1980), by minor collapse of the margins of the eruption column, or by the jetting of gas and ash from the head of the pyroclastic flow. Ash-cloud surges form the high-temperature billowing clouds that are seen rising above pyroclastic flows and are formed by elutriation of fine material from the underlying flow.

These clouds can be particularly dangerous if they become detached from the underlying flow as they can move rapidly over the ground surface whereas the underlying flow may be confined to topographic lows. Both ground and ash-cloud surges produce thin stratified deposits of juvenile material and ash, although in the case of ash-cloud surges, much of the material carried is deposited simply as an ash-fall.

Pyroclastic surge deposits typically mantle topography (in contrast to flow deposits), but will also accumulate in depressions. Single flow units are usually thin and sheet-like, but the build-up of many individual units can result in a deposit of great thickness. Different types of surge will produce deposits with different grain sizes, but in general, juvenile fragments in surge deposits are finer grained than those within flow deposits. Sorting in surge deposits is generally better than in flow deposits (because surges are less concentrated). However, a deposit comprising many surge layers may show poor sorting overall due to pulsing of the eruption.

Surge deposits commonly show sedimentary-style (depositional) structures, such as ripples, dunes and low-angle cross-stratification, because of the mechanism involved in their transport. These structures are a characteristic feature of surge deposits although in some cases, it may be difficult to distinguish these from structures formed by epiclastic processes (i.e. fluvial processes).

The deposits of *base* surges typically range in thickness from a few centimetres or metres (as is commonly seen at stratovolcanoes) to more than 100m at some phreatomagmatic volcanoes. Deposits are usually wedge-shaped in cross-section, thinning away from the vent and usually reaching only a few km in distance. Deposits are stratified and individual base surge layers may be interbedded with airfall or flow layers near to the volcanic vent. Juvenile clasts vary in composition depending on magma type, but are typically lapilli-sized or smaller due to the large degree of fragmentation that occurs in phreatomagmatic eruptions. Large lithic clasts (accessory or accidental) may be present in these deposits and ballistic clasts form bomb sags near the vent. Phreatic surge deposits contain little juvenile material and consist mainly of accessory lithics, with some accidental lithics.

Base surge deposits commonly show internal structures such as unidirectional or climbing dune-forms but may also show planar bedding, although this may contain low angle truncations (Cas and Wright, 1988). Accretionary lapilli are common and vesicles may be present in fine-grained layers, formed by the trapping of air or steam within the water-saturated deposits.

Ground surges also produce stratified deposits although these tend to be much thinner and are usually less than 1m in thickness. Ground surge deposits are expected to be found directly beneath the base of pyroclastic flow deposits. The composition of the

ground surge deposit will reflect that of the pyroclastic flow or eruption column from which it was derived, although these deposits may be richer in lithic material than accompanying flow deposits. Deposits may contain large lithic clasts, (due to the high-energy conditions of transport and deposition), however juvenile clasts tend to be lapilli-sized. Depositional structures may be present in these deposits, as well as gas segregation pipes or carbonised wood (where surges are hot).

Ash-cloud surge deposits are composed of stratified layers of fine ash, which generally do not build up to be more than 1m in thickness. These deposits mantle the top layer of the associated pyroclastic flow and their composition and grain size will be defined by the parent pyroclastic flow. Low energy conditions prevail in ash-cloud surges and hence they will not transport large particles, however, lapilli-sized vesicular juvenile clasts may be light enough to be carried. Ash-cloud surge deposits may also show depositional bedforms and gas segregation pipes.

2.1.4.4 Epiclastic deposits

As mentioned in Chapter 1, epiclastic processes can play a significant role in the development of volcanoes, particularly stratovolcanoes such as Ascension. Many different epiclastic processes occur at volcanoes, which give rise to the erosion, transportation and redeposition of pre-existing volcanic material. These vary according to the transport medium involved (i.e. air, water or ice) and may generate large volumes of volcanoclastic material. The deposits produced by such processes therefore deserve to be described along with primary pyroclastic deposits. These deposits can look very similar to primary pyroclastic deposits in the field and in some cases, identification by palaeomagnetic methods may be the only way to distinguish the two. The palaeomagnetic characteristics of epiclastic deposits are described in Chapter 6.

Some of the most common subaerial processes that occur at stratovolcanoes are mass flow processes such as rock slides, debris avalanches or mud flows and particulate processes such as reworking by rivers. Some of the major deposits generated by such processes are mud flows and lahars, rockslides and debris avalanches and fluvial or lacustrine (reworked) deposits. In the following descriptions, clasts are described as 'juvenile', although *sensu stricto*, this term should not be used because these clasts are no longer primary. It should be noted, therefore, that in the following section, 'juvenile' refers to previously erupted material that has since been incorporated into epiclastic deposits.

Mud flows, debris flows and lahars

Mud flows, debris flows and lahars are viscous mass flows of debris and fluid mud. Where coarse debris is present or absent, these flows are termed debris flows or mud flows respectively and where a flow contains contemporaneous volcanic debris, it is called a lahar (Cas & Wright, 1988). These flows may be formed in any setting where

slopes are high and pre-erupted volcanic debris can become saturated with water (e.g. from rain, rivers or lakes). Flows initiate due to slumping and can travel at high speeds for tens of kilometres and transport large boulders.

Mud flows, debris flows and lahars produce poorly sorted, massive matrix-supported deposits. Matrix is generally fine-grained. The composition of deposits will depend on that of the pyroclastic material from which they are derived and deposits may therefore contain juvenile clasts, lithic clasts (of any type), crystals and ash in varying amounts. Clasts may be well-rounded due to abrasion during transport. Debris flows are unlikely to show internal tractional structures because of their cohesive nature, but a finer grained basal shear zone may be present in which crude bedding can develop (Cas and Wright, 1988). Lahars may transport hot clasts and contain charred material, as they commonly accompany eruptions.

Rockslide and debris avalanche deposits

These deposits are formed when debris or part of the volcanic edifice is dislodged and slides or flows down slope. In the case of slides, the material that is dislodged maintains contact with the slope and *slides* as a coherent mass. In a debris avalanche, material *flows* down slope at speeds up to 300 km h^{-1} (Cas and Wright, 1988), producing a deposit composed of fractured debris avalanche blocks and matrix. These events may be a result of gravitational collapse, failure of the volcanic edifice or may be triggered by an eruption or earthquake (e.g. the 1980 eruption of Mount St Helens) and may leave large collapse scars on the volcanic edifice. Rockslides or debris avalanches may be transformed into mud flows or lahars if significant amounts of water are incorporated.

The deposits of these processes will vary depending on the material that is dislodged in the slide or fall. Rockslide deposits should retain the stratigraphy of the sliding mass to some degree and may be less fragmental than debris avalanche deposits. Debris avalanche deposits are characterized by a framework of blocks of the source volcano surrounded by a matrix of smaller fragments and accidental lithics (Ui et al., 2000) that typically produce a hummocky topography. Blocks are typically fractured and deformed but commonly preserve original stratigraphy. Clast sizes range from sand to blocks tens or even hundreds of metres in diameter and deposits vary in thickness.

Fluvial and lacustrine (reworked) deposits

Remobilisation of pyroclastic material by water (for example as mud flows or lahars) is common at stratovolcanoes. Surface runoff rates are high because explosive eruptions commonly result in the deposition of unconsolidated material on steep slopes and destroy surrounding vegetation (Major et al., 2000). Remobilised material may subsequently be deposited in streams and river systems or lakes (where these exist) to be further reworked (or settle in the case of lakes). The nature of the resulting deposits will vary depending on

the material being reworked, however fluvial (or lacustrine) deposits commonly show internal structure indicative of transportation and redeposition. Fluvial reworking will produce clast or matrix-supported breccias or conglomerates that contain heterogeneous clasts. Rounding of clasts will increase with reworking. Matrix in fluvial deposits is commonly sandy. These deposits typically show tractional sedimentary structures such as planar bedding, ripples, dunes or cross-stratification. Lacustrine deposits are typically fine-grained and, show planar stratification and grading, produced by settling of material through the water column.

2.2 ASCENSION PYROCLASTIC DEPOSITS

Many different types of pyroclastic deposit are found on Ascension Island. Ninety-seven different locations were sampled for palaeomagnetic analysis and at twenty-three of these locations, samples were also taken for geochemical analysis. Fourteen additional locations were sampled for geochemical analysis alone. The origins of many of the units sampled were not apparent at the time of sampling. For this reason, in this thesis, the deposits have been divided into three major groups according to field characteristics: 1) airfall deposits, 2) lavas/welded deposits and 3) breccia deposits. Breccia deposits have been further sub-divided according to petrologic characteristics, into: a) pumiceous breccias, b) scoriaceous breccias, c) lithic breccias, d) lava breccias and e) stratified breccias.

The field characteristics displayed by these deposits are described here and origins are inferred from field characteristics where possible. Lithologies and stratigraphic relationships displayed by the major exposures of pyroclastic material are discussed in Section 2.3. Full field descriptions for each of the units sampled for palaeomagnetic analysis are presented in Appendix C.

2.2.1 Airfall deposits

Airfall deposits comprise 37% of the units sampled on Ascension for palaeomagnetic analysis (samples were taken from 36 individual sites; Figure 2.3). They range from felsic to mafic in composition and include pumice and scoria lapilli deposits and ash falls.

2.2.1.1 Scoria cones

More than 60 individual cones are found on Ascension. They are commonly composed of moderately to poorly sorted scoriaceous lapilli or spatter. Scoria is black or brown when fresh, but most cones have an orange or red coloration due to the oxidation of iron in the minerals within the scoria (Figure 2.4). Clasts range from lapilli-sized or smaller to blocks tens of centimetres across. Scoria cones have a wide distribution over the island and vary in terms of shape and weathering. Many show asymmetry (with steep northeastern

flanks and shallower southeastern flanks) and in some cases basic lava flows have breached the sides of scoria cones. Erosion has caused many cones to become dissected and some of these exhibit internal stratification (e.g. Hollow Tooth, Figure 2.5).

The scoria cones on Ascension are likely to have been formed by Strombolian eruptions of mafic lava from *satellite vents*, which are a common feature of stratovolcanoes (Davidson and de Silva, 2000). The asymmetric nature of cones is probably due to preferential distribution of material by the prevailing trade winds. Scoria cones tend to be the product of short-lived, monogenetic eruptions

(Cas and Wright, 1988; Davidson and de Silva, 2000) and those exposed on Ascension therefore probably bear little relation to the remaining pyroclastic material on the island.

2.2.1.2 Felsic airfalls

Felsic (pumice) units comprise 78% of the airfalls sampled on Ascension for palaeomagnetic analysis (samples were taken from 28 individual sites). Two major falls, as well as a number of minor falls, have been identified in the Green Mountain Road –

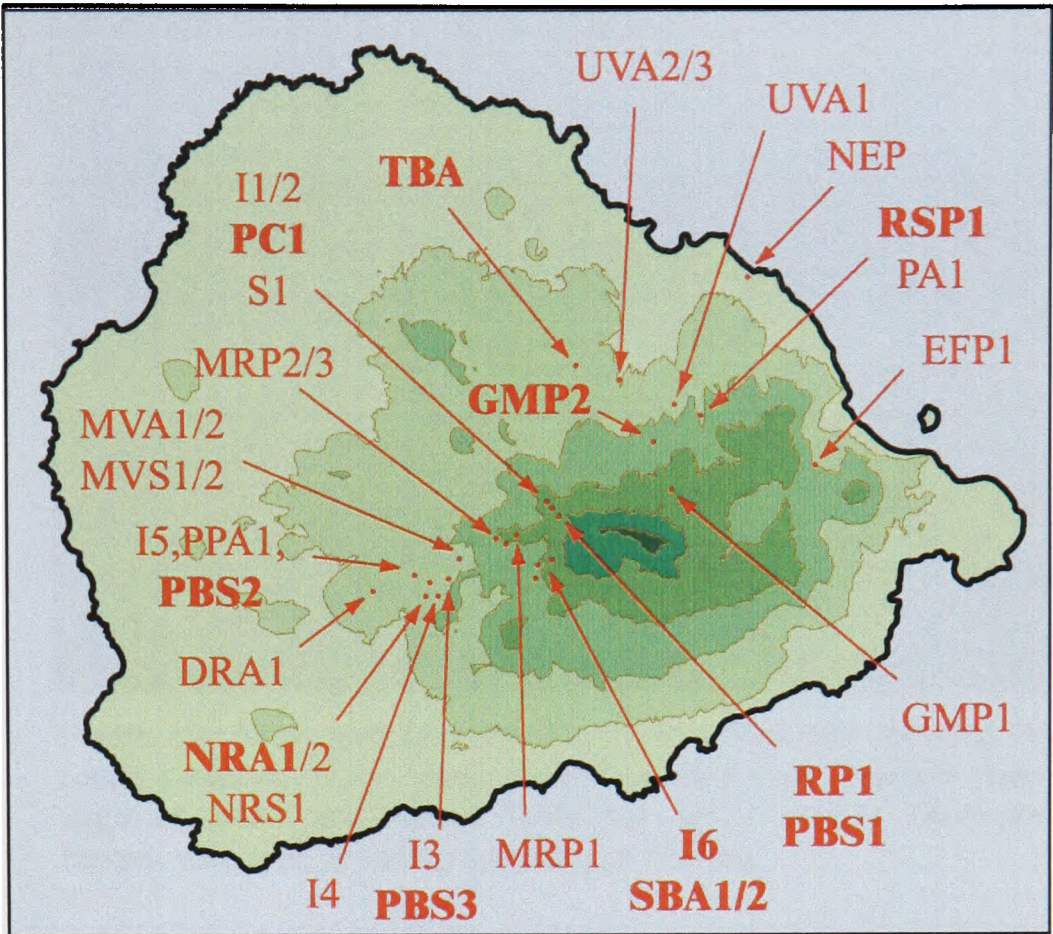


Figure 2.3: Topographic map of Ascension Island showing individual sampling locations for airfall units. Units that show features atypical of airfalls are shown in bold. Shaded areas represent contours of 500ft.



Figure 2.4: Mountain Red Hill scoria cone showing typical orange oxidation colour of scoria. Photograph taken looking to south.

NASA Road – Middletons Ridge area, and minor units are also seen in the Upper Valley Crater – Weather Post area (Figure 1.8).

Airfall units blanket the topography and in some cases mantle slopes of up to 40° (Figure 2.6). Felsic airfalls typically range from blue-grey (trachytic) to grey-white (rhyolitic) in colour and pumice clasts are generally

angular, although some units contain more rounded clasts. Pumice clasts are commonly crystal-rich and moderately to highly vesicular (although vesicularity can vary within a single airfall unit). Many units contain banded pumice. Lithic clast types include basaltic to rhyolitic lava (including glassy or banded lava), red and black scoria, obsidian (which varies from grey-green to black), welded ignimbrite and, in some cases, plutonic fragments. Lithic content varies between units. Pumice units tend to be relatively well sorted, although some localities contain pumice clasts up to 50cm in length and lithic clasts up to 50cm in length. The majority of units are matrix-poor and at some localities, pumice deposits are blackened and welded. Although at some localities pumice units are massive, the majority of units show some stratification, visible either as changes in grain

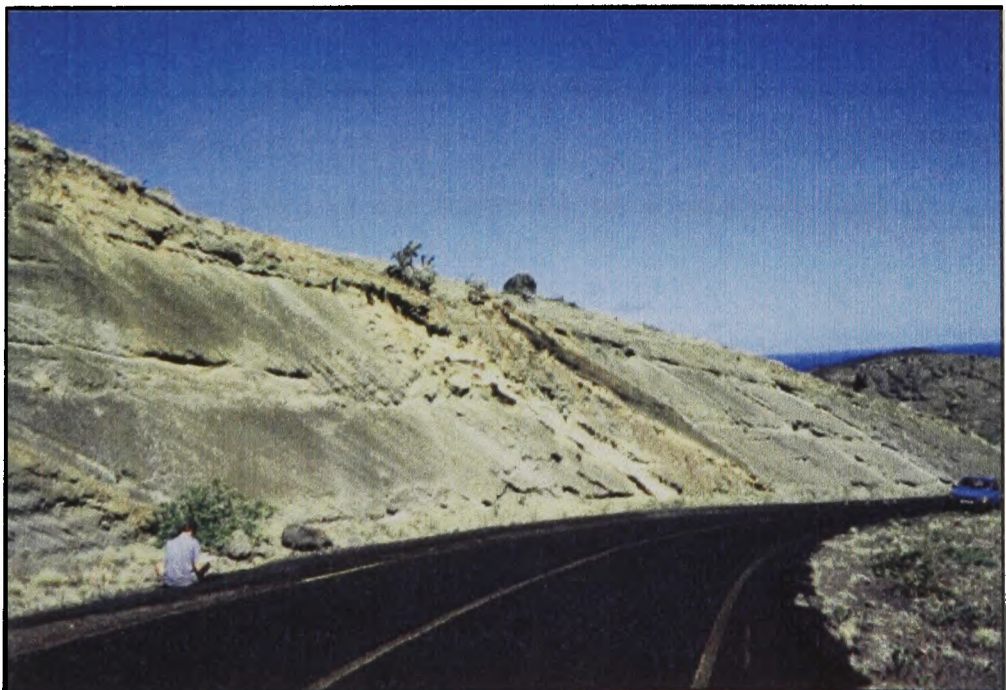


Figure 2.6: Steeply dipping pumice airfall units exposed on NASA Road (Figure 1.3). Two major airfall units are seen here (grey, well-bedded), separated by a brown flow deposit.

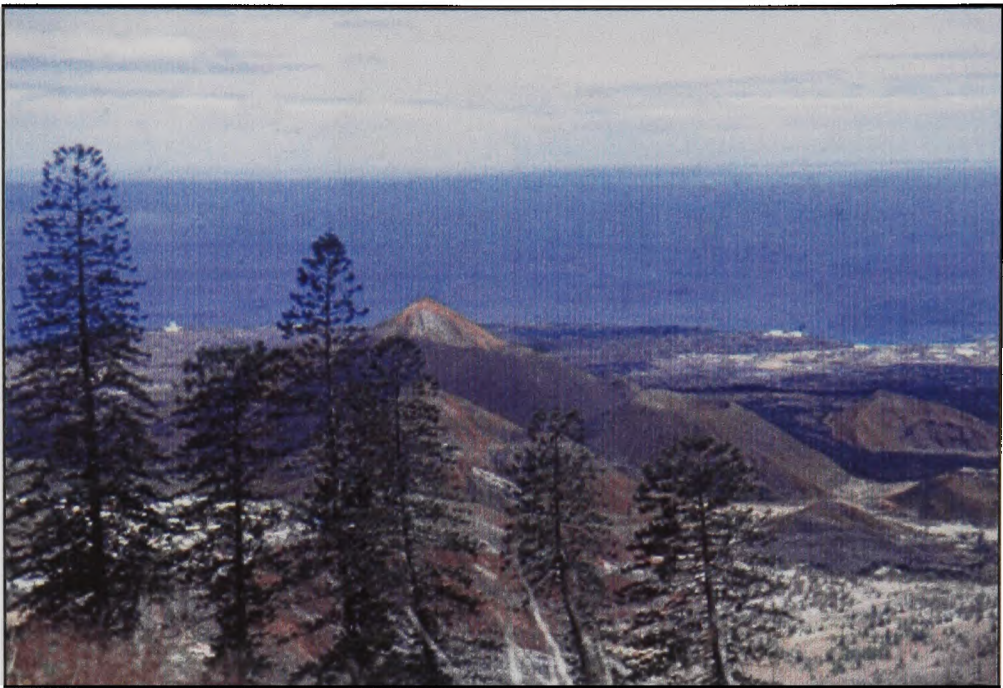


Figure 2.5: View looking north from Green Mountain showing the scoria cones of Sisters Peak (central pointed cone), perfect crater (right of centre) and Hollow Tooth (far right). Hollow Tooth has become dissected, revealing internal stratification.

size or lithic content (or occasionally colour), or as distinct layers of lithics, pumices or ash (Figure 2.7). The thickness of felsic airfall units is extremely variable. Major units reach up to ~15m in thickness e.g. units south of Middletons Ridge and on NASA Road (Figure 2.6). However, these deposits may represent the product of a number of eruptions. Further

from source, airfall units are typically less than 1m thick.

Units RP, RSP1 and SBA2 (Figure 2.3) show certain characteristics that differentiate them from the majority of airfall units on the island. RP crops out on Green Mountain road at elevations above 1900ft (~580m). It has a similar juvenile content to other airfall deposits that crop out on the mountain road, but is very lithic rich, with a concentration of lithics at the base of the unit. RP also contains spatter material and has a number of interbedded thin pink ash layers. Ash layers contain mm-sized lithics and in some areas are truncated or have been deformed by clasts from overlying layers. RSP1 is located at the base of a thick sequence of pyroclastic deposits, to the west of Little Ascension Flow (Figure 1.8). This unit is unusual in that it contains a cemented ashy matrix that can be seen coating clasts. The deposit is greater than ten metres thick and contains a wide range of lithic clast types, including dense plutonic fragments. SBA2 is a coarse unit that crops out on a spur to the south of Middletons Ridge, west of Green Mountain (Figure 1.8). It contains pumice clasts up to 20cm in length and lithic clasts up to 12cm in length. Pumice clasts in SBA2 are atypically hard and cemented into the unit and some are blackened.

Some of the thicker pumice airfall units located on Green Mountain also contain blackened or pink pumice clasts (e.g. I1; Figure 2.3). Pumice clasts from these deposits are very coarse (tens of centimetres in diameter) and in some places have been plastically deformed.

Other pumice airfall units on the island (e.g. GMP2, I6, TBA1; Figure 2.3) show stratification that is atypical of airfall units, e.g. low-angle cross-stratification, lenses of pumice or lithics and truncation of ash layers (Figure 2.8). In these units, stratification increases towards the top of the unit. Low-angle cross-stratification is also a feature of some airfalls that are inclined steeply (e.g. NRA1, NASA road; Figure 2.6, Figure 1.8). Another unusual feature, seen within upper airfall units in the Pyroclastic Plain area (Figure 1.8), is the presence of chimney or pipe-like structures (Figure 2.9). These are typically a few centimetres in diameter and are composed of 1cm-sized or smaller

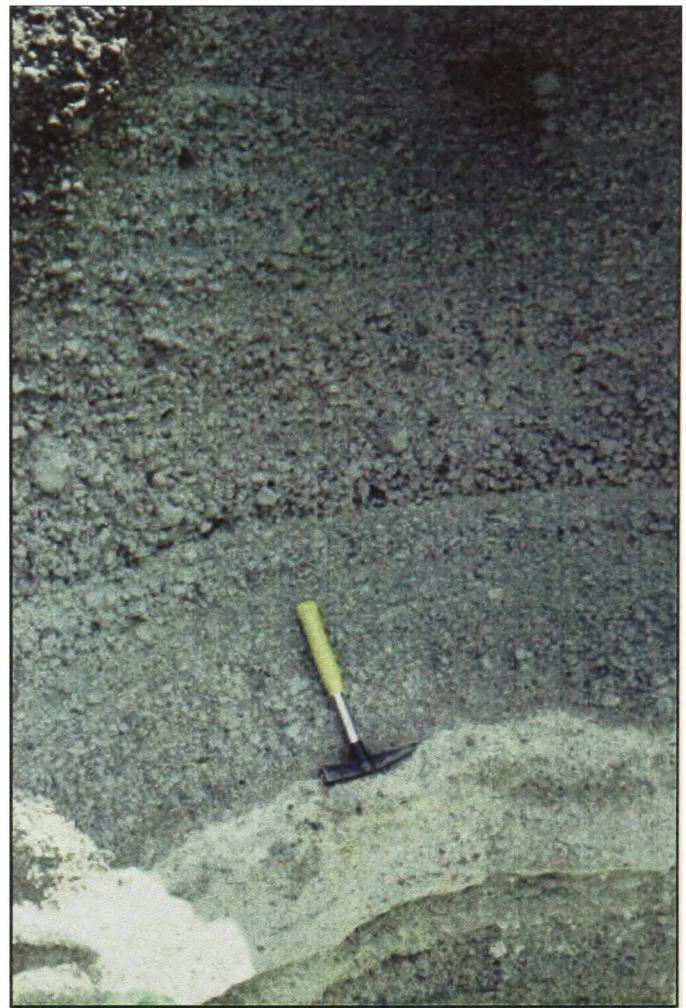


Figure 2.7: Trachytic pumice airfall (Green Mountain Rd), showing internal layering in grain size and lithic content. White unit below hammer is a flow unit separating two fall units.

(vesicular) juvenile, and lithic fragments with a cemented core of finer material. Pipes may be up to 1m in length and may cross-cut more than one stratigraphic unit.

The presence of thick, widespread airfall units indicates that relatively large (possibly subplinian) eruptions occurred on Ascension. In general, grain size in airfall deposits is a function of distance from vent, and very coarse-grained airfall units are therefore interpreted as having been erupted near-vent. However, internal variation and grading are also seen in many individual fall units and these are likely to be a product of variations in energy or pulsing of the eruption.

This can cause particles of a particular size to be released from different heights in the plume (Cas and Wright, 1988), thus producing size grading. The formation of ash layers may be a result of a temporary halt in eruption (for example as the collapse of vent material causes the conduit to become blocked). This allows fine material to settle out from the plume before recurrence of activity. This may also be the origin of lithic rich layers, which can be formed as fragments are cleared from the blocked vent. A high lithic content may also be a result of small collapses during eruption, which increase the lithic content of the eruption column (Cas and Wright, 1988).

Cross-stratification and truncation of ash layers are features often seen within flow deposits. These structures are probably the result of fluctuations in the stability of the eruption column. This can result in small or partial collapses of the column, forming



Figure 2.8: Truncation of wavy ash layer seen in trachytic airfall deposit (GMP2, north flanks of Green Mountain). Upper unit shows reverse grading of pumice clasts.

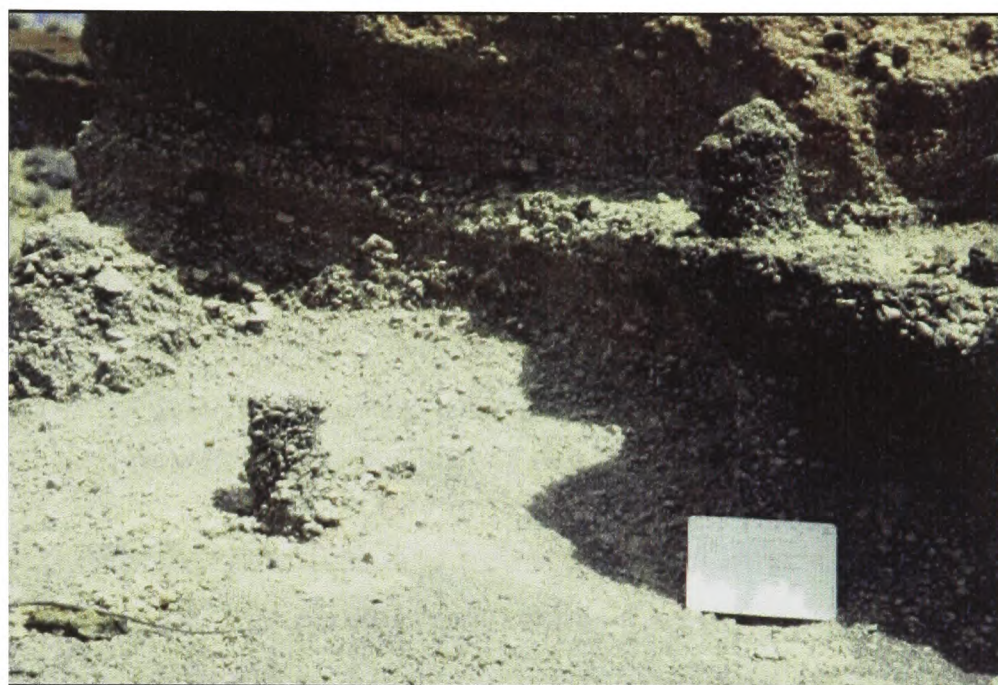


Figure 2.9: Gas segregation/fossil fumarole pipes seen within bedded trachytic airfall deposit, Pyroclastic Plain. White card is 90mm in length.

small flows or a range of deposits, which grade between fall-type and flow-type. This type of activity often precedes the complete column collapse that can form pyroclastic flows. Alternative mechanisms that may produce cross-stratification are the deposition of pumice onto steep slopes and the action of wind on tephra during fall-out (the latter has been observed in the Bishop fallout by Wilson & Hildreth, 1998). In this case, internal structure is more likely to be produced as a result of rolling or slumping of material after deposition. The pipe-like structures seen in the Pyroclastic Plain airfalls may be gas escape or fossil fumarole pipes, formed by gas streaming up through the airfall deposit from a hot flow unit beneath. Fossil fumarole pipes often contain a cement or matrix (of vapour-phase minerals e.g. tridymite or alkali feldspar) and may be formed by the percolation of gases from vesicular juvenile particles or heated groundwater through a flow after deposition.

The discontinuity of ash layers in unit RP1 is probably the result of faulting, which is common in the Mountain road area. The deformation of ash layers is likely to have resulted from the impact of falling blocks onto unconsolidated or partly waterlogged material, suggesting that RP1 may have contained water.

The blackened and hardened or deformed nature of pumices in SBA2 and I1 suggest that they are collapsed and that these deposits have undergone partial welding, which is common near-vent. SBA2 and I1 may therefore be near vent, semi-welded airfall deposits. However, an alternative origin, as the semi-welded part of a pumice flow deposit, is also possible for SBA2, as it overlies a thick welded pyroclastic flow unit.

RSP1 contains a cementing matrix, rounded pumices and heterogeneous lithic clast types. The presence of cement may be the result of exposure to water (e.g. rain) on deposition, which can cause ash particles to clump together to produce a 'sticky' ash matrix. An alternative explanation is that this is actually a flow deposit, as these are commonly matrix-rich and contain rounded pumices and varied lithic types.

2.2.1.3 Mafic airfalls

Mafic (scoria) airfall deposits are less abundant on Ascension than their felsic equivalents, comprising only 22% of airfall sampling localities (8 individual sites). However, at least three distinct airfall deposits are identifiable on Ascension. Like felsic airfalls, mafic airfalls typically comprise sheet-like deposits that drape the topography. On Ascension, they range from a few centimetres to over 6m in thickness (e.g. the scoria fall unit that caps Green Mountain, Figure 2.10). Mafic airfall deposits are easily distinguished from felsic deposits by their black or dark grey colour. However, units may have an orange colour where they have become oxidised (as is seen in many scoria cones, e.g. Figure 2.4). Juvenile (scoria) clasts are angular and vesicular, though denser than their equivalents in felsic deposits. In some deposits, juveniles vary from light, vesicular clasts to those with larger vesicles and more ropy, spatter-like surfaces. Mafic airfall deposits are typically

lithic-poor compared to felsic deposits and it was commonly a problem to find lithics for sampling. A number of units contain distinctive white plutonic fragments, typically <1cm in diameter.

Although grain size decreases with distance from vent, mafic airfall deposits are typically finer-grained than their felsic equivalents and tend to be composed of lapilli-sized clasts. As with felsic airfalls, mafic airfalls lack significant matrix. On an outcrop scale, units may be massive or stratified. Stratification is seen as juvenile-rich or lithic-rich layers or as thin lithic ash layers.

One of the scoriaceous fall deposits sampled on the island is distinctive in that it has a layer of grey-white felsic pumice at its base (Figure 2.11). This unit is exposed on the NASA Road, in Pyroclastic Plain and on the Mountain Road and was sampled at three localities: PBS1, 2 and 3 (Figure 2.3). Pumice clasts from the basal layer are highly vesicular and the thickness of the layer varies from 10 to 25cm. The boundary between felsic and mafic layers is relatively sharp, although the mafic region of the deposit contains occasional pumice clasts. White plutonic fragments are also visible in the mafic part of the deposit. Where exposed, the top of the deposit grades up into cross-stratified ash and grit layers.

Unit PC1 (Figure 2.3) is unusual in that it shows a much higher degree of internal structure than most mafic airfall units and is extremely rich in lithic material. Internal stratification tends to be non-planar and PC1 exhibits wavy (irregular) bedding and low-angle cross-stratification. Individual pods or lenses of finer-grained (generally lithic) material are also present. Several ash layers are seen within the unit, which are commonly non-continuous and contain mm-size ash-coated grains.

Mafic airfalls are a typical product of Strombolian or Hawaiian-type activity (Cas and Wright, 1988). More than three major mafic airfall deposits have been identified on Ascension, suggesting that significant Hawaiian-Strombolian activity occurred. Furthermore, the presence of mafic airfall deposits up to 6m in thick implies that a *sustained* Strombolian eruption column formed on Ascension. Thinner, minor mafic airfall units may be distal products associated with some of the larger scoria cones on Ascension.

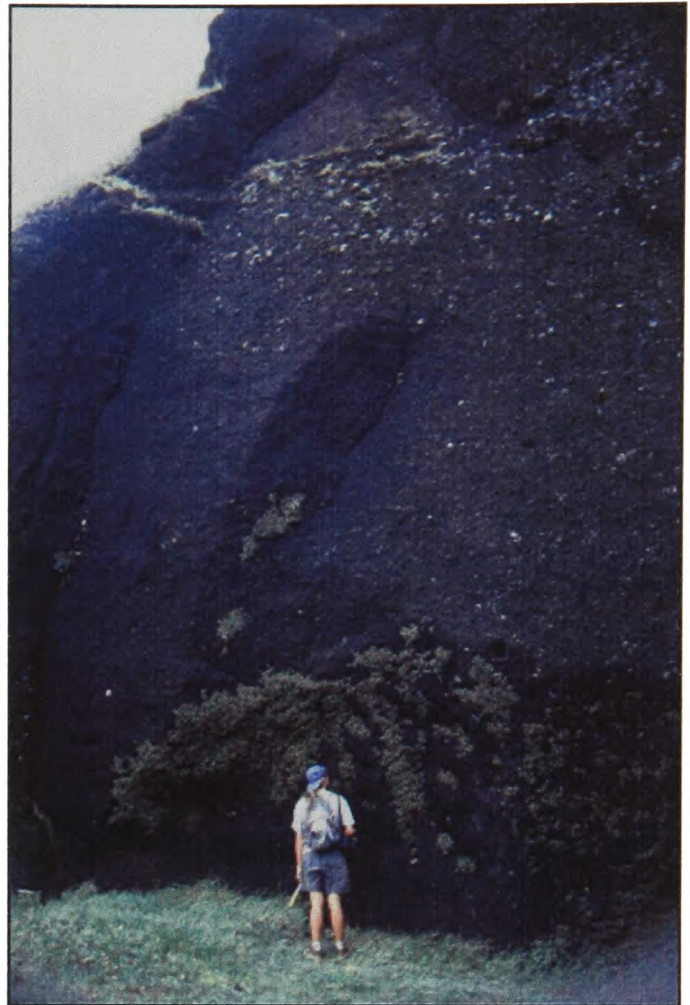


Figure 2.10: Thick mafic (scoria) airfall deposit capping Green Mountain.

Mafic airfalls on Ascension are relatively lithic-poor in comparison to felsic airfalls and this reflects the less violent nature of Hawaiian-Strombolian activity compared to Plinian activity. Deposits that contain ropy or spatter-like juvenile fragments (e.g. PC1) are interpreted as products of the least violent Hawaiian-Strombolian activity.

The two-phase nature of units PBS1/2/3 reflects a change in the composition of the material erupted over time, from silicic (white pumice) to more basic (scoria). This is interpreted as the result either of magma mixing prior to eruption or of the tapping of a compositionally stratified magma chamber. If magma mixing occurred, the intrusion of a volume of mafic magma into a felsic magma chamber may have actually been the cause of eruption (Cas and Wright, 1988; Section 2.1.1). However, the boundary between the felsic and mafic layers is reasonably sharp, which suggests that little physical mixing of the magma took place. Eruption of these deposits from a stratified magma chamber is therefore a more likely hypothesis. The tapping of deeper (more basic) levels of a stratified chamber may also explain the fact that plutonic nodules are present only in the scoriaceous part of the deposit. The presence of a stratified magma chamber beneath the island has been suggested previously by Harris (1982) and Nielson and Sibbett (1996). The (upper) mafic region of PBS is finer grained than the felsic base. This suggests that the energy of the eruption decreased with time, probably as less viscous mafic magma was tapped from deeper levels of the chamber. However, the thickness of the mafic layer (up to 5.5m), suggests that the eruption of mafic magma was still relatively vigorous. The stratified top to PBS is interpreted as the product of instabilities within the Strombolian eruption column.

The stratification seen in PC1 may also be the product of partial collapses of the eruption column, suggesting that PC1 comprises a mixture of fall and minor flow units. Partial column collapse may also explain the lithic-rich nature of the deposit. The coated grains seen within ash layers may be accretionary lapilli, which indicate the presence of water during deposition (Cas and Wright, 1988), e.g. from rain flushing.

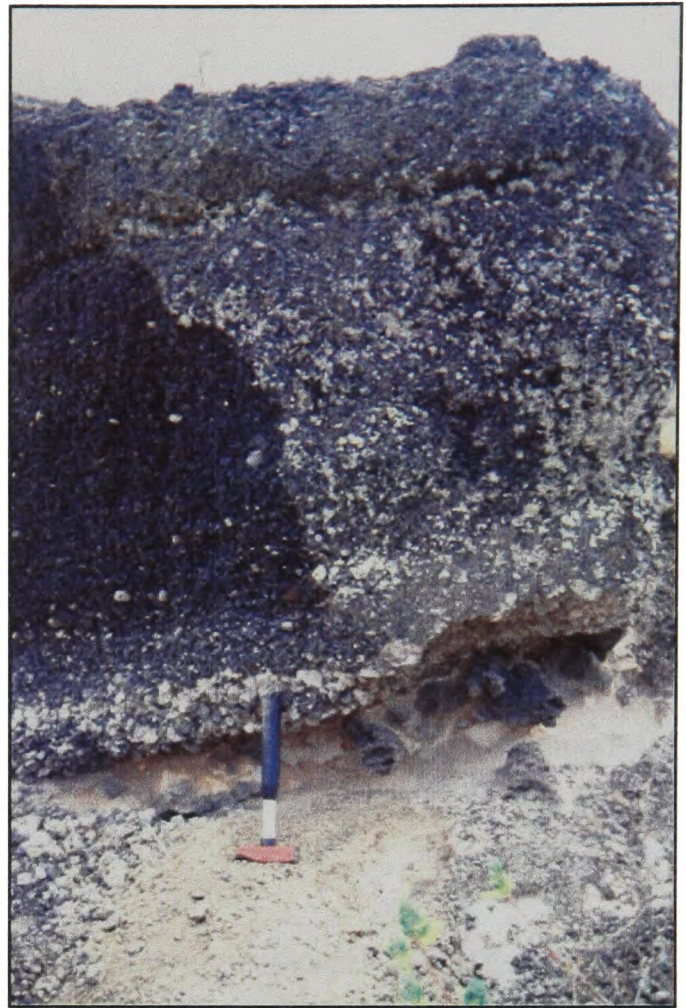


Figure 2.11: Mafic airfall deposit PBS3 (NASA road) with layer of white pumice at base (on which hammer handle is resting). Boundary between layers is relatively sharp with few pumice clasts seen in the upper part of the deposit. White clasts in this region are mainly plutonic fragments (grey spots covering right side of unit are lichen).

2.2.1.4 Ash falls

Extensive ash falls are not present on Ascension. Fine ash layers are commonly present within airfall deposits (both mafic and felsic), however these are usually no more than a few centimetres in thickness.

2.2.2 Welded deposits and lavas

Although lavas are not pyroclastic in origin, seven were sampled on Ascension for palaeomagnetic analysis, to provide information on polarity. The locations of the welded deposits and lavas sampled on Ascension are shown in Figure 2.12.

2.2.2.1 Welded deposits

Two major exposures of welded pyroclastic material were sampled for palaeomagnetic analysis on Ascension: GMI1 and SB2 ('Green Mountain Ignimbrite 1' and 'Streaky Bacon 2'; Figure 2.12).

GMI1 is the welded part of a 12m thick sequence of pumiceous deposits that crops out on the north flanks of Green Mountain (Figure 2.12). The sequence overlies a pumice airfall deposit of more than 4m thickness. GMI1 is ~4m thick and varies in colour from orange-pink to brownish-black. Texture is lava-like (lithified, coherent) and well-developed streaky fiamme can be identified (Figure 2.13). GMI1 grades downwards into ~1m of less welded, coarse 'baked' pumice clasts and angular lithics in an ashy matrix. This part of the deposit is poorly-sorted and pervades parts of the underlying fall deposit (that are inferred to have been eroded by the parent flow). GMI1 grades upwards into ~5m of semi-welded pumice breccia, which contains lithic clasts up to 1m in length. This is overlain by ~3m of cross-stratified ashy pumice flow

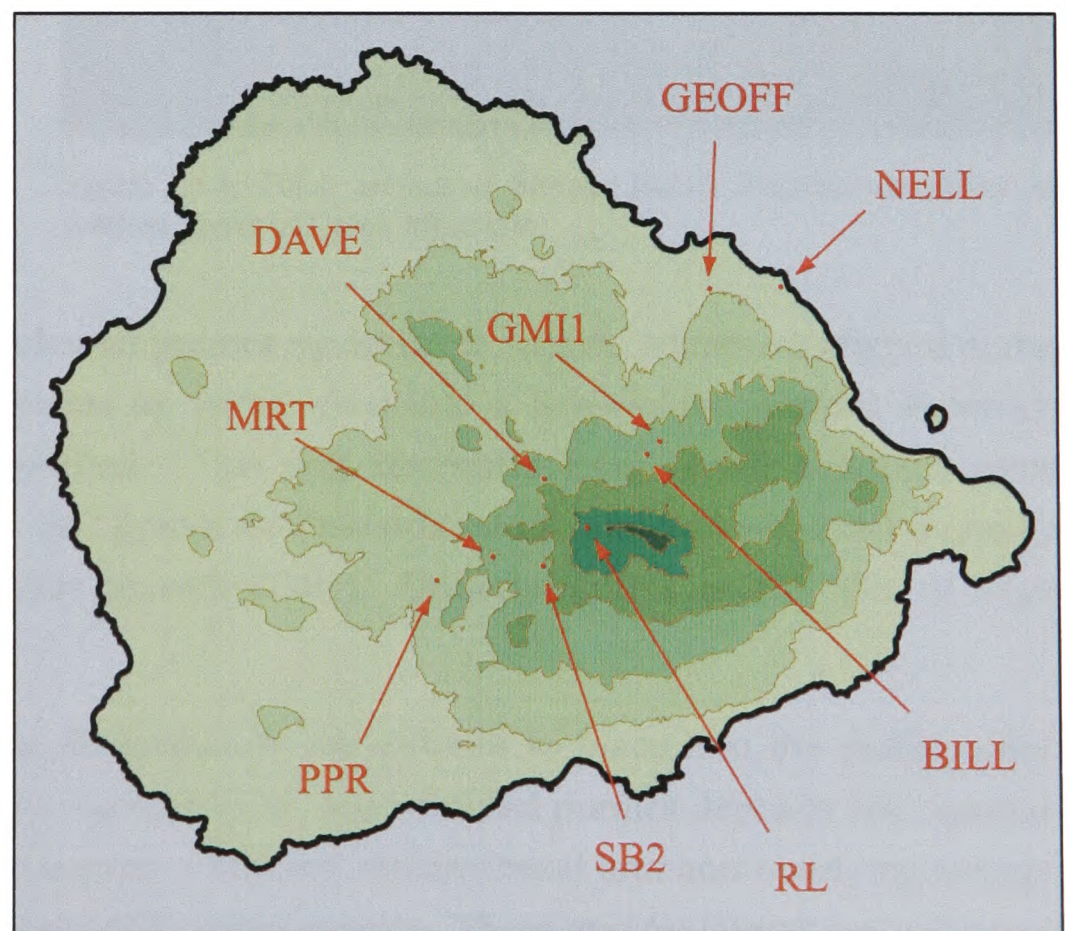


Figure 2.12: Topographic map of Ascension Island, showing individual sampling locations for welded units and lavas. Shading represents contours of 500ft.

layers. A schematic cross section showing the locations of GMI and associated units is given in Figure 2.15.

SB2 is the welded part of the 'Streaky Bacon formation', which is more than 15m thick and varies vertically and laterally in appearance and welding (Figure 2.14). SB2 is ~5m in thickness and generally has a blocky texture. At the sampling location, SB2 is dark orange-pink in colour and contains black streaky fiamme giving it a eutaxitic texture. In other areas, SB2 is purple-grey in colour and has a coherent lava-like texture. SB2 grades up into 5-6m of a very coarse, yellow-grey pumice deposit. This contains semi-

welded blocks of streaky blackened pumice up to 1m in length, which are aligned along weak bedding. This unit grades up (over ~5m) into a less-welded deposit in which individual clasts can be identified. This unit resembles felsic airfall although some pumice clasts are blackened. SB2 grades downwards into a semi-welded, blocky orange breccia unit (similar to the unit beneath GMI1). Underlying this unit is ~3m of felsic (pumice) airfall.

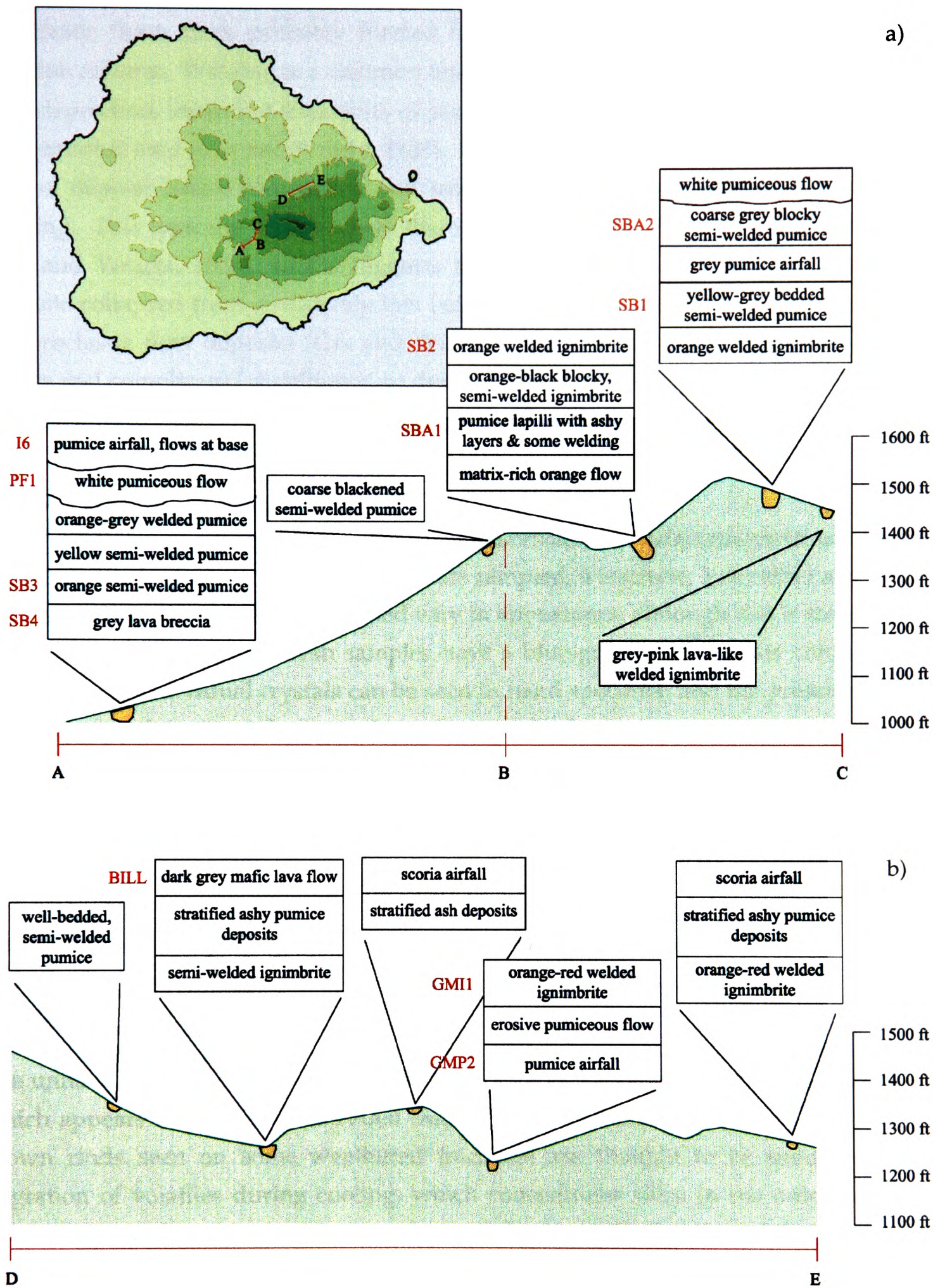
Some of the exposures in the SB formation are difficult to place into the stratigraphy. South of unit SB2, ~4m of very coarse, blocky, semi-welded pumice deposits are exposed. These are colour zoned and comprise a lithified, streaky basal unit and overlying orange, yellow and grey units of semi-welded coarse pumice. These may be lateral equivalents of the units above SB2. A schematic cross-section showing the locations of the various units of the Streaky Bacon Formation is given in Figure 2.15.



Figure 2.13: Welded pyroclastic flow deposit (GMI1) showing fiamme, north flank of Green Mountain.



Figure 2.14: Thick section of Streaky Bacon formation exposed on western flank of Green Mountain.



The Green Mountain and Streaky Bacon sequences are interpreted as the products of pyroclastic pumice flows, due to their high juvenile content, poor sorting and welding.

Pyroclastic flows were probably formed by the collapse of a Plinian (or sub-Plinian) eruption column. Welding is a common feature of large pumice flow deposits and occurs after deposition, when hot fragments of pumice and glass shards sinter together under a compactional load (Cas and Wright, 1988). Units GMI and SB2 represent the parts of this type of deposit where compaction and temperature were great enough to cause dense welding. This typically occurs where there is little heat loss from the collapsing column (Cas and Wright, 1988), which suggests that the eruption column that formed these deposits collapsed from a relatively low height. Zones of welding may be very complex in pyroclastic flow deposits (Cas and Wright, 1988) and this may explain the variable nature and complicated distribution of deposits in the Streaky Bacon formation. Faulting has also affected the area, further complicating the stratigraphy.

2.2.2.2 Lavas

Lavas comprise 7% of the units sampled on Ascension for palaeomagnetic analysis and can be divided into felsic (5 individual units sampled; 4 trachyte, 1 rhyolite) and mafic (2 units sampled). The trachytes sampled vary in appearance, although this is mainly due to the effect of weathering. Fresh samples have a blue-grey to grey-white colour and are fine-grained. Individual crystals can be seen in hand specimen and the presence of small feldspar crystals commonly gives the rock a speckled appearance. Many of these lavas exhibit streaky grey and white flow banding. Weathered trachyte is often exposed as pod-like areas with a white, ashy consistency and hardened outer edges that form thin brown 'rinds'. Unit MRT1 (Figure 2.12) contains abundant inclusions of black, basic vesicular lava.

The mafic lavas sampled on the island (BILL and NELL) are massive, blocky basaltic lava flows. They are dark-grey to black in colour, fine-grained and vesicular and in places, vesicles are elongated.

The units sampled are all parts of either lava flows or lava domes, except for unit DAVE, which appears to have been intruded into material on Green Mountain. The hardened brown rinds seen on some weathered trachytes are thought to be produced by the migration of volatiles during cooling, which concentrates silica in the outer layers as a crust (Daly, 1925). The elongate vesicles seen in the mafic flows are interpreted as the result of the continued movement of the lava after vesicles formation. Flow directions can be inferred from these elongate vesicles and suggest that BILL was erupted from Green Mountain.

2.2.3 Breccia deposits

Breccia deposits comprise 54% of the units sampled on Ascension for palaeomagnetic analysis (samples were taken from 52 individual sites). They are categorised here according to shared field characteristics.

2.2.3.1 Pumiceous breccias

Pumiceous breccias comprise 29% of the breccia deposits sampled on Ascension (Figure 2.16). All contain significant amounts of pumiceous material, but the majority also contain lithic clasts. Pumiceous breccias can be loosely grouped into those that are clast-dominated and those that contain predominantly matrix.

Clast-dominated pumiceous breccias are generally very coarse-grained and poorly-sorted. Deposits typically contain abundant pumice blocks (which can be more than 50cm in length), but are also lithic-rich (with lithic clasts up to 35cm in length). A variety of lithic clast types are exhibited, including mafic and felsic lavas, green-grey obsidian and red and black scoria. The amount of matrix in these deposits is variable.

In BPB and NEB (Figure 2.16), fine material is abundant and in some cases forms ashy layers between coarse breccia units. Some ashy material is seen in MRGB1 and MRGB2, which can pick out weak undulose stratification. NRGP1 has a fine-grained layer at its base and fines upward to an ashy layer. NRGP1 is slightly finer-grained than the other clast-supported pumiceous breccias and is found within a sequence of stratified pumice airfall deposits exposed on the NASA road. Units SB1 and SB3 contain little fine material and are distinctive in that pumice clasts are blackened. In SB1, pumice clasts are plastically deformed and up to ~1m in length. Unit MRGB2 also contains abundant blackened pumices and is rich in obsidian blocks. Unit MRGB1 contains abundant large scoria clasts.

The pumice-rich, poorly sorted nature of these deposits suggests that they are pyroclastic flow deposits. Ashy layers (e.g. in BPB, NEB1) may represent flow-unit boundaries, formed by settling of fine material from the accompanying ash-cloud or by elutriation from the flow. SB1/3 and MRGB2 contain blackened or deformed clasts and are probably therefore

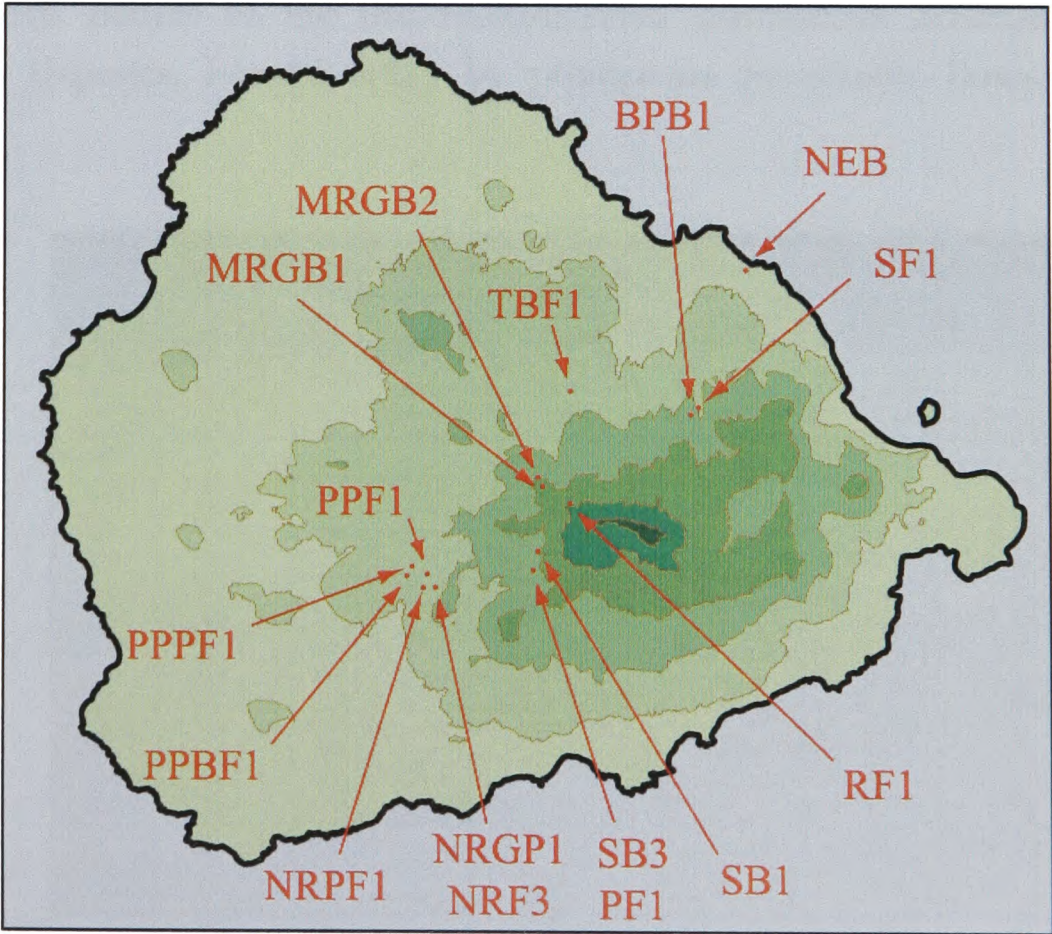


Figure 2.16: Topographic map of Ascension Island, showing individual sampling locations for pumiceous breccia units and for the scoriaceous breccia unit sampled (SF1). Shaded areas represent contours of 500ft.

partly welded. Although unit NRGP1 is interbedded with a sequence of airfall units, its poor sorting and fine-grained basal layer suggest that it is more likely to be a flow deposit. This unit may have formed by a small collapse of a Plinian-type eruption column that was also producing airfall material.

Matrix-dominated pumiceous breccias range from <1m to ~2.5m in thickness. All contain fine ashy material, the proportion of which generally increases upward through the deposit. Matrix is typically buff-brown in colour but may be pink (e.g. PF1, PPPF1), especially in the upper parts of units, where vertical joints may also be seen. Pumice clasts are typically lapilli-sized or smaller, but sorting is poor and some larger (20cm in length) clasts are seen. Pumice clasts are commonly rounded and weathered and some units contain pumices that have become flattened and aligned with bedding (e.g. NRF3, PPBF1). This can give the unit a weak stratification. Some units contain pumice-rich lenses and layers or lenses of lithic grit in which cross-stratification may be visible (e.g. PF1, PPBF1 and PPPF1; Figure 2.17). Units NRF3 and PF1 (Figure 2.16) display erosional basal contacts, and PF1 exhibits a fine-grained basal layer, as well as bomb sags. PPF1 (Figure 2.16) grades upward into a lava breccia.

TBF1 (Figure 2.16) differs from other matrix-rich deposits, as it comprises two parts: an upper brown-grey matrix-rich pumiceous unit (which exhibits undulose bedding) and a lower unit composed almost entirely of rounded pumice clasts. The boundary between units is gradational.

The poorly sorted matrix-rich nature of the matrix-dominated pumiceous breccias suggests that they are flow deposits, formed either by pumiceous pyroclastic flows, mudflows (or lahars) or by the reworking of pre-existing pumiceous material (probably by water).

The pink coloration and jointing seen at the top of some units is a common product of heating (which causes the oxidation of iron in the deposit). However, these features may also be a result of soil formation. Flattening of pumice clasts can be

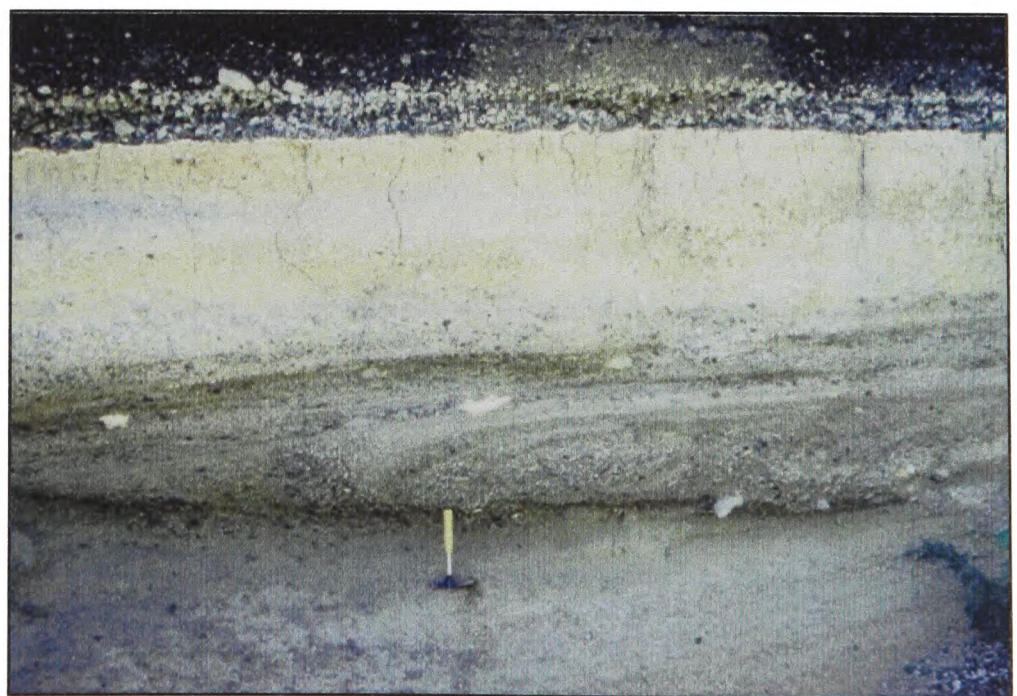


Figure 2.17: Matrix-dominated pumiceous breccia PPPF1 (Pyroclastic Plain) showing cross-stratification and grit layers.

produced by compaction during the welding of pyroclastic flow deposits, but welding was not an obvious feature of these units.

The pumiceous nature and basal layer exhibited by unit PF1 suggest that it is the product of a pyroclastic flow. Bomb sags suggest that the unit below PF1 was unconsolidated and may have contained water, allowing clasts from PF1 to sink into it.

The pink coloration and gradational upper contact of PPF1 suggest that it is a more fines-rich basal part of the overlying lava breccia unit.

Unit TBF1 may be a reworked deposit as it contains well-rounded pumice clasts, which are a common product of abrasion during reworking. However, rounding can also occur in transport within pyroclastic flows and in addition, mudflows may incorporate pre-existing round clasts.

2.2.3.2 Scoriaceous breccias

Only one unit falls into this category, SF1 (Figure 2.16). SF1 is part of an extensive sequence of pyroclastic deposits found to the west of Little Ascension Flow (Figure 1.8, Section 2.3.6). SF1 varies in thickness but at this exposure has a maximum thickness of 3–4m. The deposit is steeply dipping and has eroded underlying layers to drape down into the valley. The unit consists of coarse black scoria and spatter material with a few lithics of grey and red (oxidised) lava. SF1 is matrix poor and contains lenses of finer scoria and lithics. A fine-grained layer is seen at the base of the unit. Some ashy layers are seen within SF1 and a series of fine-grained scoria units (some stratified) overlie it.

The high proportion of juvenile material within this deposit and its erosive nature imply that it is likely to be the product of a scoria flow. This is backed up by the presence of a fine-grained basal layer (which is common in scoria flow deposits) and the overlying fine-grained units, which are interpreted as the deposits of the accompanying ash-cloud.

2.2.3.3 Lithic breccias

Lithic breccias comprise 23% of the breccia deposits sampled on Ascension for palaeomagnetic analysis. Twelve lithic breccia units were sampled (Figure 2.18). Lithic breccias all have a significant lithic content but may contain equal proportions of lithic and juvenile material. Lithic breccias have been divided into clast and matrix-dominated units.

Of the clast-dominated breccias, BX1 and EB (Figure 2.18) are coarse poorly sorted units that contain large angular lithic blocks in an ashy matrix. Lithics are mainly trachyte lava (which is banded in some cases), but obsidian, pseudo-pumice and some pumice clasts are also seen. Lithics range from centimetre size clasts to boulders that are more than 1m in length. BX1 is unconsolidated and thickness is difficult to measure. EB1 varies in

thickness, but is 4-5m at thickest and shows large-scale loading or impact structures where blocks from this unit have deformed the unit below (Figure 2.19).

CGB1 and EFFB1 (Figure 2.18) show a greater variety of lithic types, including dark grey, light grey, pink and green-grey banded lava, red and black scoria and ignimbrite. Some pumice clasts are also seen and EFFB1 has a

concentration of pseudo-pumice clasts at its base. Both units contain some matrix and CGB1 has distinct areas that are more matrix-rich. CGB1 shows some irregular layering of coarser and finer material and has a basal unit containing extremely coarse lithics (of up to 2m in length). Conversely, EFFB1 has a finer-grained stratified basal layer, although this contains coarser pumice clasts.

UVB1 (Figure 2.18) comprises two units: a lower matrix-rich unit, containing little pumice

and lithic blocks up to 50cm in length, and an upper poorly sorted coarse breccia unit. The upper unit contains lithic blocks up to 1m in length and larger blocks are rounded. Finer areas are more matrix-supported.

Unit LF1 banks up onto the trachyte dome of White Hill (Figure 2.18; Figure 1.8). LF1 is distinct from other lithic

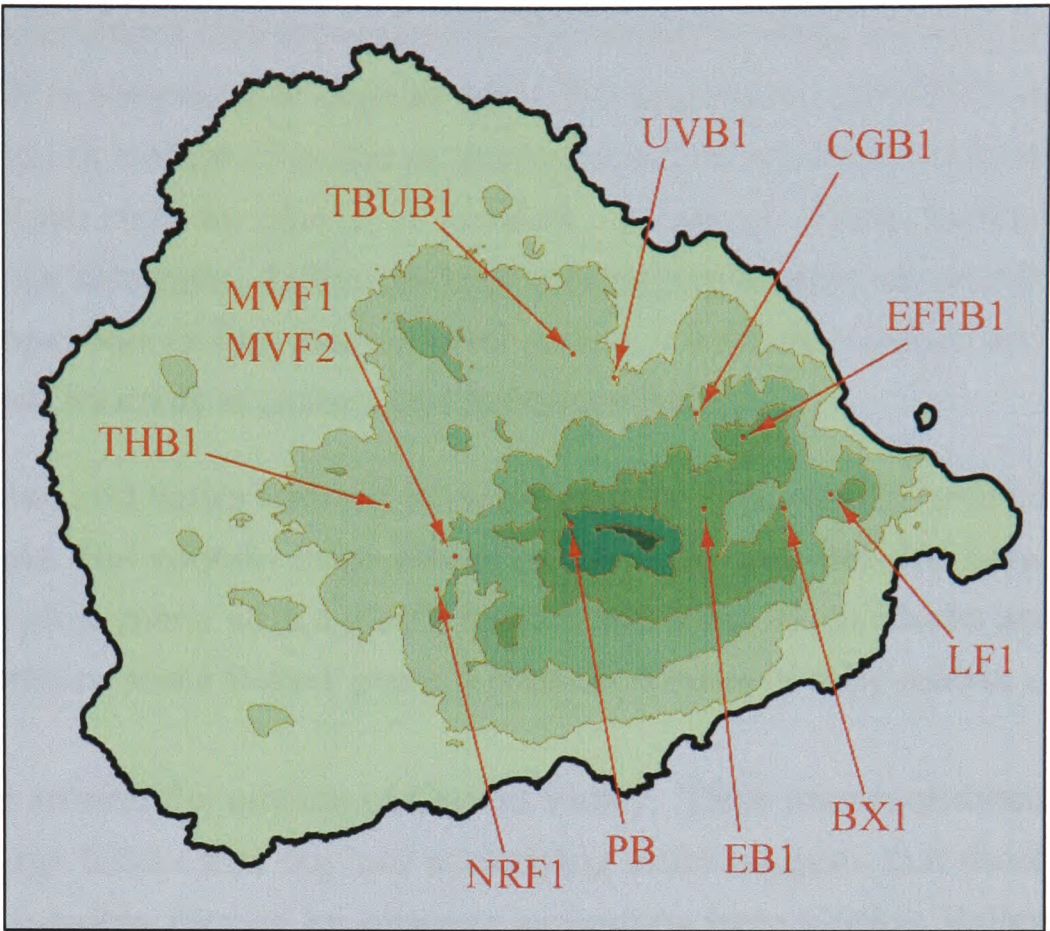


Figure 2.18: Topographic map of Ascension Island, showing individual sampling locations for lithic breccia units. Shading represents contours of 500ft.



Figure 2.19: Poorly sorted clast-rich breccia (EB1), Cricket Valley. Large clasts from EB1 have produced impact structures in the underlying ashy layers.

breccias in that it has the general colour and appearance of the trachytic airfall deposits on Ascension. However, the unit is composed of angular *lithic*-like fragments up to 60cm in length, which show a gradation in texture from dense, poorly vesicular trachytic material to more 'lava-like' clasts, which may be glassy or banded. Clasts of green, banded obsidian and black obsidian are also seen. Lithic clasts of other compositions are scarce. The unit contains a high proportion of fine ash material giving it a friable texture and some stratification is picked out by areas of coarser and finer material.

PB (Figure 2.18) is poorly-sorted and varies laterally between pumice-rich, weakly bedded areas and chaotic rubbly areas that contain large blocks of vesicular and banded lava. Lava clasts are grey, green or pink, many with a glassy texture and some larger blocks are fragmented. The unit also contains some 'baked' pumice clasts and areas of ashy matrix.

Units BX1 and EB1 are found around the outside of Cricket Valley. Their unconsolidated nature and the presence of large blocks that sag into underlying units suggests that these may be explosion breccias – possibly formed by phreatic explosions from Cricket Valley or Weather Post.

Unit EFFB1 contains a substantial amount of juvenile material, has a fine-grained basal layer and is located below an inferred pyroclastic surge deposit. This unit is probably therefore a pyroclastic flow deposit – possibly a lag breccia because of its coarse lithic-rich nature. CGB1 is also very lithic rich with a concentration of coarse lithics at its base. This may also be a co-ignimbrite breccia.

UVB1 is probably a (fluvially?) reworked deposit as it is poorly sorted and contains rounded blocks and little juvenile material and is situated at the base of a river valley. Alternatively, this may have been deposited by a mudflow, as some areas are matrix-rich and these flows can carry large boulders.

The angular nature and narrow compositional range of clasts in LF1 suggests that these are (non-vesicular) juvenile clasts and thus that this is the product of a block-and-ash flow. This may have been the result of the collapse of a lava dome on White Hill. Ashy layers may represent flow unit boundaries.

The origin of PB is difficult to ascertain from field characteristics. The pumice-rich nature of the deposit suggests it may be the product of a pyroclastic flow. However, matrix is lacking and some lava clasts are fragmented, suggesting that this may have been formed by a debris avalanche. Alternatively, this unit may be a brecciated equivalent of the trachyte lava flows that form much of the upper western flanks of Green Mountain.

Five of the lithic breccias contain significant amounts of matrix, which ranges from yellowy-orange to a creamy-buff or grey colour and is typically ashy and pumiceous. Matrix-dominated lithic breccias are poorly sorted, containing lithics that range from

<1cm to 40cm in size, and some (e.g. MVF1) contain boulders of scoria. Lithic types include red and grey (mafic and felsic) lava and scoria and pumice is usually less prominent or weathered and degraded.

Unit MVF2 (Figure 2.18) contains some lithic clasts that are coated with matrix. Matrix in the upper part of MVF2 has a brown colour and is much harder than the rest of the deposit. Unit TBUB1 (Figure 2.18) contains some boulders of a pre-existing coherent pumice lapilli deposit, and in places TBUB1 protrudes up into the overlying scoria lapilli deposit as though it has been squeezed upwards. Unit THB1 (Figure 2.18) differs from other matrix-dominated lithic breccias as it is darker brown in colour and has a sandy matrix. Sorting in THB1 is medium to poor and some clasts are sub-rounded. Lithic types are variable and include mafic, felsic and banded lava, scoria and obsidian. THB1 has an erosive base.

Like their pumiceous equivalents, matrix-dominated lithic breccias may have been formed by pyroclastic flows, mudflows or reworking, but they typically contain less juvenile material and are therefore less likely to be primary pyroclastic deposits. High-energy (erosive) processes must have been involved in the emplacement of TBUB1 to allow the incorporation of large coherent blocks of a pre-existing deposit. The protrusion of this unit up into the unit above may be a result of the escape of gas or water from the deposit. This may be a mudflow deposit. The sandy matrix, rounding of clasts and heterogeneous lithic types in THB1 suggests that this unit is reworked in origin.

2.2.3.4 Lava breccias

Lava breccias comprise 13% of the breccias deposits sampled on Ascension for palaeomagnetic analysis. Samples were taken at nine individual localities (Figure 2.20). The lava breccias are composed dominantly of blocks of lava and are commonly welded or semi-welded. Lateral variation is also common and some deposits grade in texture from rubbly breccia to coherent lava.

Units MVLB1 and NRF2 (Figure 2.20) consist of cm to dm-sized blocks of trachyte in an ashy white matrix. The majority of trachyte blocks are weathered, white and powdery, although fresh blocks are grey and some show banding. Both units are ~2m in thickness and have a creamy matrix-rich top. MVLB1 also contains clasts of vesicular mafic (black) lava.

Units NRLB1-4, PPLB1 and TV1 (Figure 2.20) are coarse breccias composed dominantly of lava and blue-grey pseudo-pumice. They vary from 2m to 6m in thickness and most have erosional basal contacts and thicken downslope or into dips. The texture of clasts varies from pseudo-pumice (which tends to be crystal-rich) to more coherent grey trachyte, which may be banded. Where trachyte clasts are weathered, they are white and powdery.

Units are poorly-sorted and contain lava blocks up to 1.5m in length (e.g. TV1). Most units contain some ashy matrix, and NRLB2/4 and PPLB1 all have a distinct upper matrix-rich region, which contains a few clasts. In NRLB4 the upper matrix-rich region is orange coloured and contains joints. The texture of NRLB2/4 and PPLB1 is laterally very variable, ranging from rubbly and

unconsolidated to coherent and lava-like. Units NRLB3/4 and TV1 all exhibit finer-grained ashy basal layers, and in TV1 the basal layer is stratified and contains dune-like structures. NRLB1 is the most lithic-rich unit and contains obsidian and plutonic blocks.

Unit SB4 (Figure 2.20; Figure 2.21) is a massive grey unit found at the base of the Streaky Bacon Formation (Section 2.2.2.1; Figure 2.15). The deposit is dominantly composed of dm-sized clasts of grey and grey-pink banded lava-like material. In places, clasts are stretched out and the surrounding matrix appears to ‘flow’ around clasts, producing a



Figure 2.21: Grey lava breccia SB4, lying beneath coarse semi-welded pumice deposit, in valleys to S of Middletons Ridge.

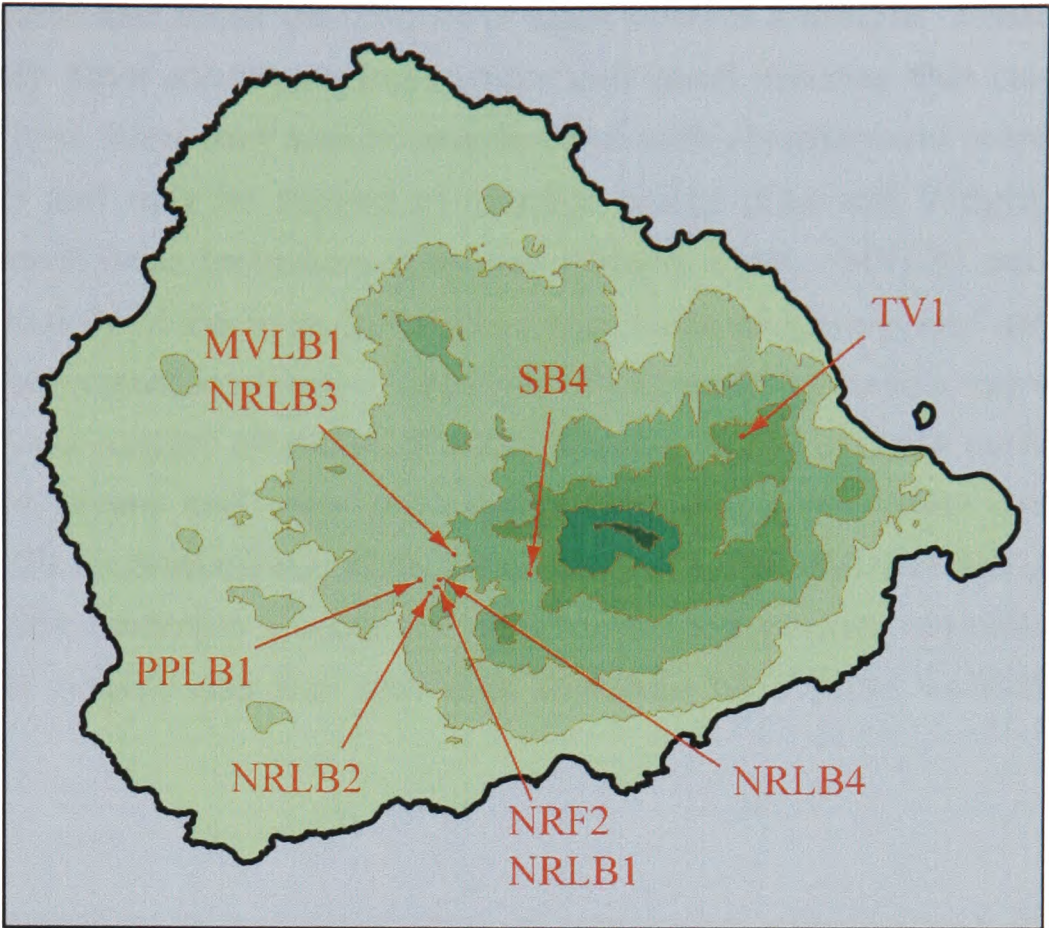


Figure 2.20: Topographic map of Ascension Island, showing individual sampling locations for lava breccia units. Shading represents contours of 500ft.

streaky fabric. Matrix is typically more lithified than in other lava breccia deposits and in places, it is difficult to distinguish clasts from the surrounding matrix.

The lava breccias are interpreted as brecciated lava flows or lithic-rich pyroclastic flow deposits that are partly welded. If a cooling lava flow

continues to move, it can deform and break into blocks or slabs to form a breccia. Felsic lavas (e.g. rhyolite) commonly have accompanying surface and basal breccias that can contain pumiceous blocks. These flows may also be interbedded with obsidian and more vesiculated pumiceous layers and may be capped by pumice blocks (Cas and Wright, 1988). Some felsic lavas contain basic inclusions (Cas and Wright, 1988). MVLB1 and NRF2 are composed almost mainly of trachyte, but also contain basic inclusions and are probably therefore parts of a brecciated lava flow. NRLB1-4, PPLB1 and TV1 have a more heterogeneous lithic content and contain abundant pseudo-pumice. Some of these units also have fine-grained basal layers and ashy tops suggesting that these units are pyroclastic flow deposits (with accompanying underlying ground surge and overlying ash-cloud surge deposits). SB4 underlies a sequence of semi-welded pumice deposits (probably of pyroclastic flow origin) and this unit may therefore be a more welded version of these deposits.

2.2.3.5 Stratified breccias

Fifteen (29%) of the breccia units sampled on Ascension show internal structure such as planar or cross stratification, dune structures or ash interbeds. The sampling locations of these units are seen in Figure 2.22.

Units CVS1/2, EFS1/2, LA1/2, SP1, LF2 and PPBB1 are all part of pyroclastic sequences that contain significant proportions of ash, typically as finely laminated interbeds.

CVS1 and CVS2 (Figure 2.22) are part of a thick (20m?) sequence of interbedded ash and breccia units found to the west of Cricket Valley (Cricket Valley Pyroclastics; Figure 1.8; Figure 2.23). Breccias units are up to 30cm in thickness and contain mainly lapilli-sized lithic clasts, with a little scoria, scarce pumice and little matrix. Ash layers are pinky-grey and show variable

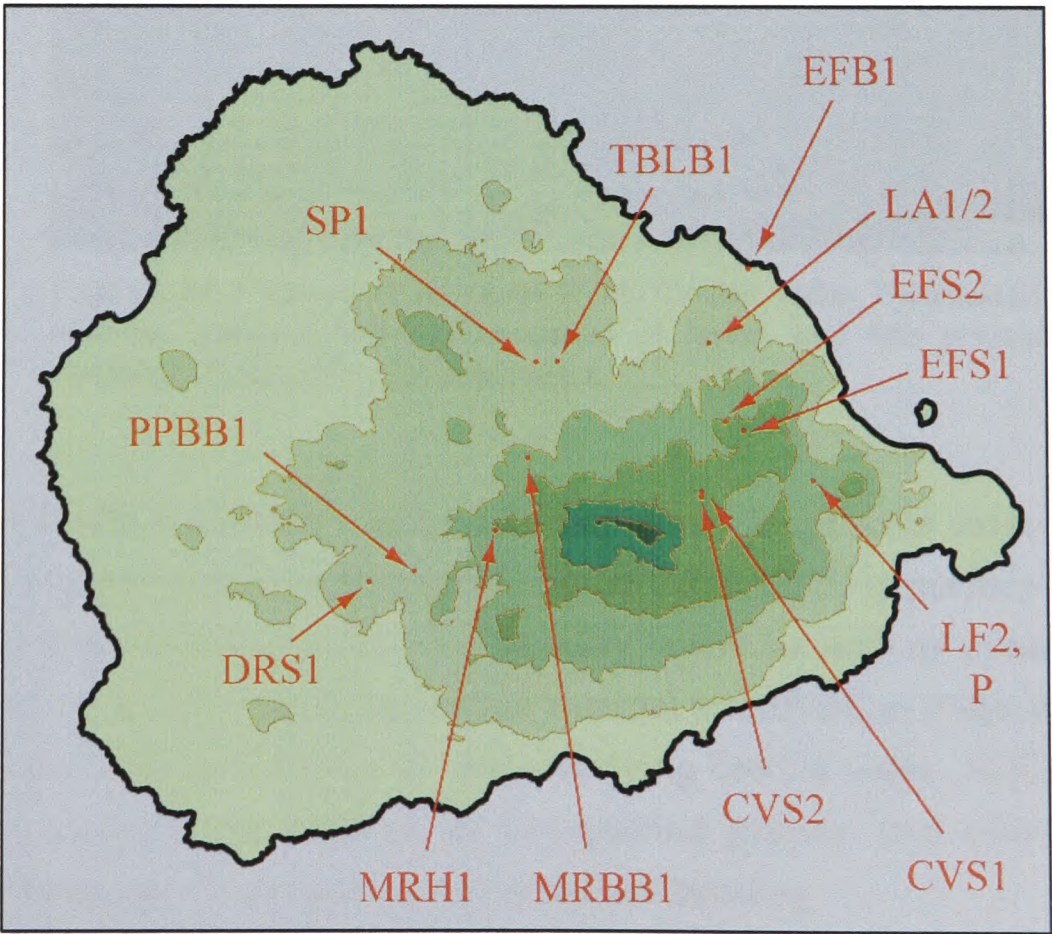


Figure 2.22: Topographic map of Ascension Island, showing individual palaeomagnetic sampling locations for stratified breccia units. Shading represents contours of 500ft.

stratification including dunes (Figure 2.23), cross bedding and truncation of ash layers (Figure 2.24) and, in upper regions, planar bedding (although this may be very low-angle cross-stratification). Ash layers contain mm-sized lithic clasts (though these were too small to sample), which in some cases are coated. Some ash layers are pitted with vesicles and in many places, ash layers have been deformed by clasts from overlying layers.

CVS1 and CVS2 are poorly sorted breccias that are surrounded by layers of ash. CVS1/2 contain some ash bands, which enclose lensoid areas of coarser lithic material

EFS1 and EFS2 (Figure 2.22) are part of a sequence of pyroclastic

deposits found to the west of Devils Cauldron (Figure 1.3) that shows large-scale cross-cutting structures, undulose bedding and dune structures (Figure 2.25). EFS1 is pumice-rich and shows undulose and cross-bedding picked out by ashy layers, as well as dune structures with wavelengths of up to 1m, which show clear internal stratification (Figure 2.26). Some ash layers have been deformed by clasts from overlying breccia units. EFS2 (Figure 2.27) comprises three packages of medium to fine-grained pumice and lithic breccias with ash interbeds. These units show planar and undulose bedding.

LA1, LA2 and SP1 (Figure 2.22) are parts of two separate sequences of interbedded white ash and breccia deposits. LA1/2 are found on Little Ascension flow (Figure 1.8; Figure 2.28). LA1 is an unconsolidated, coarse, poorly sorted breccia containing dominantly



Figure 2.23: Large-scale view of interbedded ash and breccia deposits of the Cricket Valley pyroclastic sequence. Deposits show planar stratification and dune structures. View looking south, field of view approximately 100m.

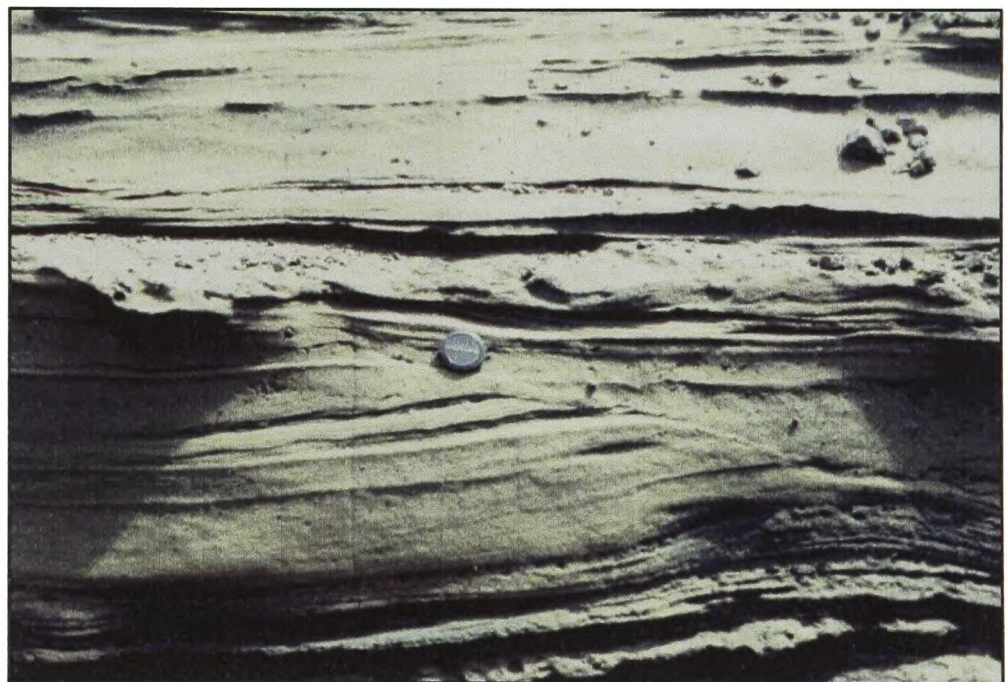


Figure 2.24: Close-up of ash layers within Cricket Valley Pyroclastics showing undulose bedding, truncation of layers, and fine breccia interbeds. Lens cap is 5cm in diameter.



Figure 2.25: Large-scale cross-cutting features seen in pumiceous breccia and ash units of EFS sequence.



Figure 2.26: Stratification and dune structures seen in ash layers of units EFS1. Dunes show internal stratification.



Figure 2.27: Pumiceous breccia unit EFS2 with underlying stratified pink ash layers, which contain bomb sags and internally stratified dunes.

pseudo-pumice. It is lithic-rich and contains trachyte, glassy banded lava and obsidian. Underlying LA1 is unit LA2, which comprises a sequence of interbedded crystal-rich pumice and lithic breccias, ash and coarser pumice layers. Ash layers are undulose and white to pink in colour. Finer layers have a concentration of coarse pumice at the top. Unit SP1 is part of another exposure of flat lying white ash units, found to the south of Butt Crater (Figure 1.3). Ash layers range from 1cm to 70cm in thickness and contain some interbeds of fine lithic grit or pumice trains. Toward the top of the sequence, layers cross-cut one another and some units show cross-stratification or soft sediment deformation. SP1 is one of a number of lithic-rich layers found near the top of the sequence and contains clasts of mafic and felsic lava and ignimbrite, but little pumice.

Unit LF2 is part of a sequence of interbedded trachyte and pumice

breccias and fine-grained ash-rich layers, found to the west of White Hill. Breccia units contain pumice, trachyte (sometimes banded) and obsidian and tend to show a fine – coarse – fine grading. Units range in thickness from 1cm to 60cm and stratification is undulose. Ashy layers have commonly been deformed by clasts from overlying layers (bomb sags). Unit P1 is a pumice and ash-rich layer from which pumices were taken for sampling.



Figure 2.28: Sequence of stratified ash and breccia deposits found on Little Ascension Flow. LA1 and LA2 are found near the top of the sequence.

PPBB1 (Figure 2.22) is part of a sequence of interbedded lapilli breccia and ash units in the Pyroclastic Plain (Figure 1.8). Breccia units are erosional, brown, matrix-supported and pumice rich, with some lithics. Ash units are irregular lensoid or channel shapes (Figure 2.29) that cross cut other units in the sequence and are up to 1m thick at their thickest parts. Some contain small lithics.

MRH1 (Figure 2.22) is part of a thick sequence (~7m) of stratified pumice, lithic and ash beds found on Middletons Ridge (Figure 1.3). These units vary in terms of clast and matrix content, grain size and sorting, and contacts between units tend to be gradational.



Figure 2.29: Interbedded ash and breccia deposits PPBB1 in Pyroclastic Plain.

Most units are matrix-supported and pumiceous and in many units, pumices are flattened and streaky. These pumice fragments are up to 25cm in length. Other units are composed of layers of stratified pink ash with occasional lenses of coarse breccia. Some of these ash units also contain fine grit layers, which are cross-stratified.

Some ash bands show soft sediment deformation. Several of these units have become altered to clays and some of the units higher up in this sequence contain accretionary lapilli.

The pyroclastic sequences to which units CVS1/2, EFS1/2 and LA1/2 belong show impressive depositional structures that are interpreted as the products either of pyroclastic surges or of reworking of pre-existing material by water. *Some* water content in these deposits can be inferred from deformed and pitted (vesicular) ash layers and coated grains (see Section 2.1.4.3). However, the fluvial reworking of these deposits would have required a substantial source of water, the presence of which is not evident elsewhere on the island. Pyroclastic surges can produce layered deposits with spectacular depositional structures and base surges commonly contain water, giving their deposits a 'sticky' appearance. The presence of bomb sags in these units suggests that the eruption of ballistic blocks was occurring at the time of deposition.

The juvenile-rich nature of EFS1/2 and LA1/2 suggests that they are likely to be primary pyroclastic (surge) deposits. However, juvenile material is less common in the SP deposits and these may therefore have been reworked from the LA deposits.

The pumice and ash units to which LF2 and P1 belong are probably pyroclastic flow deposits as units are poorly-sorted and contain high proportions of (particularly vesicular) juvenile and fine ash material. Bomb sags suggest that ejection of ballistic blocks was occurring at the same time as these units were being erupted.

Ash units at site PPBB1 have channel-like forms suggesting that these were produced by flows. These may be pyroclastic flow or surge deposits, or the product of mud flows.

The MRH1 units contain flattened and fiamme-like vesicular juvenile material, which can be produced by partial welding. They may therefore be pyroclastic flow deposits, although they also exhibit stratification, suggesting an origin as pyroclastic surge deposits. The MRH1 units are altered to clays and contain accretionary lapilli. These features indicate the presence of water during eruption and deposition and



Figure 2.30: Erosive cross-stratified pumiceous breccia MRBB1 (Mountain Rd) showing channel-fill and containing blocks of the underlying pumiceous deposit.

the MRH1 deposits are therefore interpreted as hydromagmatic pyroclastics.

Units DRS1, EFB1, MRBB1 and TBLB1 (Figure 2.22) are orange to brown matrix-supported breccias containing varying amounts of pumice and lithics (in an ashy to sandy matrix). They are poorly sorted and all show cross-bedding and some contain trains or lenses of pumice or lithic-rich material and/or exhibit wavy bedding. These are erosional and MRBB1 has cut down ~5m into the pumice unit below and contains discrete blocks of this underlying deposit. MRBB1 and TBLB1 are both rich in pumice and have channel-shaped areas that are horizontally or cross-bedded (Figure 2.30). EFB1 and MRBB1 both appear to be filling a palaeovalley. DRS1 contains areas of gritty material, blackened pipes of material and matrix-filled joints. EFB1 and MRBB1 both show a variety of lithic types including mafic and felsic lava, ignimbrite, scoria, obsidian and plutonic material. EFB1 grades upward from a more matrix-rich base, through a well stratified middle layer with ash beds to an upper coarser, clast supported region overlain by fine grit. TBLB1 also grades up from matrix-rich to more clast-rich.

The matrix-supported breccias are likely to have been formed by flows. The combination of sandy or gritty matrix with cross-stratification suggest that they are probably reworked. Some of these deposits (e.g. EFB1, MRBB1) have a heterolithic nature, which is common in reworked deposits. The blackened pipes seen in DRS1 are probably the remains of gas escape or fossil fumarole pipes.

2.3 MAJOR PYROCLASTIC SEQUENCES

This section briefly describes the lithologies and field relationships seen at the major exposures of pyroclastic material on Ascension. Stratigraphic sections for these sequences are shown (and correlated, where possible) in Enclosures 1 and 2. See Chapter 1 – Figures 1.3 and 1.8 for topographic maps of Ascension with place names and locations of the major pyroclastic sequences.

2.3.1 NASA Road/Pyroclastic Plain

The pyroclastic sequence exposed over the lower parts of the NASA Road and the Pyroclastic Plain (see Figure 1.8; Figure 2.31) comprises ~50m of deposits (Sections 2–4, Enclosure 1). The oldest units are exposed only on the upper NASA Road (Section 4) and comprise: a white, crystal-rich pumice airfall deposit, two trachytic/rhyolitic lava breccias (NRF2 and NRBL1) and four smaller matrix-rich breccias (including NRF1), which may be pyroclastic flow deposits. Overlying this are two pumiceous flows (which may be associated with NRLB1) and above these flows is the upper part of the section, which is also exposed in the Lower NASA Road and Pyroclastic Plain and comprises: a major pumice airfall deposit, a third lava breccia, at least two matrix-rich pumiceous flows

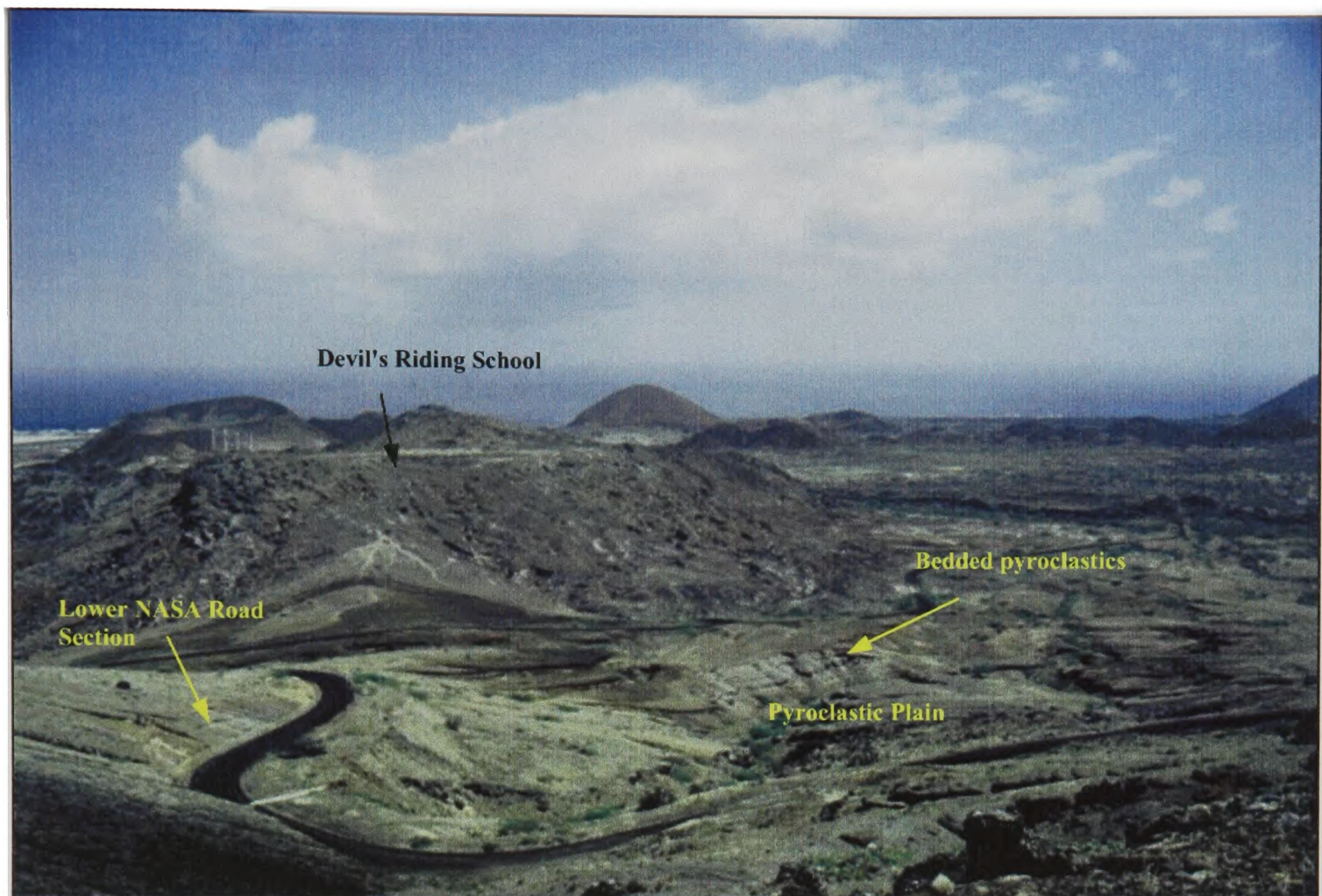


Figure 2.31: View looking west showing the pyroclastic sequence exposed on the lower NASA Road and in Pyroclastic Plain. The dip of upper (pumice airfall) units in the sequence is steep on the NASA Road (left-hand side of picture, by bend in road), but shallows in the Pyroclastic Plain (centre of picture). The dome of Devils Riding School (see Figure 1.3) is seen in the background.

(probably pyroclastic in origin), the pumice-based scoria airfall deposit described in Section 2.2.1.3, and a second major pumice airfall deposit, which is more than 10m thick, comprises a number of individual fall units and mantles topography to a very steep angle on the NASA Road (see Figure 2.6). Within the Pyroclastic Plain, there are also ~5m of matrix-rich breccias exposed that are interpreted as reworked equivalents of the primary pyroclastic deposits (e.g. PPBB1, PPPF1).

2.3.2 Middleton's Ridge/Valley

The sequence exposed in Middleton's Valley (Section 5, Enclosure 1) comprises more than fifteen individual pyroclastic units including: a coarse semi-welded scoria and pumice breccia (MVS2), which may be of airfall or pyroclastic flow origin, at least four matrix-rich pumiceous breccias of pyroclastic flow or lahar origin, a white pumice and scoria deposit (MVA2), a scoria airfall deposit (MVS1) and the two lava breccia units seen in the NASA Road Section. Overlying these units is ~15m of bedded pumice airfall. The sequence is underlain by rhyolite lava, which may be equivalent to that exposed at the base of the Pyroclastic Plain.

The Middleton's Ridge pyroclastic sequence (Section 6, Enclosure 1; Figure 2.32) is less well exposed than the Valley section. The lower part of the sequence rests on the

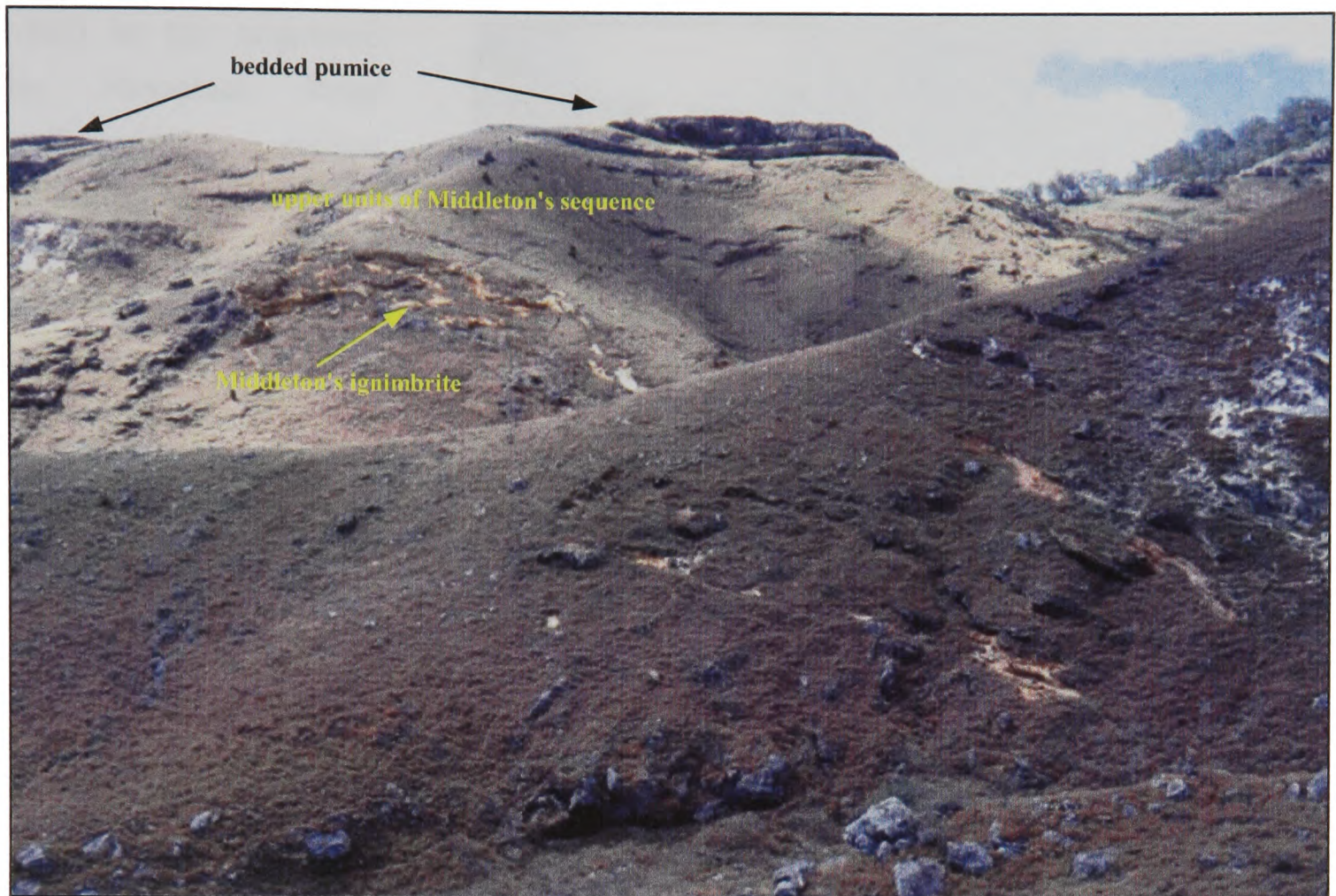


Figure 2.32: View from Streaky Bacon Ridge looking north toward Middleton's Ridge (see Figure 1.3). The orange unit exposed in the hillside is the Middleton's Ignimbrite and the grey, bedded unit capping Middleton's Ridge (upper centre and far left of the picture) is the Upper Pumice 1, which in some areas drapes slopes of more than 30°.

Middleton's Ridge trachyte (MRT1) and comprises ~10m of finely to coarsely stratified pyroclastic deposits that have been altered to clay (the 'Middleton's Ridge hydromagmatic deposits'). These include a thick (minimum 3m) orange matrix-rich breccia (the 'Middleton's ignimbrite'). Overlying the hydromagmatic deposits are: a pumice airfall deposit (MRP2), further stratified flow units (that display clay alteration), a scoria airfall unit, an additional pumice airfall unit, a 2m thick pink ash deposit, an erosive scoria flow deposit and another ashy breccia, which contains large boulders and exhibits what appears to be conchoidal fracture in places. Overlying this is ~9m of pumice airfall and more than 3m of massive scoria lapilli (airfall).

2.3.3 Green Mountain Road

The pyroclastic sequence exposed along the Mountain Road is complex and has been disrupted by faulting (due to slumping?). Exposure is not continuous and many units are exposed repeatedly due to faulting and the changing topographic height along the road. The sequence contains three distinct pumice airfall deposits, four scoria airfall deposits, two of which also display features typical of flows (e.g. erosive base, cross-bedding, lithic-rich lenses) and at least six matrix-rich pumiceous breccia deposits, which are interpreted as pyroclastic flow or mudflow (/lahar) deposits. Figure 2.33 shows cross-cutting relationships of some of the upper units (pumice airfall, mudflow deposit and scoria

airfall) in the sequence. The Mountain Road stratigraphic section shown in Enclosure 1/2 (Section 8/A) is a composite constructed from several individual logs, which are shown in Chapter 7 (Figure 7.2).

2.3.4 Streaky Bacon Formation

The Streaky Bacon Formation (Sections 9, 10,

Enclosure 1; Figures 2.14, 2.15, 2.34) comprises ~15m of pumice airfall, coarse non-to semi-welded pumice breccia and welded ignimbrite (Streaky Bacon Ignimbrite). It is exposed in 'Streaky Bacon Valley' and on the western flanks of Green Mountain, south of Middleton's Ridge (see Figure 1.3). The sequence has been incised, in areas by pumiceous breccia deposits (e.g. PF1) and a coarse scoria deposit and it is overlain by a minimum of 10m of bedded pumice airfall, which contains flow-like features (cross-bedding, lithic-rich lenses) and mantles steep topography in places (Figure 2.34).

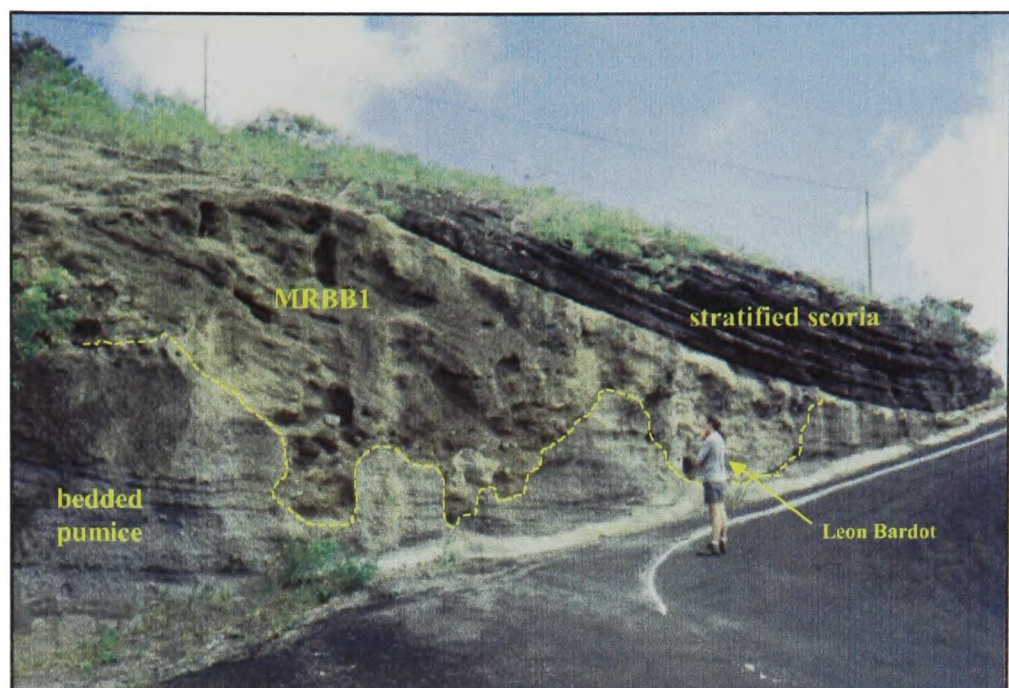


Figure 2.33: Cross-cutting relationships of upper units in the Mountain Road pyroclastic section: black stratified scoria overlies erosive brown flow MRBB1, which has incised the Upper Pumice 1 airfall.

2.3.5 Northern Green Mountain

A second exposure of ignimbrite (Green Mountain Ignimbrite) crops out on the northern flanks of Green Mountain (Sections B and C, Enclosure 2; Figures 2.14, 2.35). The central part of the deposit is welded and displays distinctive fiamme (Figure 2.13). GMI1 grades down into a semi to non-welded pumiceous breccia, which overlies (and has incised) a pumice airfall deposit. GMI1 grades upward into ~4m of semi-welded pumice breccia, which in turn is overlain by stratified pumice and ash deposits. Overlying these is a basaltic lava flow. In other areas, the welded ignimbrite is directly overlain by thin stratified scoria and pumice airfall deposits, which contain bomb sags.

2.3.6 West of Little Ascension Flow

This sequence (Section G, Enclosure 2) is one of the most extensive exposures of pyroclastic material on Ascension and is exposed in the western and eastern walls of the valley to the west of (and stratigraphically below) the Little Ascension trachyte flow (see Figure 1.8). The section is at least 40m in thickness and comprises several individual deposits, which show striking cross-cutting relationships (Figures 2.36–2.38). Individual deposits include (from the bottom upward): a basal lithic-rich pumice deposit, with weak

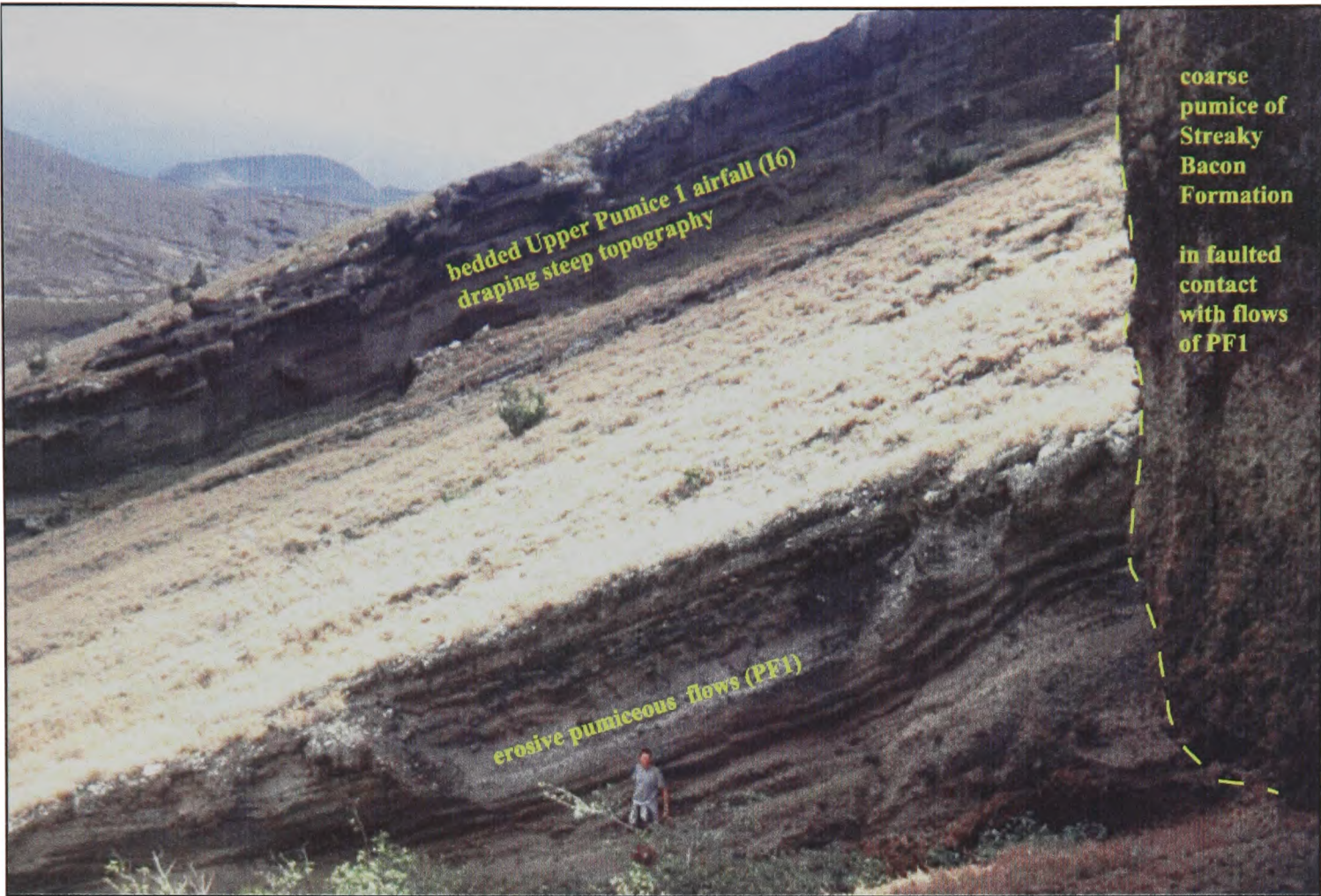
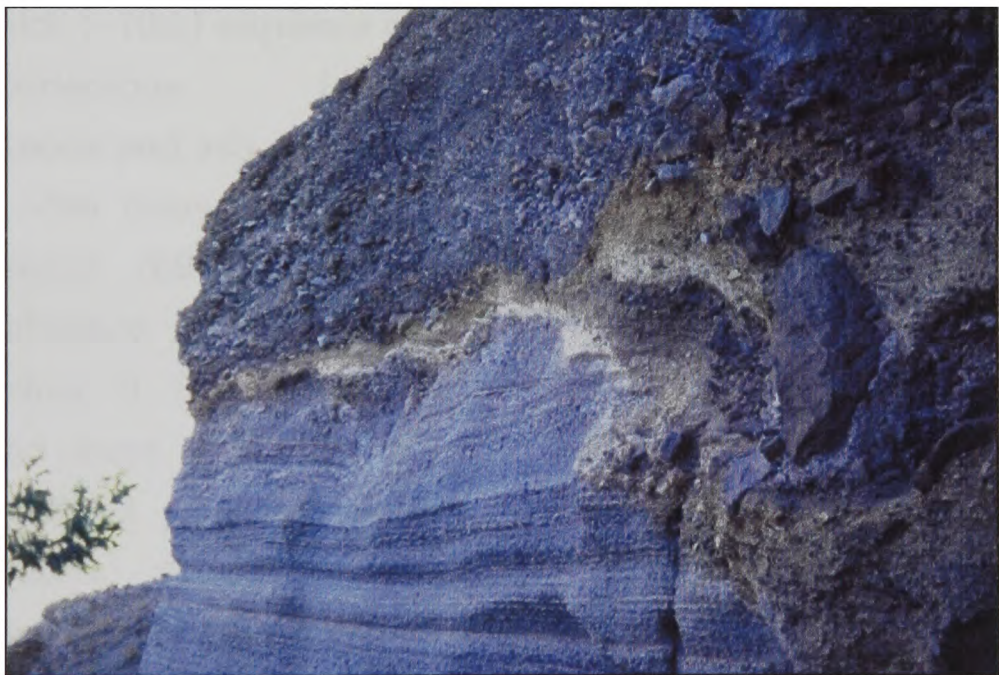
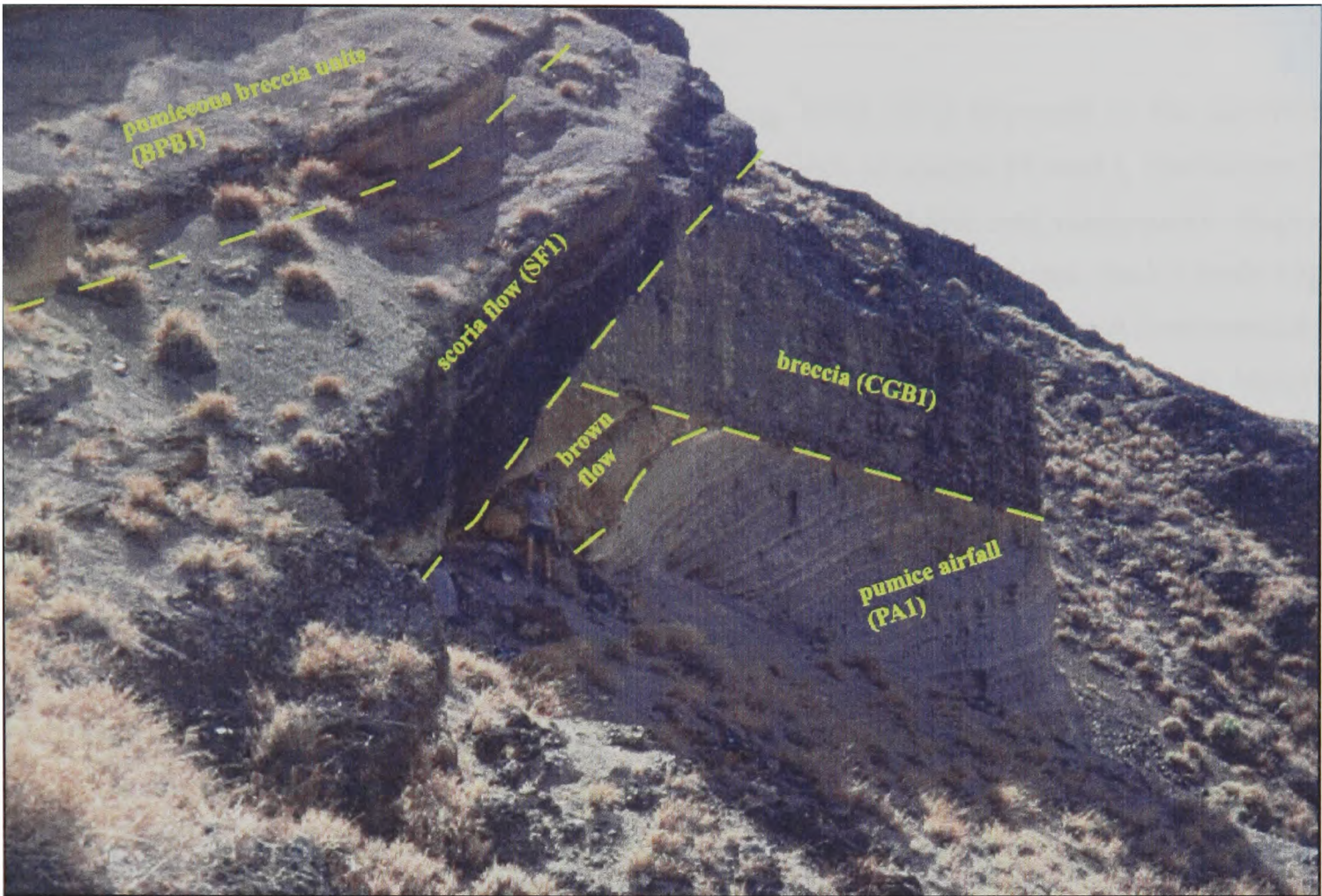


Figure 2.34: View looking southwest showing the coarse semi-welded pumice of the Streaky Bacon Formation in the foreground, here in faulted (?) contact with erosive white pumice flows (PF1). Overlying PF1 is bedded pumice airfall (unit I6; Upper Pumice 1), which displays flow-like features toward the base.



Figure 2.35: View looking south toward Green Mountain, showing the sheet-like Green Mountain Ignimbrite Formation, draping the hillside.



Close-ups of part of the pyroclastic section exposed to the west of Little Ascension trachyte flow (see Figure 1.8; Section G, Enclosure 2):

Figure 2.36 (above): cross-cutting relationships of units PA1, brown flow, CGB1, SF1 and the pumice breccias units from which BPB1 was sampled (which extend ~10m above this exposure).

Figure 2.37 (left): erosion of PA1 by the overlying coarse brown breccia.

bedding and a 'sticky' ash matrix (RSP1), a semi-welded pumice deposit, a well-bedded pumice airfall with ash bands (PA1), two erosive lithic-rich flows, which may have pyroclastic or epiclastic origins and have eroded part of the underlying pumice airfall (Figure 2.37), a very coarse lithic-rich breccia containing lithic boulders (CGB1), which may have a pyroclastic flow/epiclastic (e.g. debris avalanche/mudflow) origin, a coarse erosive scoria flow deposit that has incised the underlying deposits by several metres (SF1) and ~10m of coarse to medium grained pumice breccias, of possible pyroclastic flow origin (BPB1). These breccia units are overlain by the Little Ascension trachyte flow (on the eastern side of the valley).

2.3.7 Eastern Felsic Surge deposits

A sequence of pumice breccia and ash deposits (e.g. EFS1/2) is exposed at the southern end of (and overlying) the Little Ascension trachyte flow (Sections H and I, Enclosure 2). Individual units within the deposits are massive to well-bedded and commonly display characteristic internal features such as cross-bedding, dune structures and bomb sags (Figures 2.26, 2.27). In some places, upper units cross-cut units directly (and conformably) below them (Figure 2.25). The sequence is capped by a coarse trachytic volcanic breccia (TV1; Figure 2.39). The sequence extends further north on top of the Little Ascension flow, but here deposits are much finer-grained white ash beds with breccia interbeds (LA1/2; Section M, Enclosure 2; Figure 2.28).

2.3.8 Cricket Valley

The area to the west and north of Cricket Valley is host to the 'Cricket Valley Pyroclastics' (see Figure 1.8). The CVP section comprises (from the bottom up): a thick (~10m) sequence of scoriaceous lapilli breccia and ash deposits, a ~5m coarse explosion breccia (EB1) that has deformed ashy layers below it (Figure 2.19), and more than 15m of stratified pink ash and breccia deposits that display ripple and dune structures and cross-bedding (see Figure 1.8; Figures 2.23, 2.24).

2.3.9 Hummock Point

The pyroclastic section exposed at Hummock Point (Section N, Enclosure 2; Figure 2.40) lies above basaltic lava flow NELL and below



Figure 2.38: Large-scale view of the pyroclastic section exposed to the west of Little Ascension trachyte flow (see Figure 1.8; Enclosure 2). The section pictured is exposed in the western wall of the valley.

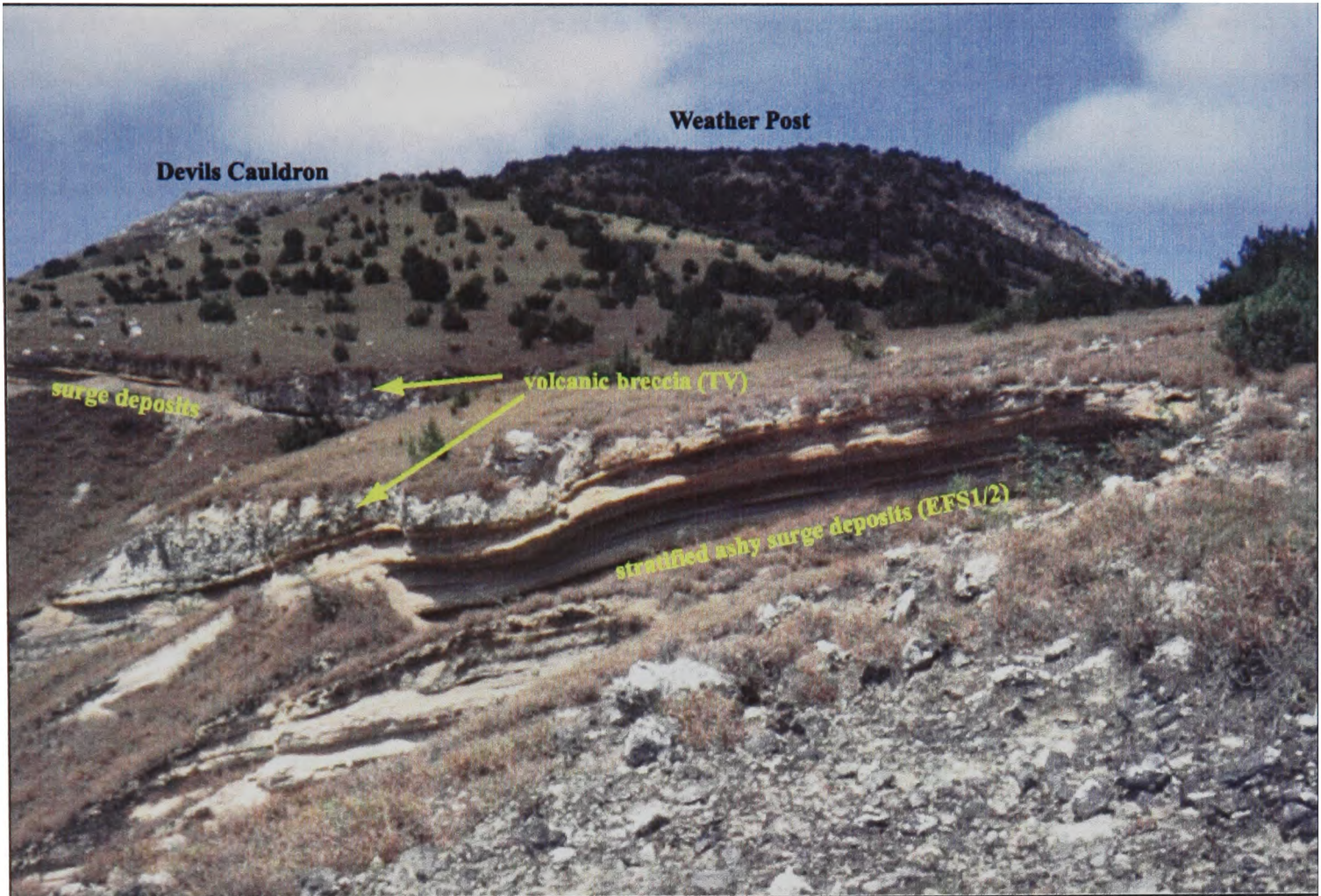


Figure 2.39: View looking southeast toward Weather post and Devil's Cauldron, showing the stratified pumiceous surge deposits from which EFS1/2 were sampled and the overlying coarse trachyte breccia (TV), which displays variable thickness. The distal equivalents of EFS1/2 (LA1/2) are located further to the north (off to the left of the picture).

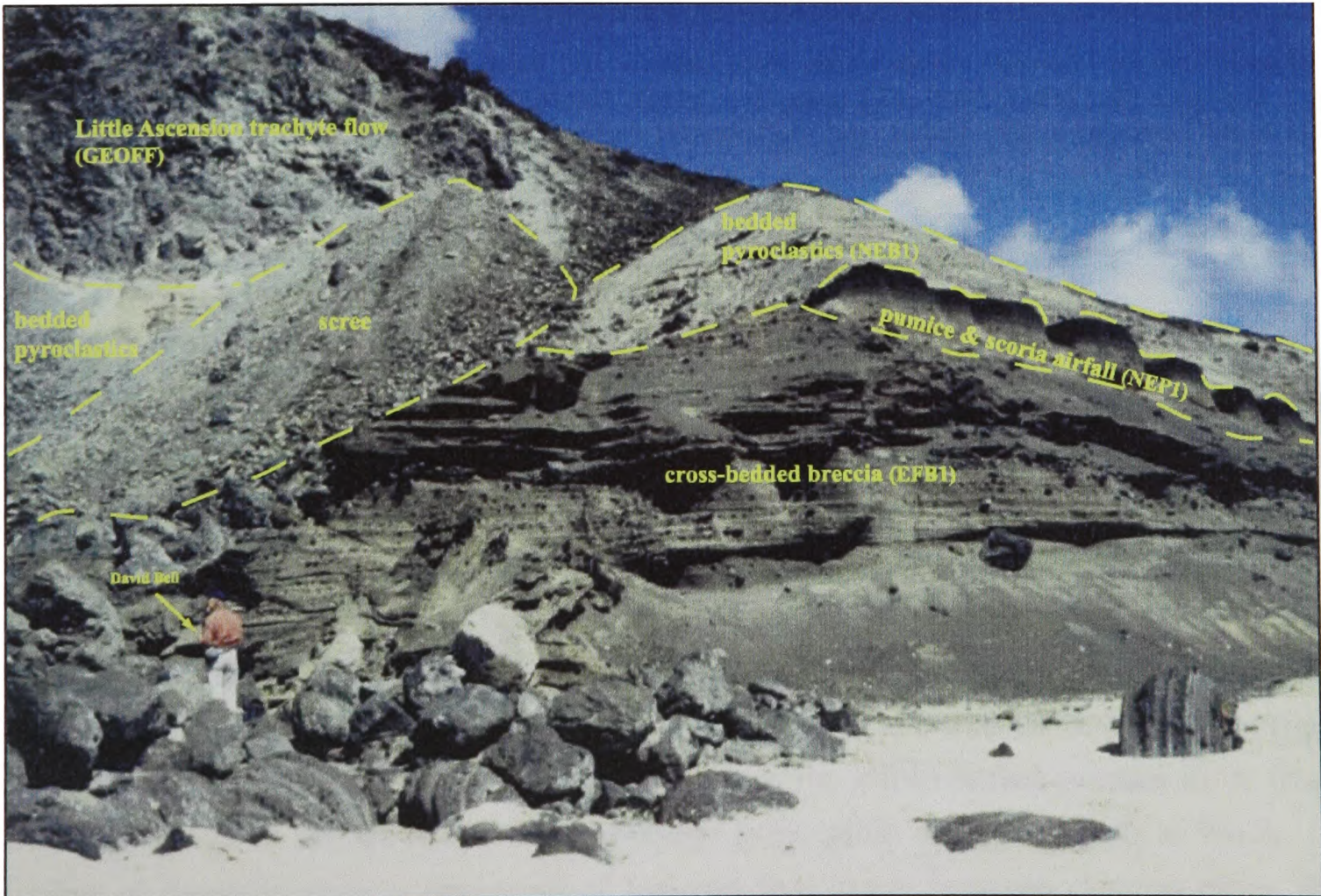


Figure 2.40: Pyroclastic sequence exposed at Hummock Point (cross-bedded breccia EFB1, pumice and scoria airfall NEP1, and coarse pumiceous breccias NEB1), which lies above NELL basaltic lava flow (not in picture) and below Little Ascension trachyte flow.

the Little Ascension trachyte flow, GEOFF. The section comprises (from the bottom up): a cross-bedded, lithic-rich breccia (EFB1), which is inferred to be epiclastic in origin, a scoria and pumice airfall deposit (NEP1), and a sequence of ash-rich pumiceous breccias (NEB1), which are interpreted as pyroclastic flow deposits.

2.3.10 Cricket Valley – White Hill – Spire Beach track area

A sequence of pumice and pseudo-pumice breccias is exposed in the areas between Cricket Valley and White Hill (Figure 2.41), and in the valley running from Weather Post to Spire Beach (see Figure 1.8; Sections J–L, Enclosure 2). These breccias include: bedded pumice deposit EFP1, which is of airfall or epiclastic origin, interbedded ash and pumice/pseudo-pumice breccias (from which LF2 was sampled), which are interpreted as pyroclastic flow deposits, and the pseudo-pumice, ash and obsidian breccia of LF1, which is interpreted as a block-and-ash-flow.

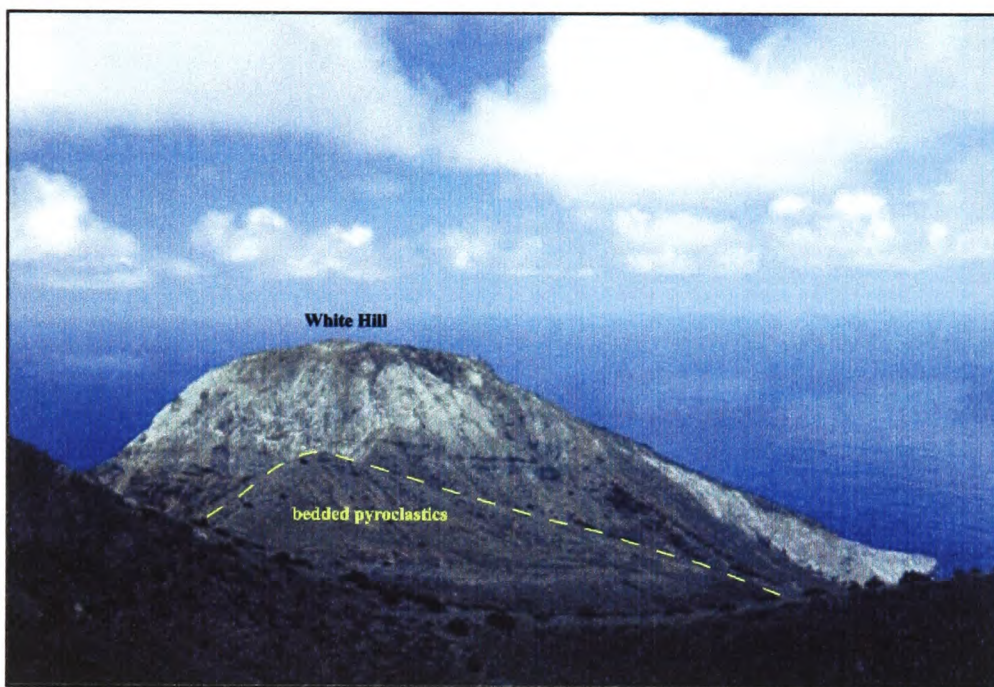


Figure 2.41: Bedded pyroclastic deposits exposed between White Hill and Cricket Valley, including LF2 breccia and ash units and LF1 inferred block-and-ash-flow unit (which banks up onto White Hill dome).

2.4 CONCLUSIONS

In many cases, it is not possible to ascertain the origin of the pyroclastic deposits sampled on Ascension from field characteristics alone, as different transport and deposition processes (i.e. pyroclastic, epiclastic) can produce similar looking deposits. It is clear from the field characteristics exhibited by the pyroclastic deposits on Ascension that the presence or absence of certain features (e.g. truncated ash layers, a reddened jointed matrix) cannot always be reliably used as a diagnostic tool. Many of these features can be produced by more than one process. In addition, even units that have the same origin may exhibit different field characteristics. For example, semi-welded pumice units from Ascension range in colour from white, through grey, pink, orange, yellow to black. A number of deposits show a spectrum of features that grade between deposit types, for example many of the airfall units on the island show both airfall and flow features. To allow accurate identification of pyroclastic rocks, field observations should therefore be

combined with other information, such as palaeomagnetic analysis.

Chapters four to six describe the palaeomagnetic characteristics of the pyroclastic deposits on Ascension, and combine this data with field evidence to determine the origins of these deposits more accurately.

Chapter 3

PALAEOMAGNETISM AND PALAEOMAGNETIC CHARACTERISTICS OF PYROCLASTIC ROCKS

This chapter focuses on palaeomagnetic characteristics of pyroclastic rocks, whilst introducing the general concepts behind palaeomagnetic theory and the acquisition of magnetisation. Included in the chapter are descriptions of the technique of palaeomagnetic emplacement temperature determination, as well as a summary of a pilot study carried out at Ruapehu volcano, New Zealand, which uses this technique.

3.1 GENERAL CONCEPTS

An understanding of palaeomagnetic theory requires the understanding of a number of fundamental concepts, the most basic of which are described in this section. A more in depth explanation of palaeomagnetism may be found in a number of texts, such as Tarling (1971), Collinson (1983), O'Reilly (1984), Butler (1992) or Tauxe (1998).

3.1.1 Magnetic theory

The movement of an electrically charged particle produces a magnetic field. The result of this is that all materials display some magnetic properties because of the motion of their elemental particles. The fundamental units of magnetic charge are *dipoles*; a combination of positive and negative charges, ($\mathbf{m}$ and $-\mathbf{m}$ respectively), which exhibit a *dipole moment*, or *magnetic moment*. At the atomic level, magnetism is a result of the movement of electrons. Two kinds of electron motion define the magnetic properties exhibited by an element. Firstly, electrons orbiting the nucleus of an atom will have an *orbital angular*

momentum, L . The orbiting electron forms a loop of current, which generates a magnetic field, (a magnetic moment), which can be expressed as:

$$\mu = iA$$

(1.1)

where μ = dipole moment, i = current and A = area of loop.

Secondly, each electron has a *spin angular momentum*, s , that is, each electron spins around its own axis, which may have one of two orientations; positive or negative ('up' or 'down'). The superimposition of these forms of electron motion gives the *total angular momentum* of the atom. However, magnetism in solids is almost entirely due to the magnetic moment associated with electron spin (O'Reilly, 1984). The magnetic characteristics displayed by an atom depend on the arrangement of its electrons. Electrons are arranged around the nucleus of an atom in *shells* (states of successively higher energy). Within a shell, electrons exist in orbitals, which are described by a number and a letter (e.g. 1s, 2p, 3d, 4f), according to their distance from the nucleus (Figure 3.1).

	inner shells	sub-shells			
		3s	3p		
Na	1s ² 2s ² 2p ⁶	↑			
Mg		↑ ↓			
Al		3s ²	↑		
Si			↑	↑	
P			↑	↑	↑
S			↑ ↓	↑	↑
Cl			↑ ↓	↑ ↓	↑
Ar			↑ ↓	↑ ↓	↑ ↓

Figure 3.1: Part of the periodic table of elements showing shells 1-3 (after O'Reilly, 1984). The overall magnetic moment (from electron spin) increases from Al – P, as single, parallel electrons (arrows) are added to each orbital, then decreases, (as electrons are paired) from P to Ar. Argon and Magnesium have fully filled outer shells and thus no net magnetic moment.

According to the Pauli Principle, no two electrons in an orbital may occupy the same state. Thus each orbital can contain a maximum of two electrons, one with a positive spin direction and one with a negative spin direction. Where electrons are paired in this way, their charges cancel out, and consequently, filled orbitals have no net magnetic moment. Conversely, where *unpaired* electrons exist in an orbital (i.e. the orbital is incompletely filled), the atom will possess an overall magnetic moment, as the spin moments of single electrons are not cancelled out. Furthermore, as single electrons are preferentially added

with parallel spins, spin moments are combined and the net magnetic moment increases according to the Hund rule (O'Reilly, 1984). The resultant moment (from spin) is at a maximum when the outer shell is half full and decreases as further electrons are added until the shell is full and there is no net moment (Figure 3.1).

3.1.2 Magnetic susceptibility and ferromagnetism

Regardless of the arrangements of their electrons, a basic response is common to all materials upon the application of a magnetic field. This is because the applied field exerts an aligning torque on electron orbits, causing them to rotate, producing a magnetisation parallel or anti-parallel to the applied field. The response (i.e. the magnetic moment) produced by a particular material upon the application of a magnetic field is dependent on its *magnetic susceptibility*, χ . Magnetic susceptibility can therefore be effectively regarded as the ease with which a material can be magnetised. Susceptibility is a dimensionless parameter, which links magnetic moment and applied field in the equation:

$$J = \chi H \quad (1.2)$$

where J = magnetic moment (A/m), χ = susceptibility and H = applied field (Tesla).

(Magnetisation, M , may be substituted for J in this equation. Magnetisation is defined as the magnetic moment per unit volume (A/m)).

The contrasting magnetic behaviour of different materials is hence reflected in their susceptibilities, which in turn is a result of their differing electron configurations. This makes susceptibility a useful tool to distinguish between individual magnetic minerals.

In most materials, when an applied field is removed, electron orbits return to their original position and the magnetisation is lost. This type of behaviour is called *diamagnetism* or *paramagnetism*¹ (see, for example, Tarling 1971; Collinson, 1983). However, some materials exhibit a *spontaneous magnetism*; that is they possess a magnetisation even in the absence of an applied field. This is a result of strong interactions between adjacent atomic magnetic moments (exchange interactions). In these materials, atoms are packed into the crystal lattice in such a way that electron orbitals of adjacent atoms overlap. This causes electrons from adjacent atoms to try to adhere to the Pauli principle of both atoms simultaneously, which effectively means that electrons are shared between adjacent atoms. This results in strong parallel coupling of electron spin moments throughout the material and these aligned moments give rise to a strong permanent spontaneous magnetism. This behaviour is termed *ferromagnetism* and is

¹ Diamagnetic materials (e.g. quartz) contain filled electron orbitals, which will rotate to produce a moment antiparallel to an applied magnetic field. Paramagnetic materials (e.g. fayalite) contain incompletely filled orbitals, which will rotate to produce a moment parallel to an applied magnetic field.

displayed by Fe, Ni, Co and some rare earth elements. The ferromagnetic minerals found in volcanic rocks tend to be oxides of iron and titanium, e.g. magnetite, haematite or minerals of the titanomagnetite series, and are discussed further in Section 3.5.

3.1.3 Remanent magnetisation

For the palaeomagnetist, the most important property of a ferromagnetic mineral is its ability to retain a *remanent magnetisation*; i.e. a record of an applied field after it has been removed. This process can be illustrated on a graph of magnetisation versus applied field (Figure 3.2). Figure 3.2 shows that as an external field is applied to a ferromagnetic mineral, magnetisation (J) increases with increasing field (H), along the path shown in red, until the *saturation magnetisation*, J_s is reached. Increasing the magnetising field above the J_s will *not* result in an increase in magnetisation, i.e. J_s is the maximum magnetisation that the mineral can hold. If the field (H) is then decreased to zero, magnetisation (J) also decreases, but it *does not* fall back to zero when H reaches zero, but a *remanent magnetisation* is retained. This is known as the *saturation isothermal remanence*, J_{rs} (Collinson, 1983). If H is then increased in the *opposite* direction, J will continue to decrease, to reach zero at a value of H equal to the *coercivity*, H_c . Coercivity can therefore be regarded as the force required to reduce J_s to zero; i.e. to cause the induced magnetisation to reorient. Increasing H beyond H_c results in an increase in J in the *opposite* direction until saturation is reached ($-J_s$). Reversal of this process, (i.e. taking the applied field from $-J_s$, through zero to J_s), will produce a 'mirror image' curve.

If saturation magnetisation is *not* reached, the magnetisation path is slightly different and J will follow a path similar to the dashed line (Figure 3.2) once the rock is removed from the field. Here, the remanent magnetisation is effectively equivalent to the applied field and is simply termed the *isothermal remanence* J_r . In nature, a small magnetisation is induced in rocks in this way, due to the influence of the geomagnetic field. However, this typically comprises only part of the rock's total magnetisation and is actually extremely small

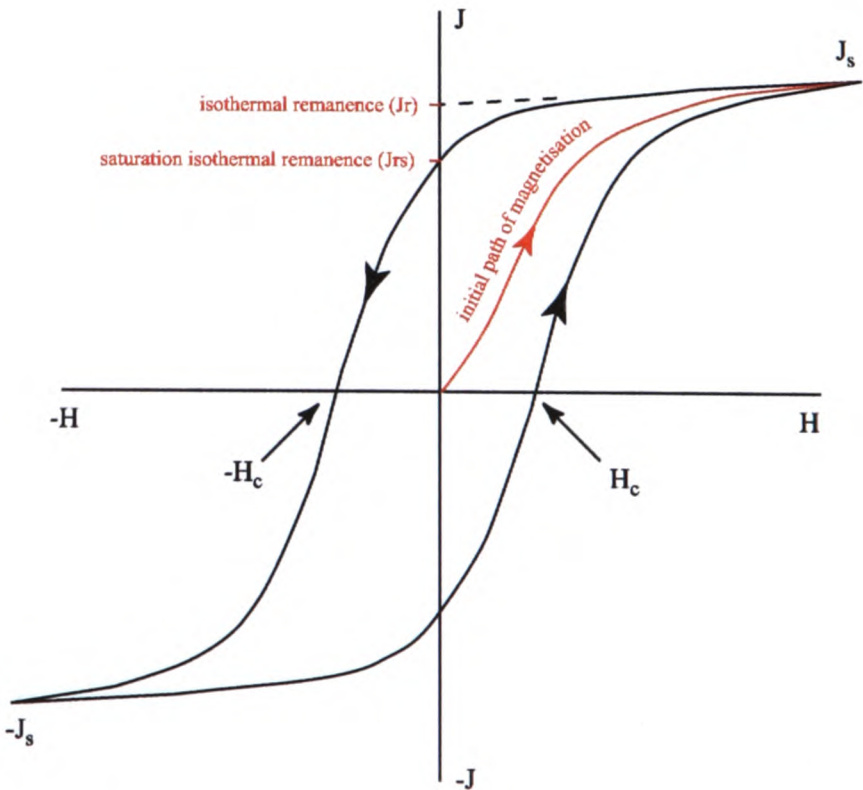


Figure 3.2: Plot of induced magnetisation (J) versus applied field (H) for a ferromagnetic material, showing the way in which a remanent magnetisation is acquired.

compared to magnetisation acquired by the rock on formation, or through alteration processes (e.g. TRM, CRM; see Section 3.3).

3.1.4 Curie temperature

Another important property of ferromagnetism is that it is strongly temperature dependent. Ferromagnetic properties (e.g. saturation magnetisation) will effectively decay with increasing temperature until at the *Curie temperature*, T_c (or Néel temperature, T_N), ferromagnetism is lost completely. This is because as temperature increases, so too does the distance between atoms in the ferromagnetic mineral, because of thermal expansion. This weakens the coupling of adjacent atoms until at T_c orbitals no longer overlap and the behaviour of atoms changes from ferromagnetic to paramagnetic. This process is reversible however, and on cooling below T_c ferromagnetism is regained. The loss of ferromagnetism occurs at a particular temperature for each individual ferromagnetic mineral and hence Curie temperature can be used to identify or distinguish between particular ferromagnetic minerals. Values of T_c for some of the common Fe-Ti oxides are shown in Table 3.1 (Section 3.5).

An example of the decay of ferromagnetic properties with temperature is shown in Figure 3.3, which shows saturation magnetisation (J_s) versus temperature for two ferromagnetic minerals (magnetite and haematite). Figure 3.3 shows that the value of J_s decreases with increasing temperature until J_s reaches zero at the Curie temperature. This figure also illustrates the way in which Curie temperature varies for each individual ferromagnetic mineral.

3.2 ACQUISITION OF MAGNETISATION

The way in which a rock acquires a magnetisation depends on the magnetic properties, size and shape of its constituent magnetic grains. Grain magnetisation is governed by certain internal energies (e.g. magnetostatic energy and interaction energy), which are

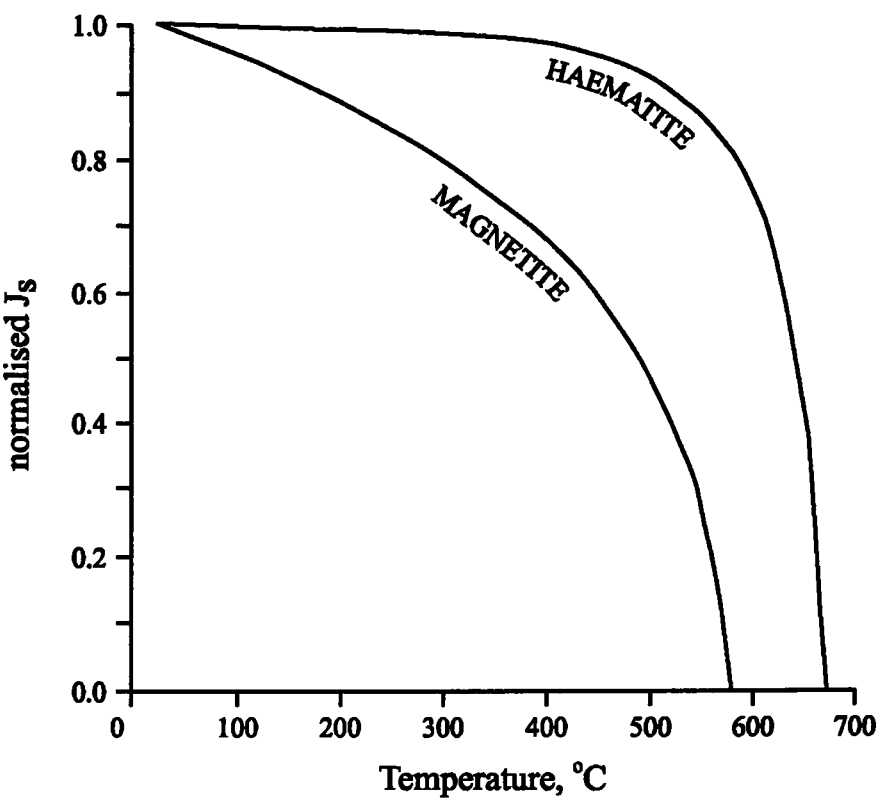


Figure 3.3: Plot of normalised saturation magnetisation (J_s) versus temperature for magnetite and haematite (after Butler, 1992, who redrew the diagram from Pulliah et al., 1975). J_s has been normalised by dividing by J_{s0} (saturation magnetisation at room temperature). The intersection of the J_s curve with the x-axis equals the Curie temperature, which is approximately 580°C for magnetite and 680°C for haematite.

effectively a barrier to magnetisation, and grains will consequently form an internal arrangement of atoms that attempts to minimise these energies. Hence atomic magnetic moments are arranged into regions, referred to as *magnetic domains*; the larger the grain is, the more domains it must possess to minimise its internal energy. Magnetic properties will vary according to the size (and hence domain structures) of the grain.

The extent to which internal energies affect magnetisation depends on the saturation magnetisation (J_s) of the grain. Small grains have low J_s and consequently have low internal energies. It is therefore not necessary for the grain to form domains; in fact it is energetically less favourable (Butler, 1992). Small grains therefore contain only one domain and are thus termed *single-domain* grains. Haematite has a low J_s and so is single-domain up to a grain diameter of $15\mu\text{m}$. Magnetite has a much higher J_s and consequently cubic grains of magnetite are single-domain only below $\sim 0.05\text{--}0.06\mu\text{m}$ grain diameter (Dunlop and Özdemir, 1997). However, grain *shape* also affects grain properties and the way in which the grain is magnetised. All magnetic grains have what is called a *magnetocrystalline easy direction*, which is the direction along which they are most easily magnetised. In equant grains, the magnetocrystalline easy direction lies along particular crystallographic directions (i.e. the [111] direction in cubic magnetite). In elongate grains, however, magnetisation is acquired more easily parallel to the long axis, so the grain is preferentially magnetised along its length. This is called *shape anisotropy*. Elongate magnetites can therefore be single-domain up to $1\mu\text{m}$ in length (Butler, 1992). Volcanic rocks typically contain minerals with a range of grain sizes and shapes and hence magnetic properties will vary from grain to grain. Moreover, elongate crystals are common in volcanic rocks and some of the magnetic grains found in igneous rocks are therefore likely to be single-domain. This is beneficial to the palaeomagnetist, as single-domain grains are efficient carriers of a remanence as they have high coercivities (i.e. the force required to 'reset' their magnetisation is relatively high) and are thus stable over (geologically) long periods.

With increasing grain size, the number of domains within that grain must also increase. Large grains can contain great numbers of domains and are called *multi-domain* grains. Multi-domain grains are less useful to the palaeomagnetist as they typically have relatively small coercivities and hence their magnetisation decays quickly in comparison to that of single-domain grains. However, recent work by McClelland and Shcherbakov (1995) and Muxworthy (1997) has shown that some multi-domain grains *are* capable of holding a stable remanence.

Rather than a distinct boundary, there is a gradation in grain size from single to multi-domain grains. Within this spectrum, exist grains with just a few domains and these are termed *pseudo-single domain* grains. These grains have moderate values of J_s and coercivity (H_c), but can retain a stable remanence over time. In effect, these grains act much like

single-domain grains. Magnetite grains are pseudo-single domain over a range of approximately 0.1-10 μm .

In rapidly cooled volcanic rocks, the great proportion of grains tend to be <10 μm in size and in addition, deuteric oxidation of volcanic rocks tends to produce intergrowths of grains that are smaller than the Fe-Ti oxide grains that crystallised from the melt². This makes volcanic rocks good carriers of a stable magnetic signal.

3.2.1 Relaxation time, superparamagnetism and blocking temperature

The stability of a remanence carried by a particular ferromagnetic grain can be defined by the *relaxation time*, τ , of the grain. This is the time taken for the remanence held by a grain to decay (and hence for the grain to reach equilibrium with its surroundings). The relaxation time for a grain is dependent on grain volume, coercive force, saturation magnetisation and temperature. For *single-domain* grains, relaxation time can be described in the equation of Néel (1949):

$$\tau = \frac{1}{C} \exp\left(\frac{vH_cJ_s}{2kT}\right) \quad (1.3)$$

where τ = relaxation time, C = frequency factor $\sim 10^8 \text{ s}^{-1}$, v = grain volume, H_c = coercive force, J_s = saturation magnetisation and kT = thermal energy (k = Boltzmann's constant and T = absolute temperature).

The part of the equation, vH_cJ_s , equates to the force opposing the rotation of magnetisation (J_s) and can be described as the *blocking energy* (Butler, 1992). If blocking energy is high, relaxation time is long and remanence is stable. However, blocking energy may be overcome by increased thermal energy (kT in Equation 1.3). Consequently, although relaxation time is directly related to coercive force (H_c) and volume (v) of the grain, it is also strongly dependent on temperature. Hence a grain of a particular volume may have a relaxation time on the order of geological time at room temperature, but a relaxation time of just a few seconds at elevated temperatures. For example, for an elongate grain of magnetite (0.1 μm $\times$ 0.02 μm), $\tau < 1$ μsecond at 575°C but $\tau >$ the age of the earth at 510°C (Butler, 1992). Grains for which relaxation time is so short that the grain cannot hold a stable magnetisation are called *superparamagnetic*. The temperature at which a grain becomes superparamagnetic is primarily governed by grain size and shape. For example, at room temperature, magnetite grains of less than $\sim 0.025\mu\text{m}$ are superparamagnetic. Figure 3.4 shows relaxation time as a function of temperature for a single-domain grain of magnetite (length 0.1 μm , width 0.02 μm). The figure shows that relaxation time decreases

² Deuteric oxidation occurs commonly in volcanic rocks, upon cooling and typically involves the exsolution of titanomagnetite into more Ti-rich and Ti-poor phases.

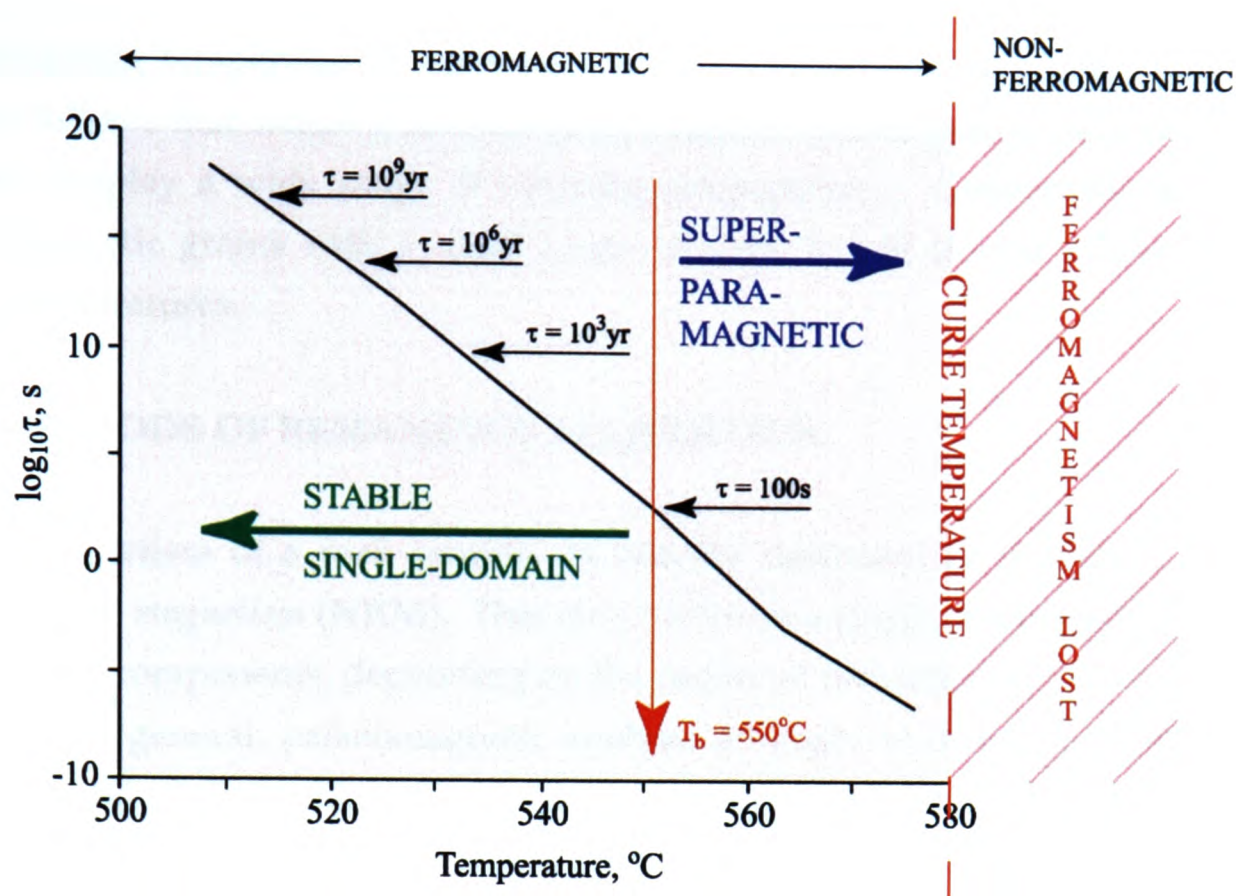


Figure 3.4: Semi-log plot of relaxation time (τ) as a function of temperature (T), for a single domain grain of magnetite (after Butler, 1992). At $T_b = 550^\circ\text{C}$, $\tau = 100\text{s}$. Above 550°C , the grain exhibits superparamagnetic behaviour and remanence is unstable. Below 550°C relaxation time increases such that the grain exhibits stable single domain behaviour and a remanence is 'blocked in'. Above 580°C (the Curie temperature for magnetite), ferromagnetism is lost.

exponentially with increasing temperature. Taking the temperature of 550°C as an example, the graph shows that at this temperature, the relaxation time of the grain is 100s (that is an acquired remanence will decay in 100 seconds). Above this temperature, the grain is still ferromagnetic (up to the Curie temperature, T_c , above which ferromagnetism is lost), but relaxation time decreases such that the grain exhibits superparamagnetic behaviour. Below 550°C , however, relaxation time increases such that the behaviour of the grain changes from superparamagnetic to stable single domain; i.e. relaxation time is long enough for a stable remanence to be *blocked in* to the grain. This phenomenon is common to all grains; each grain of a given volume will have a temperature above which relaxation times are so short that a remanence is not stable, and below which a stable remanence becomes 'locked' in. This temperature is called the *blocking temperature*, T_b . The relationship between relaxation time and blocking temperature can be represented on a *blocking diagram* or *nomograph*, which displays the time-temperature stability of remanence for grains of different volumes (Figure 3.5).

As each grain has a blocking temperature, it follows that that grain must also have an *unblocking* temperature, T_{ub} . This is the temperature at which remanence is lost (i.e. the grain becomes superparamagnetic and magnetisation is 'reset') on demagnetisation of the grain. T_{ub} may have a different value to T_b depending on the conditions under which demagnetisation takes place, but is usually $\approx$ to T_b for single domain grains.

Because blocking temperature (and hence unblocking temperature) is affected by grain volume, it follows that where a rock contains magnetic grains with a wide range of sizes, it will also display a wide range of blocking temperatures. Conversely, where a rock contains magnetic grains with a small range of sizes, it will exhibit a narrow range of blocking temperatures.

3.3 METHODS OF REMANENCE ACQUISITION

The total magnetism of a rock sample, as initially measured in the lab, is termed the *natural remanent magnetism* (NRM). This may comprise a single component of magnetism or a number of components, depending on the nature of formation and geological history of the rock. In general, palaeomagnetic analysis attempts to distinguish between these components and often to eliminate any secondary components to allow measurement of the characteristic remanence (i.e. TRM for volcanic rocks).

This section describes the main mechanisms by which a remanence may have been acquired by the pyroclastic rocks examined in this study.

3.3.1 Thermoremanent magnetisation

A thermoremanent magnetisation (TRM) is acquired as an igneous rock cools from high temperatures, in the presence of a magnetic field. As the rock is likely to contain ferromagnetic grains of various sizes, so it will exhibit a range of blocking temperatures (T_b s). The result of this is that rather than forming at once, a TRM is formed over a range of temperatures, as the rock cools below T_c and through the individual T_b s of its constituent magnetic minerals. As temperature decreases, relaxation time increases for a particular population of grains increases, until at the blocking temperature (T_b), remanence (i.e. a record of the local magnetic field) is locked into those grains.

The fraction of the total TRM formed over a particular temperature interval is called the partial TRM (pTRM). Each pTRM records only the

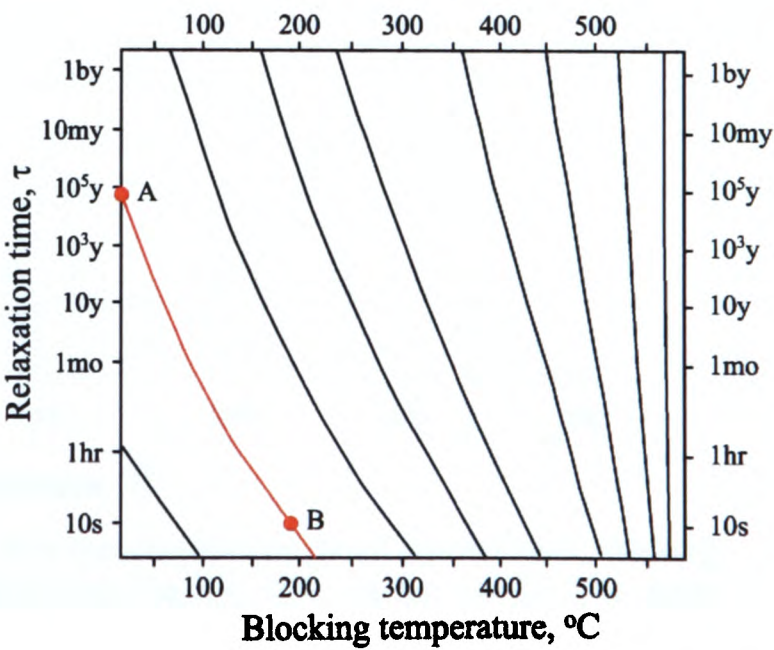


Figure 3.5: Blocking diagram (nomograph) for magnetite (redrawn from Butler, 1992, who modified the diagram of Pulliah et al., 1975). Lines represent the relationship between relaxation time and temperature for grains of a particular size. For the population of grains labelled in red, relaxation time $\approx 10^5$ years at ambient temperature, but only ~ 10 seconds at 200°C.

characteristics of field applied at that temperature interval, and subsequent changes in the field at lower temperatures will not affect previous pTRMs. Hence the TRM acquired over the entire cooling interval is equal to the sum of the pTRMs acquired over each adjacent temperature interval (see Figure 3.6). This is known as the Law of Additivity of pTRMs. A result of this is that if, after formation, an igneous rock is *reheated* to a temperature, T , below T_c (but above the ambient temperature), magnetism will be effectively reset in any grains with $T_b < T$ and a new pTRM will be locked into those grains on subsequent cooling. Whilst grains with $T_b < T$ will record the new pTRM, those grains with $T_b > T$ will not have been affected and will hence retain the original TRM. By this mechanism, a rock may acquire a number of different pTRMs, which may each be different in orientation and intensity, depending on the prevailing characteristics of the magnetising field during their respective cooling periods.

Although TRM may be easily reset by increased temperatures, at ambient temperature it is stable over geological time (relaxation time of grains is sufficiently long) and is hence a reliable carrier of a magnetic signal.

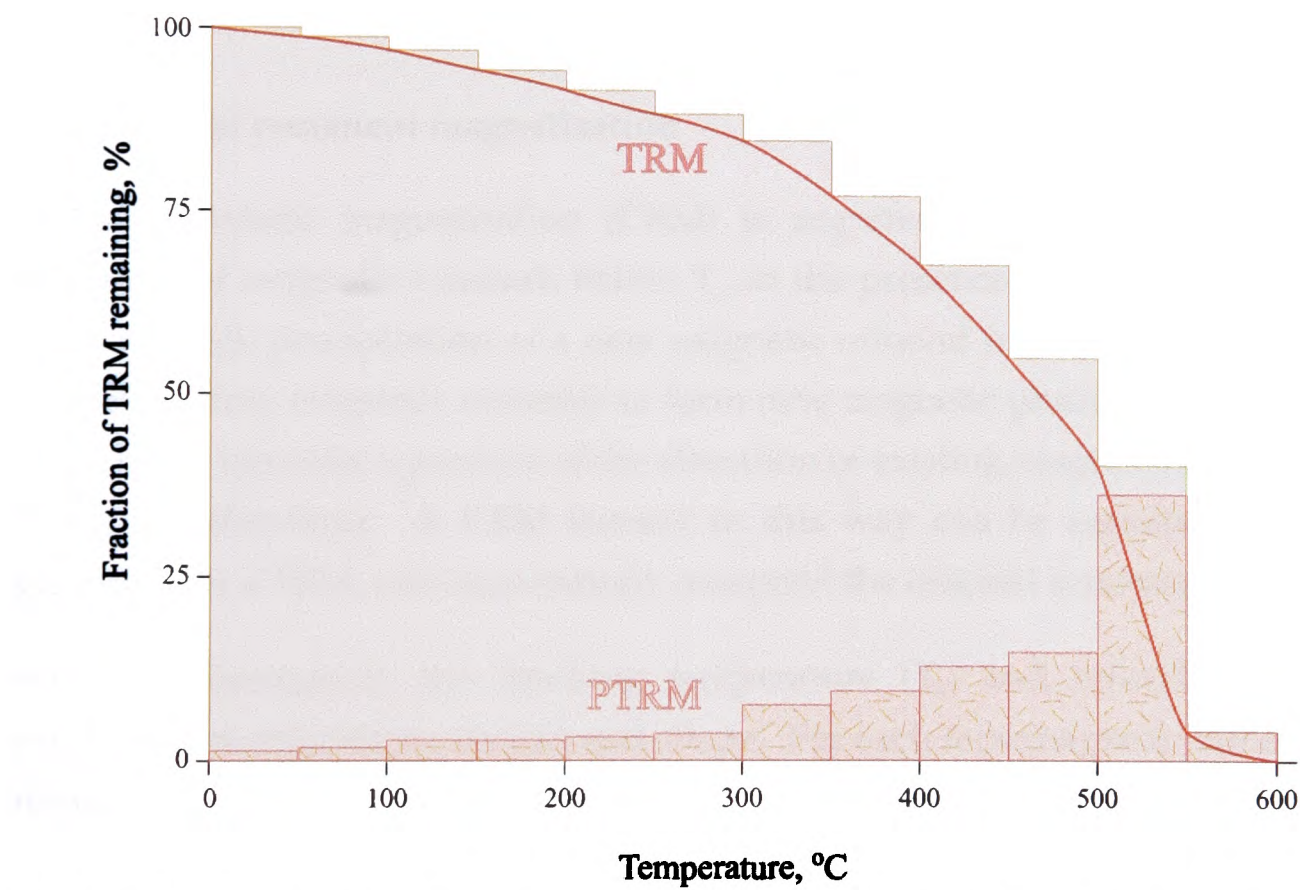


Figure 3.6: Distribution of blocking temperatures in a hypothetical sample of igneous rock, showing the relationship between PTRM and TRM (modified from Tarling, 1971; Butler, 1992). The upper line represents the percentage of the TRM remaining after each heating step during thermal demagnetisation. The stippled area (labelled PTRM) represents the amount of TRM removed during each heating step. In this case, the majority of the TRM is removed over the 500°C to 550°C interval.

3.3.1.1 (p)TRM acquisition in pyroclastic rocks

Acquisition of (p)TRM in pyroclastic rocks is typically more complicated than it is in lavas or intrusive igneous rocks. When a pyroclastic eruption takes place, fragments of magma

(juvenile clasts), crystals and fragments of country rock (lithic clasts) are explosively ejected. These components may be transported in an eruption column, to fall-out as an airfall deposit, or may be incorporated into and deposited by a hot pyroclastic flow or surge. On deposition and cooling, juvenile clasts will acquire a TRM in a similar way to a lava. However, lithic clasts are expected to hold a pre-existing magnetisation (TRM) that was acquired on formation. If heating of the lithic clasts occurs (to a temperature, T) in the eruption column, flow or surge, part of the clasts' primary magnetisation with $T_b \leq T$ will be 'reset' and overprinted by a new, pTRM, upon deposition and cooling. The new pTRM will be acquired parallel to the direction of the geomagnetic field at the time. Lithic clasts from hot pyroclastic deposits are therefore expected to display a two-component magnetism (TRM + pTRM). The primary (high T_b) TRM component will have a random orientation with respect to the direction of the geomagnetic field (at the time of deposition), due to rotation of clasts during transport. However, the secondary (low T_b) pTRM component will lie in a similar direction in each clast from the deposit, sub-parallel to the direction of the local geomagnetic field (see Figure 3.12a).

Palaeomagnetic analysis of lithic clasts from pyroclastic deposits can provide an estimate of the emplacement temperature of that deposit (Section 3.4.1).

3.3.2 Chemical remanent magnetisation

A chemical remanent magnetisation (CRM) is acquired in rocks by the growth or transformation of magnetic minerals below T_c in the presence of a magnetic field. This may occur through precipitation of a new magnetic mineral from solution or due to the alteration of existing magnetic minerals to form new magnetic phases. In the case of this study, CRMs are typically a product of the alteration of existing magnetic minerals (due to weathering or reheating). A CRM formed in this way can be equally as stable over geological time as a TRM, and may entirely overprint the original remanence.

As previously mentioned, the blocking temperature (T_b) and relaxation time for a magnetic grain are affected by its size and shape. For each ferromagnetic mineral there is an optimum grainsize range within which the grain is single-domain and will hold a stable remanence (e.g. between $\sim 0.025\mu\text{m}$ and $\sim 0.5\text{--}0.6\mu\text{m}$ grain diameter for cubic magnetite). If a grain is subject to alteration, its size and shape may change, removing it from the optimum grainsize range and hence causing its relaxation time to decrease considerably, the result of which is that a stable remanence can no longer be held. Conversely, alteration may cause small superparamagnetic grains to increase in size, and thus to move *into* the optimum grainsize range. As the grain reaches the *blocking volume*, its behaviour will change from superparamagnetic to single-domain, allowing a remanence (CRM) to be blocked in. The direction of this CRM will generally reflect that of the external field. However, if the new (daughter) grain is affected by the internal

energies of the original grain, the CRM may deviate from the directions of the external field because of the internal field created by the original grain.

3.3.3 Viscous remanent magnetisation

A viscous remanent magnetism (VRM) may be acquired by a rock during prolonged exposure to weak magnetic fields (e.g. the ambient field of the earth). The extent to which a rock will acquire a VRM depends on the length of time that the rock has been exposed to the magnetising field and the temperature at which this has occurred. Over extensive periods of exposure, grains with short relaxation times (e.g. larger multi-domain grains, or small single-domain grains) can acquire a VRM as their magnetic moments gradually realign themselves with the magnetising (ambient) field. Primary magnetism (e.g. TRM) will decay more quickly in these grains, than in those with longer relaxation times. All grains with relaxation times $<10^9$ years have the potential to acquire VRM (Butler, 1992). Acquisition of VRM increases logarithmically with time (Butler, 1992) and this means that natural VRMs tend to record the recent geomagnetic field. VRM acquisition also increases with temperature and thus the VRM acquired over geologically extensive periods at *ambient* temperature can be acquired in a fraction of the time at *elevated* temperatures. A VRM acquired at significantly elevated temperatures is termed a thermoviscous remanent magnetism (TVRM).

The way in which VRM acquisition varies with time and temperature can be illustrated on a nomograph (see Figure 3.5). This shows the combination of temperature and relaxation time that will unblock (reset) magnetisation (in this case VRM) for ferromagnetic grains of different volumes. The graph shows that for a given grain volume, a (T)VRM which has been acquired over a geological timescale at ambient temperature may be unblocked over a much shorter time (e.g. on a laboratory timescale) by exposing the sample to elevated temperatures. Analysis of nomographs makes it possible to calculate the maximum temperature to which a (T)VRM is expected to be present in rocks of a certain age. In this study, the rocks studied are inferred to have a maximum age of ~1Ma (Harris et al., 1982; Nielson and Sibbett, 1996; Kar et al., 1998). However, any VRM component in these rocks is expected to record the recent field direction (i.e. display normal polarity), due to the logarithmic increase of VRM with time and can therefore only have been acquired over the last 0.78Ma (the approximate date of the most recent magnetic reversal). According to Bardot (1997), a (T)VRM acquired over 0.78Ma will be removed by 163°C. The calculations of Bardot (1997) use the magnetite nomograph of Pulliah et al. (1975) and are therefore strictly only valid for rocks in which the primary magnetisation is carried by magnetite. However, nomographs for titanomagnetite are not well-constrained, the value of Bardot (1997) is therefore used (as an approximation) in this thesis.

The presence of VRM or TVRM can be a problem when trying to distinguish between

primary and secondary components of magnetism. However, in most cases, a (T)VRM can be removed by thermal demagnetisation (Section 3.4.1).

3.3.4 Isothermal remanent magnetism

An isothermal remanent magnetisation (IRM) is acquired by applying a magnetic field to a sample for a short period at a given temperature. This can occur in nature where a rock is struck by lightning (Collinson, 1983; Butler, 1992). The intensities of such IRMs are typically much higher than those of TRMs, but are generally less stable with respect to time (Butler, 1992).

3.4 DEMAGNETISATION TECHNIQUES

To decipher the palaeomagnetic information that a sample holds, it is necessary to isolate and analyse the various components that comprise the NRM of that sample. Two major techniques are used for this purpose: thermal demagnetisation and alternating field (AF) demagnetisation. Both techniques rely on the fact that secondary components (e.g. VRM) are typically carried by grains with relatively short relaxation times (Butler, 1992; Tauxe, 1998). Such grains will in turn typically have low blocking temperatures and low coercivities, making them relatively easy to remove in comparison to primary NRM components.

In this study, thermal demagnetisation (rather than AF demagnetisation) was used, because information on the thermal history (e.g. blocking temperatures) of the rocks was required.

3.4.1 Thermal demagnetisation

Thermal demagnetisation involves the heating of a sample to a particular temperature and subsequent cooling in the absence of a magnetic field (in reality in a field of $<5\text{nT}$, 0.01% of the Earth's field). The procedure is dependent on the relationship between grain relaxation time, blocking temperature (T_b) and temperature. Heating to a temperature, T , has the effect of resetting magnetism in all grains with $T_b \leq T$ (because of increased thermal agitation). On cooling, as with pTRM acquisition, these grains will block in new magnetisations. However, as cooling occurs in a zero field, the directions of the new magnetisations will be random (rather than aligned with an external field), so will no longer contribute to the overall magnetism. The heating and cooling process is repeated to successively higher temperatures and remanence is measured after each step. An increasing proportion of the NRM (carried by grains with increasingly high blocking temperatures) is removed with each temperature step, until ultimately all components of magnetism are removed and NRM is reduced to zero (see Figure 3.6). Progressive thermal demagnetisation (PTD) therefore makes it possible to isolate individual fractions

of the NRM that are removed over a particular blocking temperature interval.

Secondary NRM components (particularly VRMs) can generally be removed easily using PTD, as they tend to be carried by grains with short relaxation times. Such grains will, in turn, have low blocking temperatures (Butler, 1992; Tauxe, 1998) and thus heating to a temperature $\geq T_b$ of the VRM-carrying grains will remove the VRM.

Where a clast has experienced more than one heating episode (as is the case for clasts from many pyroclastic deposits) it will possess more than one (p)TRM. Progressive thermal demagnetisation can be used on such clasts to provide an estimate of the temperature(s) to which the clast was heated. In the case of clasts from pyroclastic deposits, the most recent heating episode typically corresponds to the *emplacement temperature* (T_e), of the clast. In order to calculate emplacement temperature using thermal demagnetisation, the peak heating temperature (T) is increased until the secondary (low T_b) pTRM is removed, but the primary (high T_b) TRM remains intact. Above this temperature, the primary TRM starts to be removed. The emplacement temperature is placed between the highest temperature step at which the secondary magnetism is present, and the next highest heating step after which the primary magnetism starts to be removed (i.e. T_e = the maximum temperature to which the secondary pTRM persists).

The data obtained from progressive thermal demagnetisation are a series of vectors that depict the change in direction and intensity of the NRM with increasing temperatures. Such data can be visualised either on a stereoplot, or by plotting the 3D vector paths onto two orthogonal planes (a horizontal [N-E-S-W] plane and a vertical [up-N-down-E] plane) and "unfolding" them into a 2D vector component plot called a Zijderveld diagram (Zijderveld, 1967; see Figure 3.7 and Appendix C for further details). Progressive thermal demagnetisation also provides a plot of percentage intensity versus unblocking temperature for a sample ('blocking temperature spectra' or T_b spectra; see Figure 3.7). The maximum unblocking temperature (i.e. the temperature by which the sample is fully demagnetised) can be used as an approximation for (maximum) Curie temperature for the sample's constituent ferromagnetic mineral(s). Figure 3.7 shows two examples of Zijderveld plots and their corresponding blocking temperature spectra along with a stereoplot representation of vector directions. The figure illustrates the difference between blocking temperature (T_b) and Curie temperature (T_c); in both samples, the low blocking temperature component is removed by $\sim 320^\circ\text{C}$. As TBUB1-3 has only a single-component of magnetism (plot c), the sample is *fully* demagnetised by 320°C (plot d), and 320°C is therefore equivalent to the *Curie temperature* for TBUB1-3. However, BPB2 has two components of magnetism (plot a) and only part of the sample (the low- T component) is demagnetised by 320°C ; *full* demagnetisation of the sample only occurs at $\sim 625^\circ\text{C}$ (plot b). Hence for BPB2, 320°C equates to a *blocking temperature*, not the Curie temperature (which is 625°C).

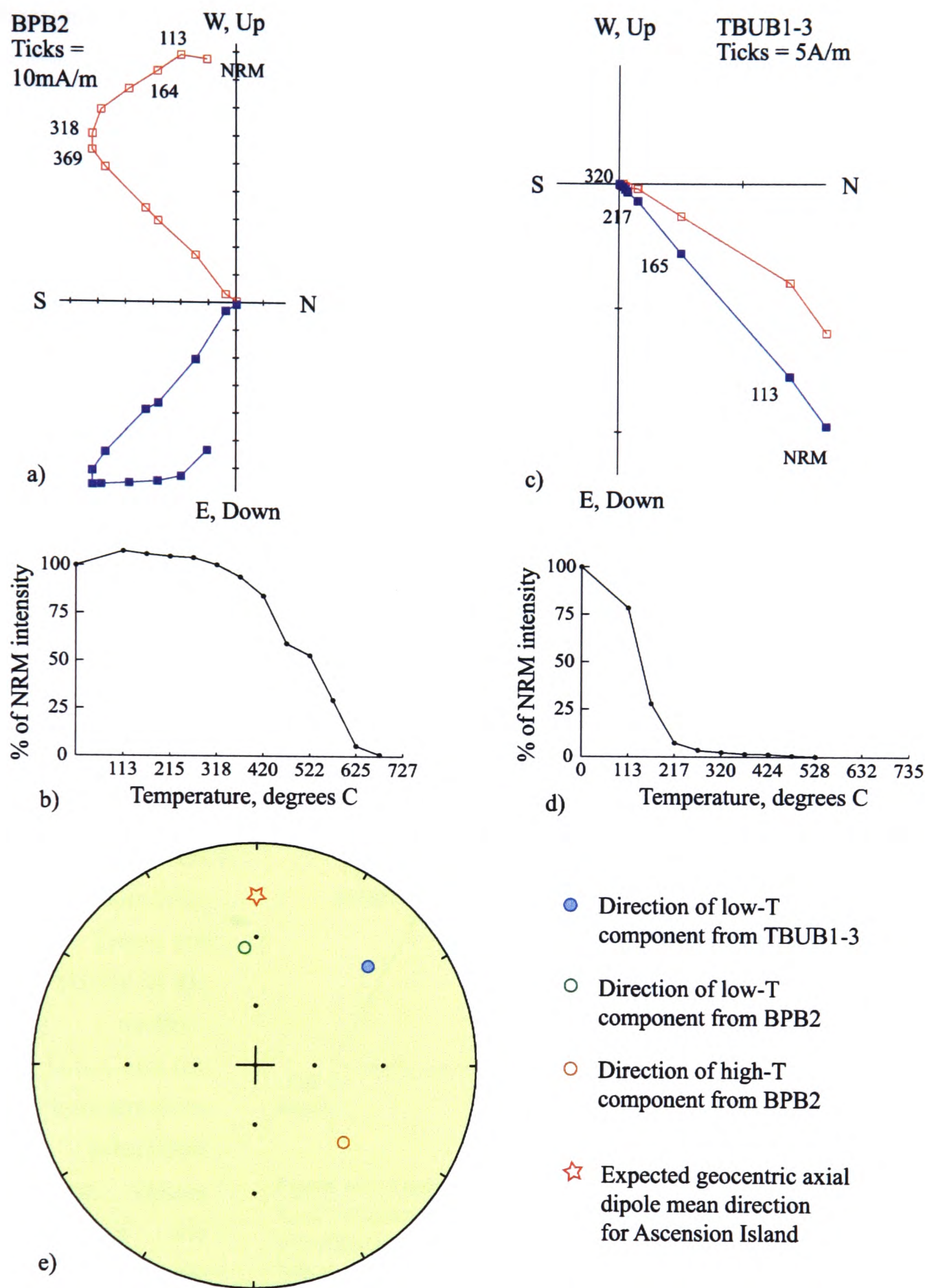


Figure 3.7: Zijderveld plots (z-plots), blocking temperature (T_b) spectra and equal area stereoplot for two samples from Ascension Island. The z-plots for BPB2 (plot a) and TBUB1-3 (plot c) show that they exhibit a two-component and a single-component remanence respectively. Points represent heating increments of 50°C except where indicated otherwise and temperatures on z-plots and T_b spectra have been corrected to account for the thermal gradient of the demagnetising furnace. The directions of the vector components for TBUB1-3 and BPB2 can also be displayed on a stereoplot (plot e), which shows the expected geocentric axial dipole mean direction for Ascension (360/-15) for reference. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively. In both samples the low blocking temperature component is removed by ~320°C. In TBUB1-3, this equates with full demagnetisation (as seen from the T_b spectra; plot d) and hence 320°C is the *Curie temperature* for the sample's magnetic minerals. However, in BPB2, only the low-T component is removed by 320°C and full demagnetisation only occurs at ~625°C (plot b). Hence in BPB2, 320°C equates to a *blocking temperature*, and the *Curie temperature* is ~625°C.

The characteristics displayed by T_b spectra for clasts from Ascension pyroclastic deposits are discussed further in Section 3.6.3.

3.5 MAGNETIC MINERALS

If an accurate interpretation of remanence is to be made, it is necessary to ascertain which magnetic mineral(s) carry that remanence. It is therefore important to have some knowledge of the magnetic minerals that occur in nature (for example in the rocks sampled on Ascension Island), and of the magnetic properties that they display. The most common naturally occurring magnetic minerals are the iron oxides and these can be plotted within the FeO – TiO₂ – Fe₂O₃ ternary diagram (Figure 3.8). Two solid solution series are particularly important in palaeomagnetism: the titanomagnetite series (ulvöspinel – magnetite) and the titanohaematite series (ilmenite – haematite; Figure 3.8). These are discussed briefly in the following section. Table 3.1 lists Curie (or Néel) temperatures and saturation magnetisation values for some of the common magnetic minerals.

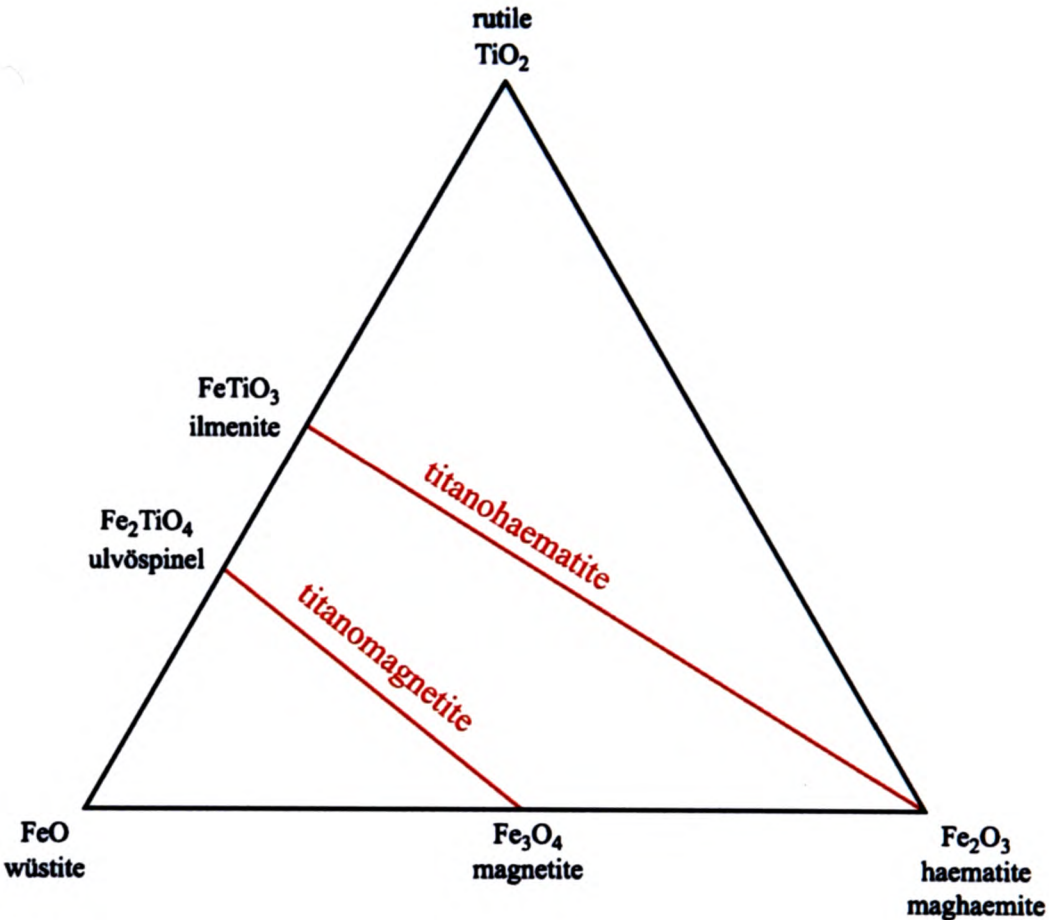


Figure 3.8: Ternary diagram of FeO – TiO₂ – Fe₂O₃, showing some of the most common iron oxides. Red lines represent the titanomagnetite and titanohaematite solid solution series. Substitution of Ti in the crystal lattice increases upwards along the red lines. Modified from Butler, 1992; Tauxe, 1998).

3.5.1 The titanomagnetite series

Minerals of the titanomagnetite series (Fe_{3-x}Ti_xO₄) are the most common of the naturally occurring magnetic minerals. They occur as primary minerals in igneous rocks, but magnetite may also be formed by alteration of other minerals (e.g. by reduction of iron hydroxides or by deuteric oxidation of volcanic rocks; Dunlop and Özdemir, 1997; Tauxe, 1998).

magnetic mineral	T_c/T_N (°C)	J_s (kA/m)
magnetite	580	480
maghaemite	590-675	380
titanomagnetite (TM60)	150	125
haematite	675	~2.5
goethite	~120	~2
pyrrhotite	~320	~80

Table 3.1: Values for Curie/Néel temperature and saturation magnetisation for some of the common magnetic minerals. Data from Dunlop and Özdemir (1997).

Titanium (Ti) content in titanomagnetites increases (upward along the red line in Figure 3.8), from magnetite (Fe_3O_4) to ulvöspinel (Fe_2TiO_4). The amount of Ti substitution can be symbolized by x , with magnetite at $x = 0$, also represented by TM0, and ulvöspinel at $x = 1$, also represented by TM100. Compositions between magnetite and ulvöspinel are referred to as TM '100x', i.e. if $x = 0.6$, the mineral is referred to as TM60. Substitution of Ti results weakens the exchange coupling in titanomagnetites, which results in a decrease in Curie temperature (Figure 3.9). Ti- substitution also results in a decrease in saturation magnetisation (J_s ; see Table 3.1) and a slight increase in coercivity (Tauxe, 1998).

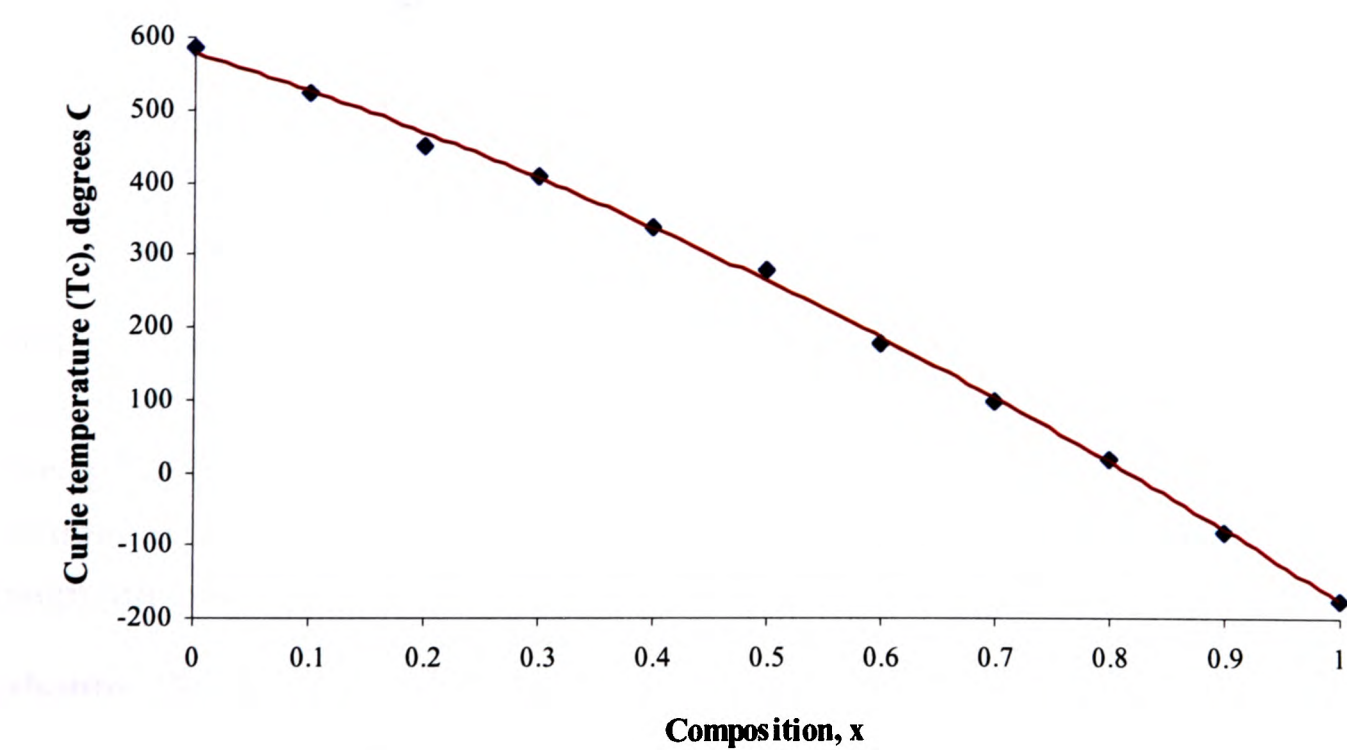


Figure 3.9: Plot of T_c as a function of increasing titanium content for titanomagnetite ($\text{Fe}_{3-x}\text{Ti}_x\text{O}_4$) of varying titanium content (x). After Erwin, 2001, who modified the graph from Xu et al. (1996).

3.5.1.1 Maghaematization

Titanomagnetites (including magnetite) are unstable in air and are therefore prone to

oxidation, even at low temperatures (e.g. $\leq 200^\circ\text{C}$; Dunlop and Özdemir, 1997). This process is called *maghaematization* and yields *(titano)maghaemites*. Maghaematization typically results in an increase in Curie temperature and a decrease in saturation magnetisation (see Table 3.1).

Maghaemite ($\gamma\text{Fe}_2\text{O}_3$) has the same composition as haematite (see Figure 3.8), but has a different crystal structure³. It is a common weathering product of magnetite and is found in both subaerial and submarine environments. In palaeomagnetic terms, its occurrence typically indicates the presence of a CRM component (Dunlop and Özdemir, 1997). Maghaemite is metastable at room temperature but on heating, will revert to haematite (Tauxe, 1998).

3.5.2 The titanohaematite series

Minerals of the titanohaematite series can be defined by the formula $\text{Fe}_{2-y}\text{Ti}_y\text{O}_3$. Titanohaemites of intermediate compositions (i.e. $y \approx 0.5\text{--}0.7$) can occur as primary minerals in rapidly cooled dacitic pyroclastic rocks. However, these minerals are unstable at ambient temperature and will eventually exsolve toward an intergrowth of Ti-rich and Ti-poor phases (Dunlop and Özdemir, 1997). This can result in the self-reversal of TRMs in such rocks (Dunlop and Özdemir, 1997). Haematite (Fe_2O_3) is common in sediments (e.g. in red sandstones) where it may be formed as a primary mineral or through oxidation of other minerals (e.g. high temperature deuteric oxidation of volcanic rocks or the dehydration of iron oxyhydroxides such as goethite; Tauxe, 1998). Coercivity and Néel temperature (Table 3.1) are relatively high for haematite, meaning that it is capable of carrying a stable magnetic signal.

3.5.3 Other magnetic minerals

Goethite (αFeOOH) is the only naturally occurring iron oxyhydroxide that is magnetic (Tauxe, 1998). It is a common weathering product of iron-bearing minerals and may also be precipitated from iron-bearing solutions. Goethite is metastable and therefore tends to dehydrate to haematite (Tauxe, 1998). Néel temperature for goethite is low in comparison to magnetite or haematite, at $\sim 100^\circ\text{C}$ to 150°C (see Table 3.1).

Pyrrhotite (Fe_{1-x}S) is a common accessory mineral in igneous metamorphic and sedimentary rocks, however it does not typically dominate remanence (Dunlop and Özdemir, 1997). Pyrrhotite transforms irreversibly to magnetite on heating above 500°C and at higher temperatures will transform to haematite (Dunlop and Özdemir, 1997).

³ Maghaemite ($\gamma\text{Fe}_2\text{O}_3$) has a body-centred cubic (spinel) structure whereas haematite ($\alpha\text{Fe}_2\text{O}_3$) has a rhombohedral (corundum) structure.

3.6 PALAEOMAGNETIC CHARACTERISTICS OF PYROCLASTIC DEPOSITS

The palaeomagnetic characteristics displayed by a particular deposit can provide information on depositional mechanisms, age and correlation of the deposit. Analysis of palaeomagnetic characteristics can also yield information on the post-depositional history of the deposit (e.g. the events leading to the acquisition of a secondary magnetisation). This section uses examples from Ascension Island to describe the expected palaeomagnetic characteristics (remanence, magnetic polarity, emplacement temperature, magnetic mineralogy and secular variation) of pyroclastic deposits *in general*. The actual palaeomagnetic characteristics displayed by the different types of deposit sampled on Ascension (airfall deposits, welded deposits and lavas, and breccia deposits) are discussed in detail in Chapters 4, 5 and 6 (respectively).

3.6.1 Remanence characteristics

The remanence characteristics displayed by juvenile and lithic clasts from a particular pyroclastic deposit will be primarily dependent on the way in which that deposit was formed. Remanence characteristics will therefore vary between different types of pyroclastic deposit. However, any rock that undergoes heating to (and thus cooling from) high temperatures will acquire a thermoremanent magnetism (TRM) that will be aligned with the geomagnetic field at the time of formation (Section 3.3.1). This direction may be normal or reversed, depending on the polarity of the geomagnetic field at the time of deposition. In pyroclastic eruptions, parts of the pre-existing volcanic edifice (lithic clasts) are explosively ejected with hot juvenile fragments and gas to form an eruption column. These clasts may fall back to earth as an airfall deposit, or if column collapse occurs, they may be deposited as a pyroclastic flow or surge deposit.

3.6.1.1 Juvenile clasts

On deposition and cooling in situ, juvenile clasts from hot pyroclastic deposits are expected to acquire a magnetisation (TRM) parallel to the geomagnetic field. However, this TRM component will only be acquired by the fraction of grains with blocking temperatures (T_b s) less than the emplacement temperature (T_e), as these grains will block in a TRM once the clast has come to rest (post emplacement). Grains with $T_c > T_b > T_e$ will also acquire a TRM, but this will be weak and lie in a direction distinct from the geomagnetic field. This is because these grains will have blocked in remanence during transport in the eruption column, flow or surge, when clasts are likely to rotate and tumble. The magnetisations blocked into these grains will therefore be acquired in a range of directions, which will effectively cancel each other out. In reality, a slight 'net remanence' may remain, but this will be weak and is not expected to reflect the geomagnetic field direction, or to contribute significantly to the net remanence of the clast.

If a juvenile clast is completely cool on deposition, all of its remanence will have been acquired during transport and hence it is expected to display a weak remanence in a direction distinct from the geomagnetic field.

Juvenile clasts from pyroclastic deposits are therefore expected to display either: a) a *partial* TRM in the fraction of grains with $T_b \leq T_c$ that lies parallel to the geomagnetic field at the time of deposition (assuming that cooling continues in situ after deposition), or b) a weak magnetization, in a direction distinct from that of the geomagnetic field (assuming the clast is cold on deposition). However, in contrast to the expected behaviour, Zlotnicki et al. (1984) and McClelland and Druitt (1989) have observed that pumices from airfall deposits display a single-component remanence (parallel to the geomagnetic field) that extends *up to the Curie temperature*, whatever the emplacement temperature (e.g. Figure 3.10a). Similar behaviour is displayed by juvenile clasts from pyroclastic flow and surge deposits sampled on Ascension Island. Zlotnicki et al. (1984) and McClelland and Druitt (1989) have proposed that this single-component remanence is in fact a chemical remanent magnetism (CRM; Section 3.3.2) that has overprinted the original TRM. Pumice (volcanic glass) is chemically unstable and is thought to alter readily. Sparks et al. (1999) suggest that gases such as H_2O , which are originally exsolved from volcanic glass (pumice) within ignimbrites, may be *resorbed* back into the glass, minutes to hours after deposition. This is likely to result in chemical alteration and hence subsequent acquisition of a CRM. Juvenile clasts from hot pyroclastic deposits are therefore expected to display a *single-component CRM*, which will persist to the Curie temperature. The direction of the CRM is not expected to differ from the original TRM direction, because alteration is expected to occur so quickly after deposition. The directions of CRM components from different juvenile clasts within the same airfall deposit will be similar and should be closely grouped around the expected geocentric axial dipole mean direction (GAD) for the sampling location (000/-15 for Ascension; e.g. Figure 3.10c). The GAD mean direction is time averaged and thus is more appropriate for comparison than the present day field direction.

3.6.1.2 Lithic clasts

Prior to incorporation in a pyroclastic eruption, lithic clasts will hold a pre-existing magnetisation (TRM), acquired on formation (e.g. a single-component TRM for lavas). During eruption and transport in a hot eruption column, flow or surge, lithic clasts will be reheated (by volcanic gases and heat transfer from hot magmatic fragments) such that the magnetisation in grains with $T_b \leq T_c$ will be 'reset'. On deposition and cooling (in situ), this magnetisation will be replaced by a new TRM, aligned parallel to the geomagnetic field. The clast will now hold two components of magnetism; a low-temperature (low-T) component aligned with the geomagnetic field and a high-temperature (primary) component with a direction distinct from the geomagnetic field (Figure 3.10b). Directions of low-T components will be similar between clasts from the same deposit and hence they

will be closely grouped (around the geomagnetic field direction) when viewed on a stereoplot (e.g. Figure 3.10c). However, directions of high-T components will be randomly orientated between clasts from the same deposit, because of the rotation of clasts during transport. The directions of high-T components will not therefore show grouping when viewed on a stereoplot (e.g. Figure 3.10c).

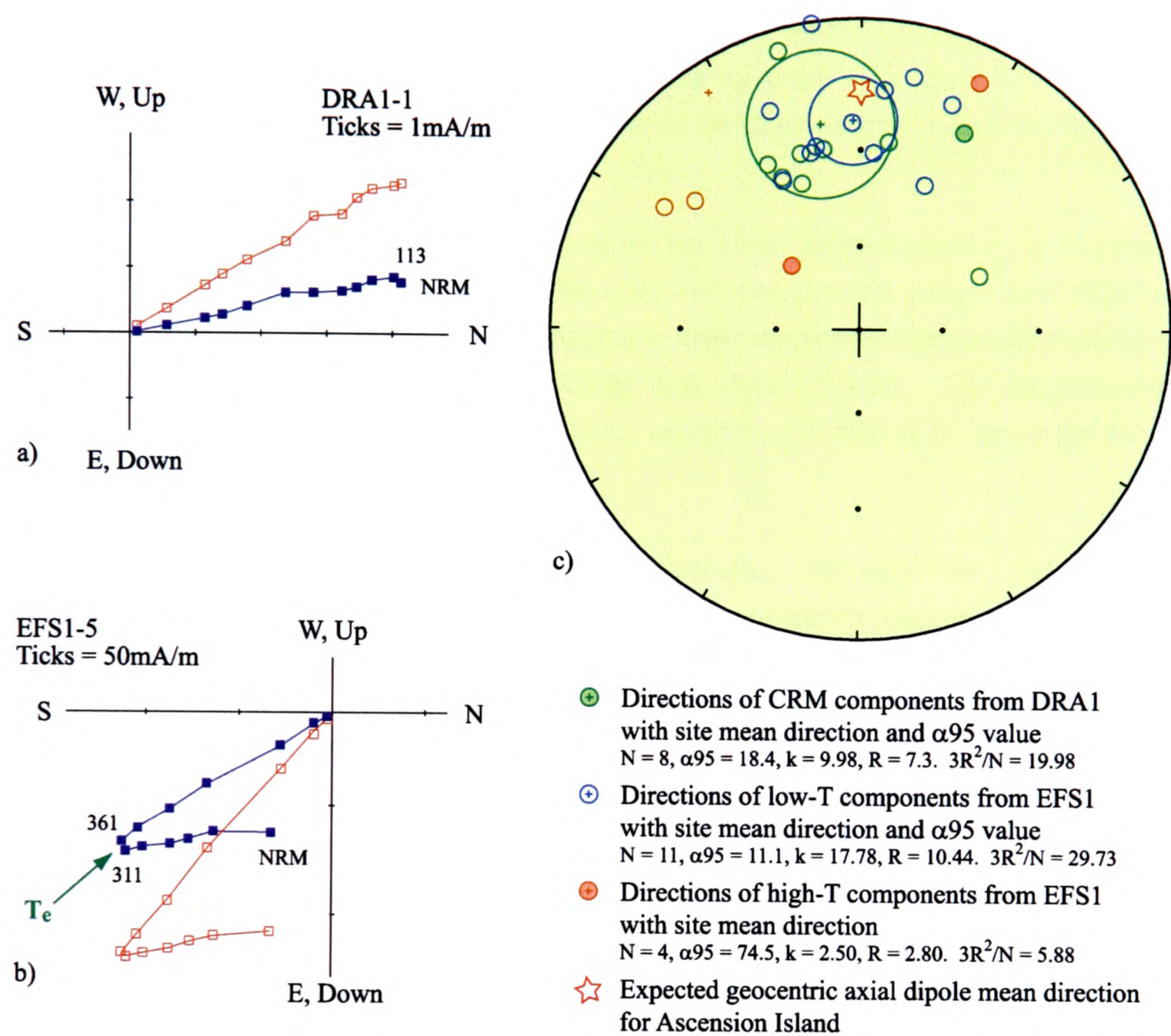


Figure 3.10: Zijderveld plots (z-plots) and equal area stereoplot showing typical remanence characteristics for: a) a typical juvenile clast and b) a typical lithic clast from pyroclastic deposits sampled on Ascension (units DRA1 and EFS1). DRA1-1 (a) displays a single-component remanence (CRM), in a direction sub-parallel to the expected GAD for Ascension (000/-15). The directions of CRM components for juvenile clasts from unit DRA1 are similar and are grouped about a direction approximating the expected GAD. EFS1-5 (b) displays a two-component remanence. The low-T component lies sub-parallel to the expected GAD for Ascension and the high-T component lies in a direction distinct from the expected GAD. T_e for EFS1-5 is between 311°C and 361°C. Directions of low-T components for lithic clasts from EFS1 are grouped and their mean direction approximates the expected GAD for Ascension (plot c). Conversely, directions of high-T components are 'randomly orientated', i.e. they are not grouped (plot c). Values given in (c) are *Fisher statistics* which provide a measure of the amount of scatter of the directions around the mean direction: N = number of clasts, α_{95} =the 95% confidence limit, k =the best estimate of the precision parameter, R =the vector resultant of N vectors & $3R^2/N$ is a statistical test of randomness for a population of samples such that if $3R^2/N > 7.18$ the population may be considered to be non-random. See Appendix C for a full description of Fisher statistics. Points on z-plots represent heating steps of 50°C except where indicated otherwise and temperatures have been corrected to account for the thermal gradient of the demagnetising furnace. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

If a two-component lithic clast is incorporated and reheated in a subsequent pyroclastic eruption, it will acquire a further TRM component (in grains with $T_b \leq T_c$) as previously described. The clast will now exhibit a *three-component* remanence, with a low- T component parallel to the geomagnetic field, (at the time of cooling) and two high- T components that are distinct from the geomagnetic field direction (e.g. Figure 3.11a). Such a clast will exhibit two T_e s, the lower (temperature) of which reflects the most recent heating episode and the higher of which (the ‘relict’ T_e) represents the temperature to which the clast was heated in the previous heating episode. The relict T_e is expected therefore to reflect the emplacement temperature of the deposit from which the clast was sourced.

If a lithic clast is heated to a temperature *above* the Curie temperature of its magnetic minerals, *all* primary magnetization will be reset and overprinted with a new TRM on subsequent cooling. The clast will now display a *single-component* remanence parallel to the geomagnetic field at the time of cooling (e.g. Figure 3.11b). The emplacement temperature for the clast cannot be calculated, except to say that it is above the Curie temperature of the clast's magnetic minerals.

Multi-component lithic clasts from hot pyroclastic deposits are valuable in palaeomagnetic studies as they can provide an estimate of the emplacement temperature (T_e) of the clast and hence of its parent deposit. The emplacement temperature is taken as the temperature to which the lowest temperature TRM component persists (Section 3.4.1).

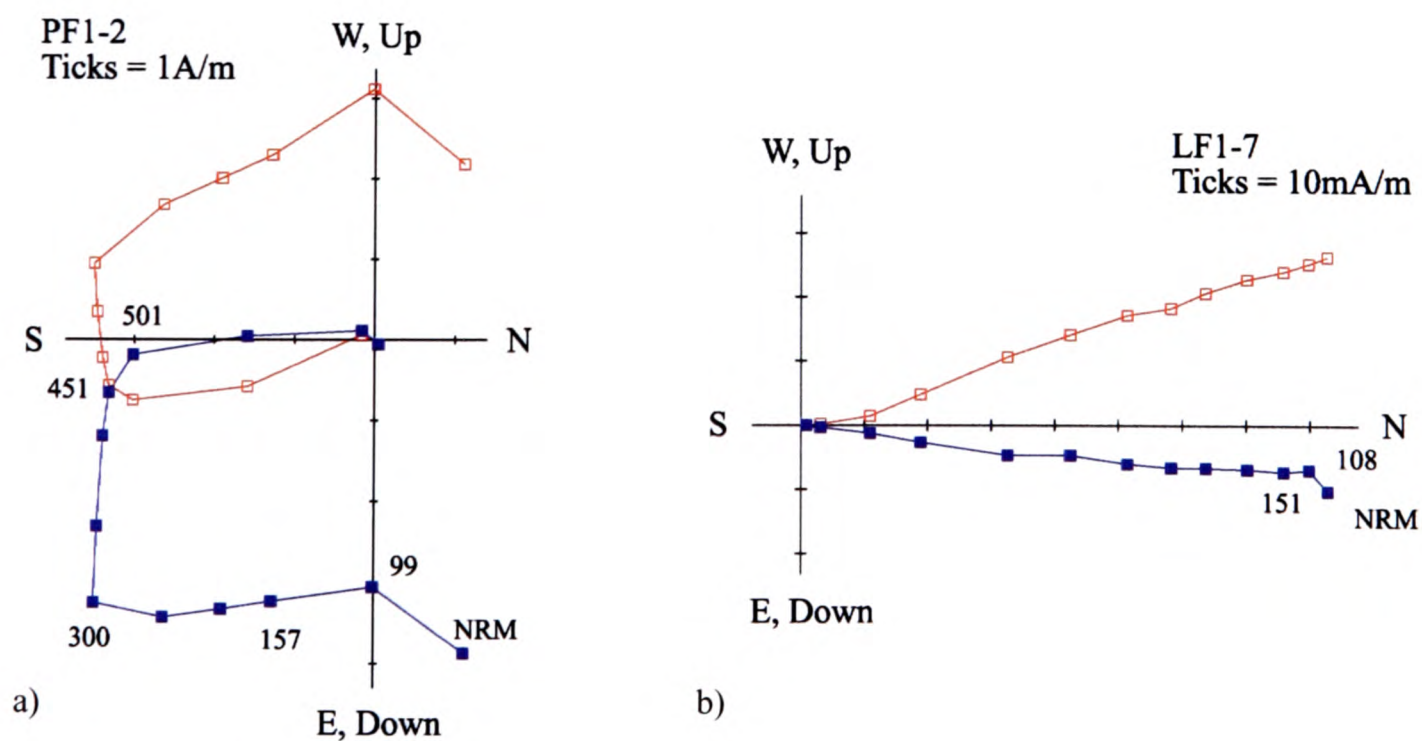


Figure 3.11: Zijderveld plots for lithic clasts from hot pyroclastic deposits from Ascension Island that display a) a three-component remanence and b) a single-component remanence. T_e for PF1-2 (a) is $\sim 300^\circ\text{C}$ and its ‘relict T_e ’ is between 451°C and 501°C . T_e for LF1-7 (b) is above the Curie temperature of the clast's magnetic minerals, but cannot be more precisely calculated. Points represent heating steps of 50°C except where indicated otherwise and temperatures have been corrected to account for the thermal gradient of the demagnetising furnace.

3.6.1.3 Remobilisation (reworking) of pyroclastic deposits

If a previously hot pyroclastic deposit is remobilized at *ambient temperature* (e.g. by collapse of the deposit or reworking by water), the directions of all components of magnetism will become 'randomised' as the clasts rotate during transport. Clasts from reworked deposits will therefore exhibit low-T and high-T components that are distinct from the geomagnetic field direction at the time of deposition (e.g. Figure 3.12). In addition, directions of both low-T and high-T components will be randomly orientated between different clasts from the same deposit (e.g. Figures 3.12c, 3.13b). Hence the analysis of remanence characteristics can allow differentiation between different types of pyroclastic deposit. In their 1979 paper, Hoblitt and Kellogg provide a classification for volcanoclastic deposits, according to their palaeomagnetic characteristics. In this thesis, the remanence characteristics of individual clasts (and where possible entire deposits) are described using a modification of Hoblitt and Kelloggs' classification, after Erwin, 2001 (Table 3.2). Primary *hot* pyroclastic deposits (e.g. airfalls, pyroclastic flow or surge deposits) are expected to contain **type 1** clasts (Table 3.2), i.e. clasts in which low-T components lie parallel to the geomagnetic field at the time of deposition (e.g. Figures 3.10b, 3.11a,b). In type 1 deposits, low-T directions are similar between clasts (Figure 3.12a). Conversely, deposits emplaced at *ambient temperature* (e.g. mudflows, debris flows,

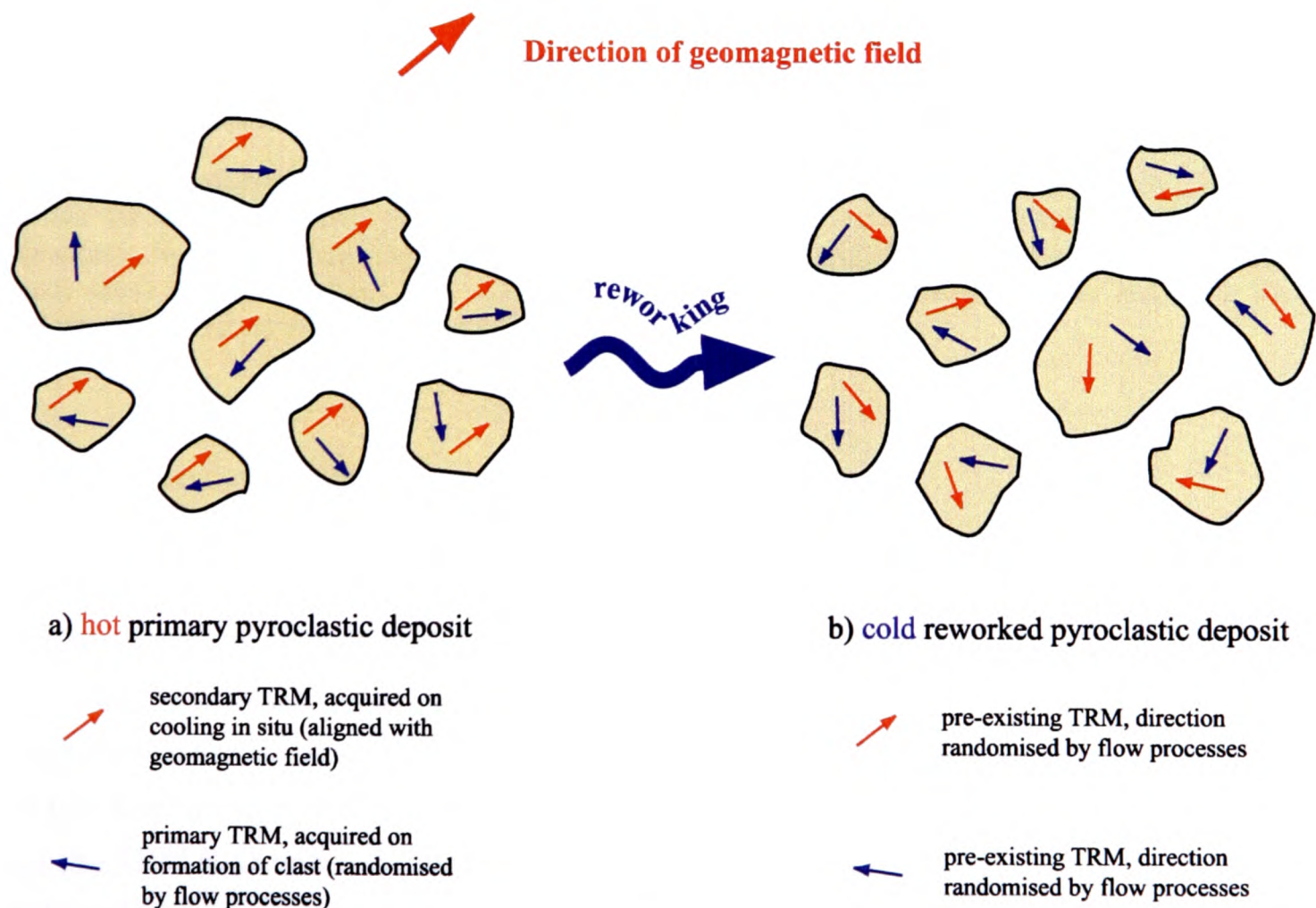


Figure 3.12: Sketch showing the effect of reworking (at ambient temperature) on hot pyroclastic deposits. Directions of low-T components in the hot pyroclastic deposit (a) are similar between clasts, aligned with the geomagnetic field, whilst directions of high-T components are random between clasts. In the reworked deposit (b), directions of both low-T and high-T components are random between clasts.

debris avalanches, fluvially reworked deposits) are expected to contain **type 2** clasts, i.e. clasts in which the directions of both low-T and high-T components are distinct from the geomagnetic field direction (e.g. Figure 3.13). In type 2 deposits, both low-T and high-T directions are randomly orientated between clasts (Figure 3.12b).

type	remanence description	interpretation of clast/deposit
1 a	one component , orientated parallel to ambient field (at time of cooling)	clast emplaced at temperature above T_c ($T_e \geq T_c$)
1 b	two components : low-T component // to ambient field high-T component randomly orientated	1a/2a clast reworked and emplaced at intermediate temperature ($T_c > T_e > \text{ambient}$)
1 c	three components : low-T component // to ambient field med-T component randomly orientated high-T component randomly orientated	1b/2b clast reworked and emplaced at intermediate temperature ($T_{e1} > T_{e2} > \text{ambient}$)
2 a	one component , randomly orientated with respect to ambient field direction	1a/2a clast reworked without heating ($T_e = \text{ambient}$)
2 b	two components : low-T component randomly orientated high-T component randomly orientated	1b/2b clast reworked without heating ($T_e = \text{ambient}$)
2 c	three components : low-T component randomly orientated med-T component randomly orientated high-T component randomly orientated	1c/2c clast reworked without heating ($T_e = \text{ambient}$)

Table 3.2: Palaeomagnetic classification of clasts from volcanoclastic deposits, after Erwin, 2001, who modified the classification of Hoblitt and Kellogg (1979). T_e = emplacement temperature, T_c = Curie temperature. In the following chapters, VRM components are not included in the classification of remanence (except where stated otherwise). A clast that displays two TRM components and an additional VRM is therefore referred to simply as two-component (sub-type b).

3.6.1.4 Secondary NRM

The remanence of juvenile or lithic clasts may be complicated by the acquisition of further magnetic components, after deposition (or after initial CRM acquisition in the case of juvenile clasts). If post-depositional alteration occurs, clasts may acquire a (further) CRM, which can be problematic in the analysis of magnetic components. If chemical alteration occurs whilst the deposit is still cooling, any newly formed magnetic grains with $T_b < T_e$ will block in a remanence as the clast continues to cool. This will be indistinguishable from the TRM that will be formed in the direction of the geomagnetic field, in any original (unaltered) grains with $T_b < T_e$. However, if the new grains have $T_b > T_e$, magnetisation will be acquired instantly upon formation, in the direction of the geomagnetic field. The clast will now contain two sets of grains with $T_b > T_e$: original (unaltered) grains, which will carry the primary remanence (that will lie in a direction distinct from the

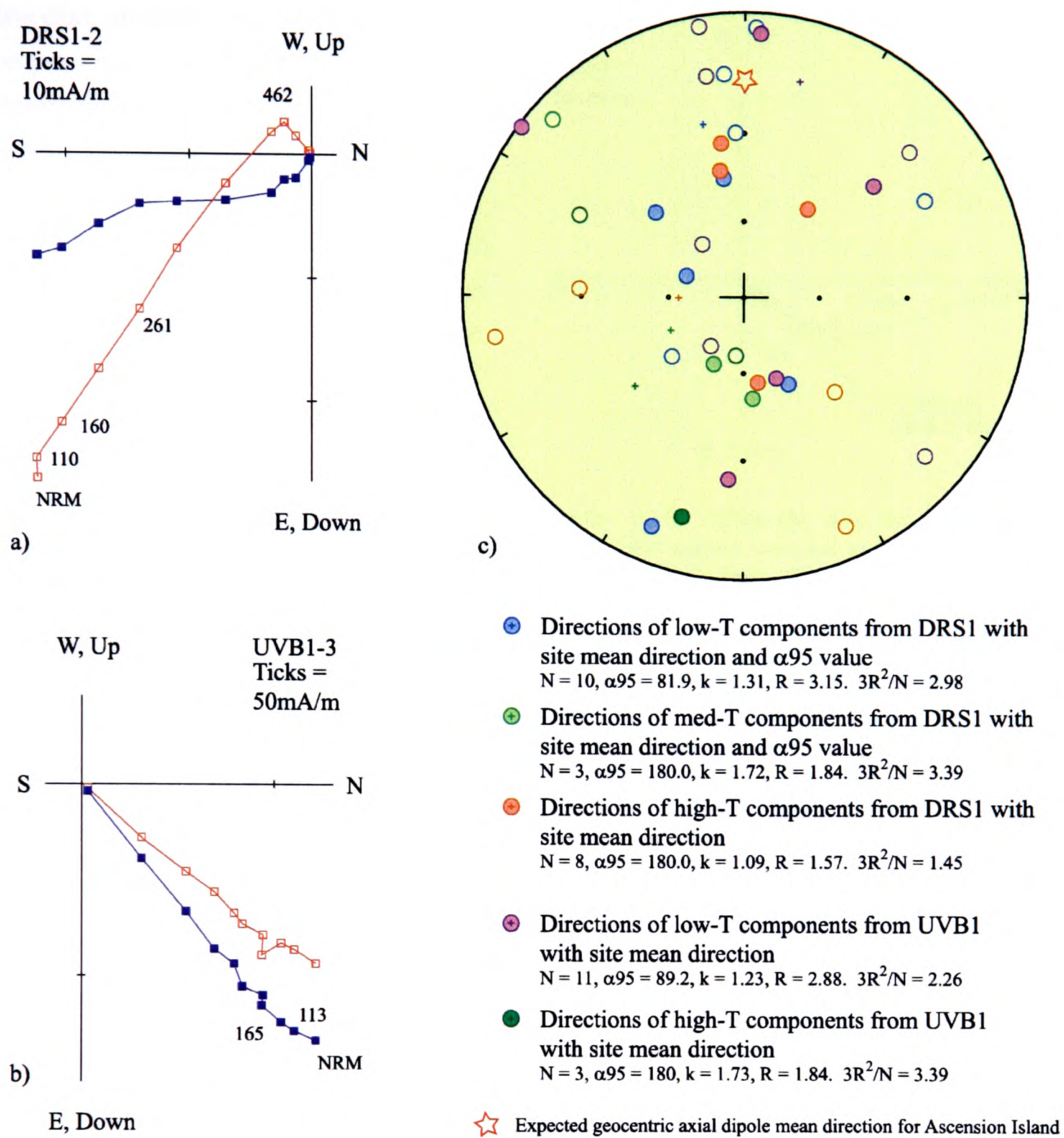


Figure 3.13: Zijderveld plots (z-plots) and equal area stereoplot showing typical remanence characteristics for lithic clasts from cold (reworked?) deposits sampled on Ascension (units DRS1 and UVB1). DRS1-2 (a) displays a three-component remanence and low-T, medium-T and high-T components all lie in directions distinct from the expected GAD for Ascension (360/-15). Relict T_s for DRS1-2 are 261°C and 462°C. UVB1-3 (b) displays a single-component remanence, in a direction distinct from the expected GAD for Ascension. The directions of low-T, med-T (where present) and high-T (where present) components for all lithic clasts sampled from DRS1 and UVB1 are shown in plot c. Directions of all components (from both units) are randomly orientated, i.e. they show no grouping. Points on z-plots represent heating steps of 50°C except where indicated otherwise and temperatures have been corrected to account for the thermal gradient of the demagnetising furnace. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

geomagnetic field), and newly formed grains, which will have acquired a remanence in the direction of the geomagnetic field. An estimate of the direction of the high-temperature component may therefore be biased towards that of the geomagnetic field at the time of alteration. Hence, if clasts from a deposit are affected by CRM, high-temperature components may be loosely grouped (erroneously) around the ambient field

direction. In addition, low-T and high-T components from CRM affected clasts commonly exhibit curved trajectories on vector component plots (z-plots; e.g. Figure 3.14). However, it should be noted that curvature of vector components may also result from the overlap of the blocking temperature spectra of low-T and high-T components and does not therefore always imply the presence of a CRM.

A viscous remanent magnetism (VRM) may also be acquired by juvenile or lithic clasts, simply through prolonged exposure to the geomagnetic field. This can also be problematic in palaeomagnetic analysis, as VRM components can be difficult to distinguish from low-temperature TRM components. This is discussed further in Section 3.6.2.

3.6.2 Emplacement temperature

A number of factors govern the emplacement temperature (T_e) that a pyroclastic deposit will display. For hot pyroclastic deposits, factors include magmatic temperature, column height and grain size, as well as factors such as distance from vent and incorporation of air or water. Different pyroclastic units therefore display different T_e s, depending on their genesis and distribution. In general terms however, proximal pyroclastic deposits should have higher T_e s than their distal equivalents. Material deposited close to the volcanic vent is expected to have cooled to a lesser extent than material that has travelled further from the vent. Exceptions may arise where water is involved in the eruption, as this can result in the cooling of early eruptive (proximally deposited) material (see for example McClelland and Bardot, 2000). Where T_e is high enough, welding may occur, both in airfall deposits and in pyroclastic flow or surge deposits. Variations in T_e for airfall deposits, welded deposits and breccias from Ascension Island are discussed further in chapters 4, 5 and 6.

Estimates of T_e for pyroclastic deposits can be obtained from thermal demagnetisation of lithic clasts from these deposits. Within a specific pyroclastic unit, it is likely that the T_e s of individual lithic clasts themselves will vary, due to variations in grain size and source

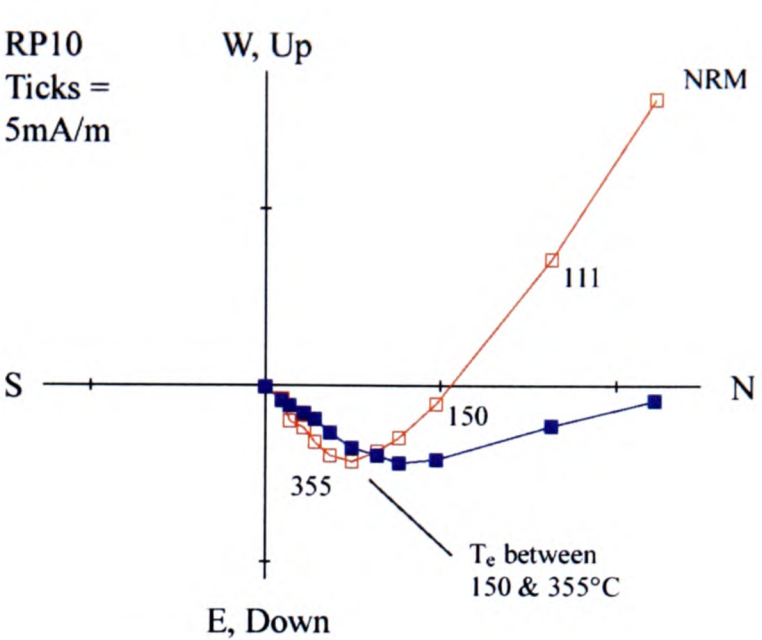


Figure 3.14: Zijderveld plot for a clast from a pyroclastic deposit sampled on Ascension, which is inferred to have been affected by CRM. Low-T and high-T components from RP10 exhibit curved trajectories, meaning that T_e can only be estimated at between 150°C (the last point that lies on the true low-T trajectory) and 355°C (the first point that lies on the true high-T trajectory). Points represent heating steps of 50°C except where indicated otherwise and temperatures have been corrected to account for the thermal gradient of the demagnetising furnace.

area (McClelland & Druitt, 1989). Greater T_e s will be recorded by both larger clasts (that were hot on incorporation), which will have retained more heat on deposition, and by clasts that are sourced from deep within the conduit (as opposed to those that originate from shallower depths). Clasts with different initial temperatures (T_{init} s) will heat up or cool down within the deposit (because of redistribution of heat between neighbouring clasts), to an average or *equilibrium* temperature (T_{eqm}). For the hottest clasts, T_e will be equal to T_{init} , but subsequent cooling will occur (in situ) from T_{init} to T_{eqm} . However, cooler clasts may actually *heat up* from T_{init} to T_{eqm} within the flow or eruption column, meaning that T_e will be equal to T_{eqm} . Lithic clasts are therefore expected to have a variety of emplacement temperatures, ranging from T_{eqm} to the highest T_{init} . The 'average' emplacement temperature for the deposit is therefore best approximated to the lowest value of clast T_e within the deposit (McClelland & Druitt, 1989). This is true for palaeomagnetic T_e estimates for all hot pyroclastic deposits and is especially valid for flow deposits, where completely cold accessory lithics may be incorporated into the deposit.

3.6.3 Magnetic mineralogy

Different clasts from pyroclastic deposits are expected to display a range of magnetic mineralogies, ranging from single-phase (e.g. purely magnetite or titanomagnetite) to multi-phase (e.g. titanomagnetite plus magnetite, or magnetite plus haematite). Determination of clast mineralogy (and hence which minerals carry remanence) is important if an accurate analysis of remanence characteristics is to be made, however mineralogy cannot typically be used to differentiate between different types of deposits. The main remanence carriers within a clast can be determined from analysis of the temperature-dependent susceptibility of the clast (see Appendix A). This yields an estimate of the Curie temperature(s) (T_c s) of the magnetic phase(s), from which the remanence carriers can generally be identified (see Table 3.1; e.g. Figure 3.15). However, temperature-dependent susceptibility measurements are time consuming and it was therefore not viable to carry out such measurements for the ~1000 clasts sampled on Ascension. An alternative method by which magnetic mineralogy can be estimated is through analysis of blocking temperature (T_b) spectra. This method is significantly less time-consuming (as T_b spectra data are produced automatically during demagnetisation) and in the majority of cases, the T_b spectrum provides a reliable estimate of Curie temperature and hence the sample's mineralogy (see Figure 3.15). For this reason, T_b spectra analysis was the primary method used to estimate magnetic mineralogy, with temperature-dependent susceptibility measurements carried out on selected clasts to corroborate conclusions drawn from T_b spectra.

In this thesis, clasts have been placed into one of seven major groups according to the unblocking temperatures (i.e. Curie temperatures) that they display (Table 3.3; Figures 3.16a–j).

Major groups are further divided according to the *shape* of the T_b spectrum, which is interpreted to reflect the grain size distribution of the sample's magnetic minerals. A sharp decrease to T_c (a *discrete* spectrum; subtype 1; e.g. Figures 3.16a,c,e) suggests that the sample contains magnetic grains with only a *small* (narrow) range of sizes, whereas a gradual decrease to T_c (a *distributed* spectrum; e.g. Figures 3.16b,d,f) suggests that the sample contains magnetic grains with a *wide* range of sizes.

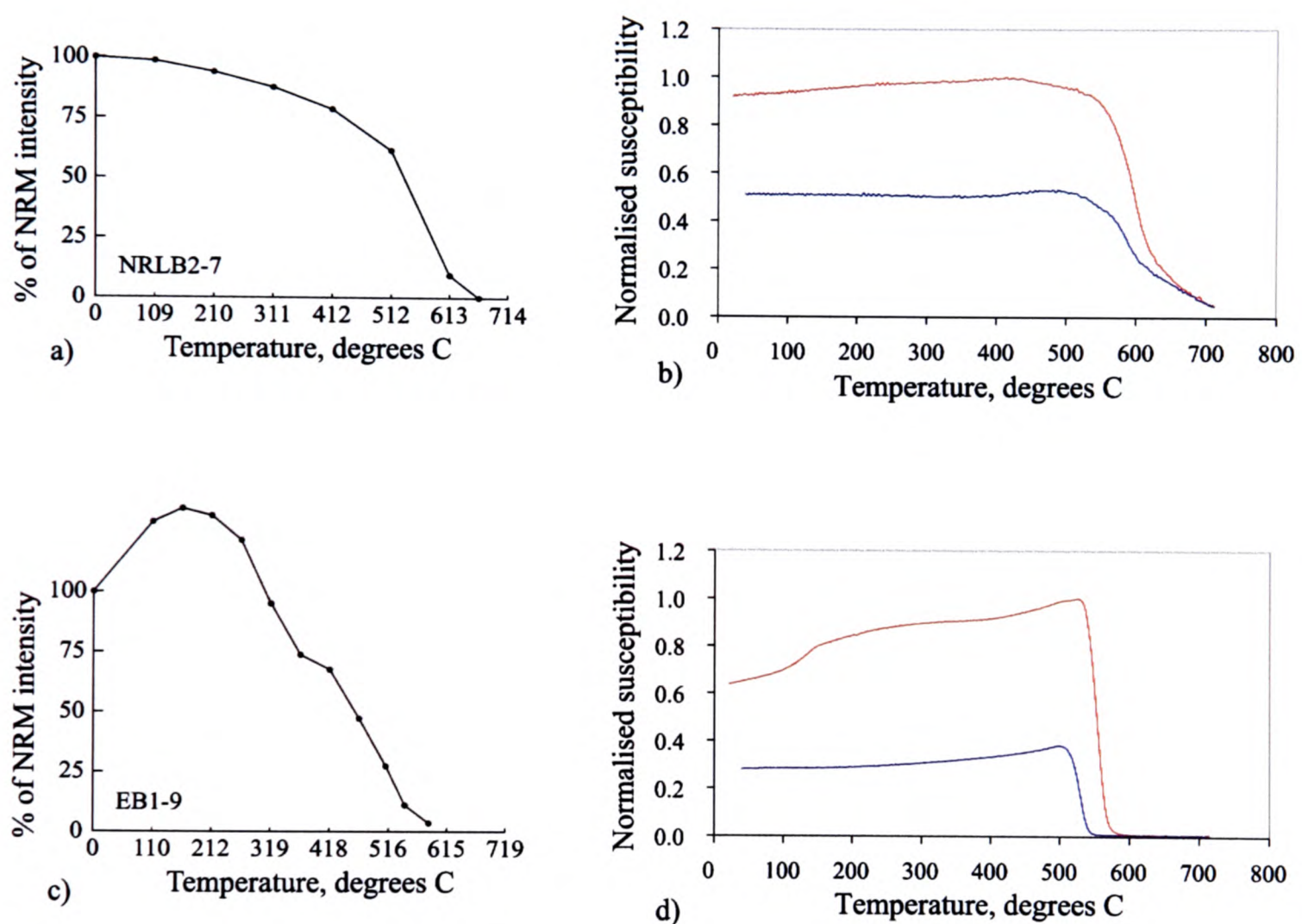


Figure 3.15: Comparison of blocking temperature (T_b) spectra and temperature-dependent susceptibility (high-T χ) for two samples from Ascension pyroclastic deposits. In each case, the T_b spectrum is comparable to the high-T χ plot, allowing approximations of T_c to be made. Temperatures on T_b spectra have been corrected to account for the thermal gradient of the demagnetising furnace. Sample NRLB2-7 exhibits a simple high-T χ curve (plot b), which displays a single decrease in susceptibility at $\sim 600^\circ\text{C}$, suggesting that remanence is carried by maghaemite. This is reflected in the T_b spectrum (plot a), which displays a single decrease in intensity at a similar temperature. The high-T χ curve for EB1-9 (plot d) is more complex, with an initial increase in susceptibility to $\sim 150^\circ\text{C}$, a continued increase to $\sim 400^\circ\text{C}$ and a final increase followed by major decrease in susceptibility at $\sim 580^\circ\text{C}$. This is reflected by the T_b spectrum for EB1-9 (plot c), which displays an initial increase in intensity to $\sim 150^\circ\text{C}$, followed by decreases at $\sim 400^\circ\text{C}$ and $\sim 580^\circ\text{C}$. Remanence in EB1-9 is inferred to be carried by three mineral phases; two titanomagnetites plus magnetite. Moreover, the increase in susceptibility seen before the final decrease in d) is a *Hopkinson Peak*, which is a characteristic feature of single-domain magnetite. Red and blue lines on high-T χ plots represent heating and cooling curves respectively. The decrease in susceptibility that is seen in the cooling curves of plots b) and d) is the result of alteration of the samples (annealing) upon heating.

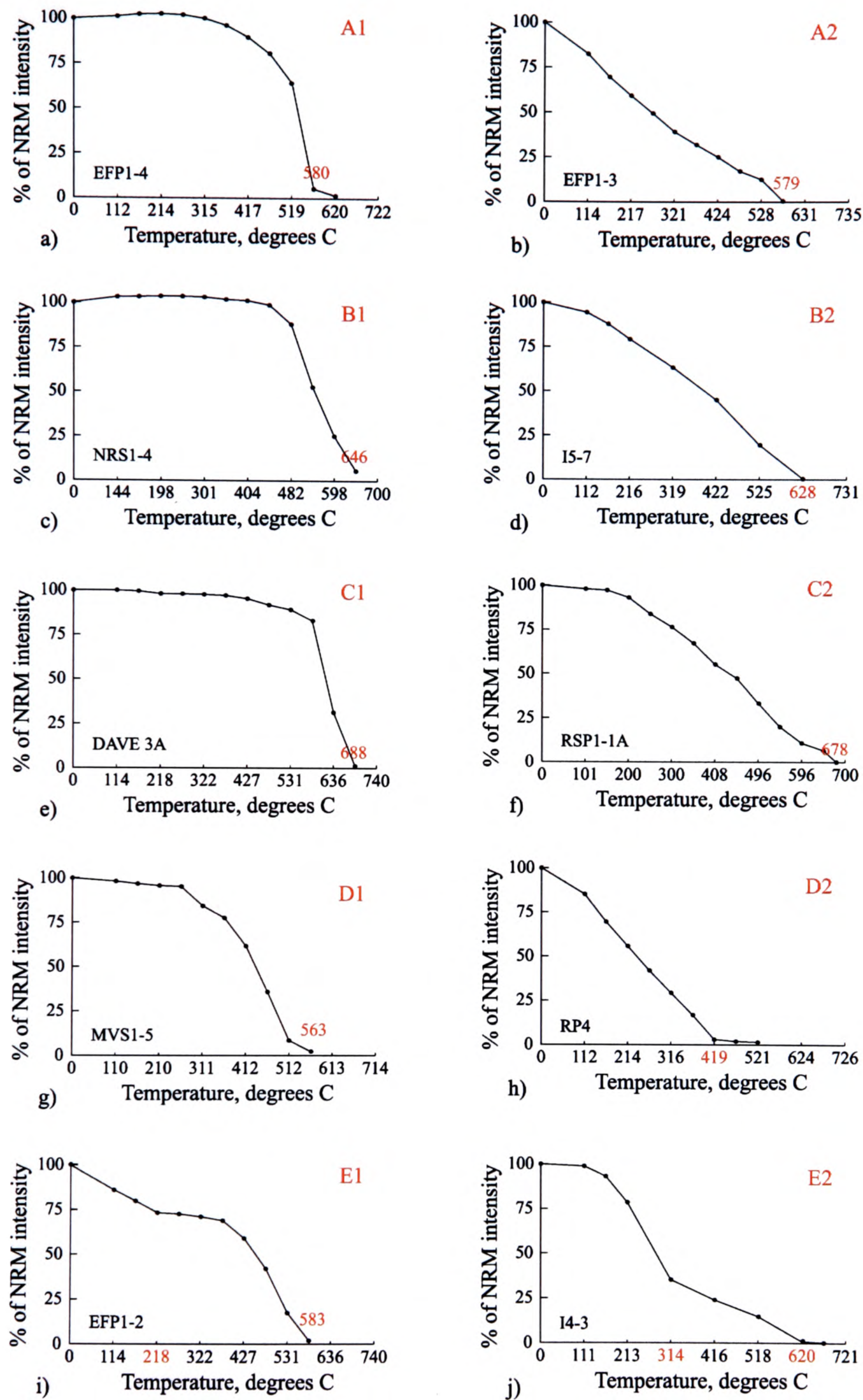


Figure 3.16: Examples of the different types of blocking temperature spectra displayed by clasts from deposits sampled on Ascension Island. Spectra are labelled (in red) according to the classification shown in Table 3.3. Curie temperatures are shown in red and sample names in black. Temperatures have been corrected to account for the thermal gradient of the demagnetising furnace. See over for further plots.

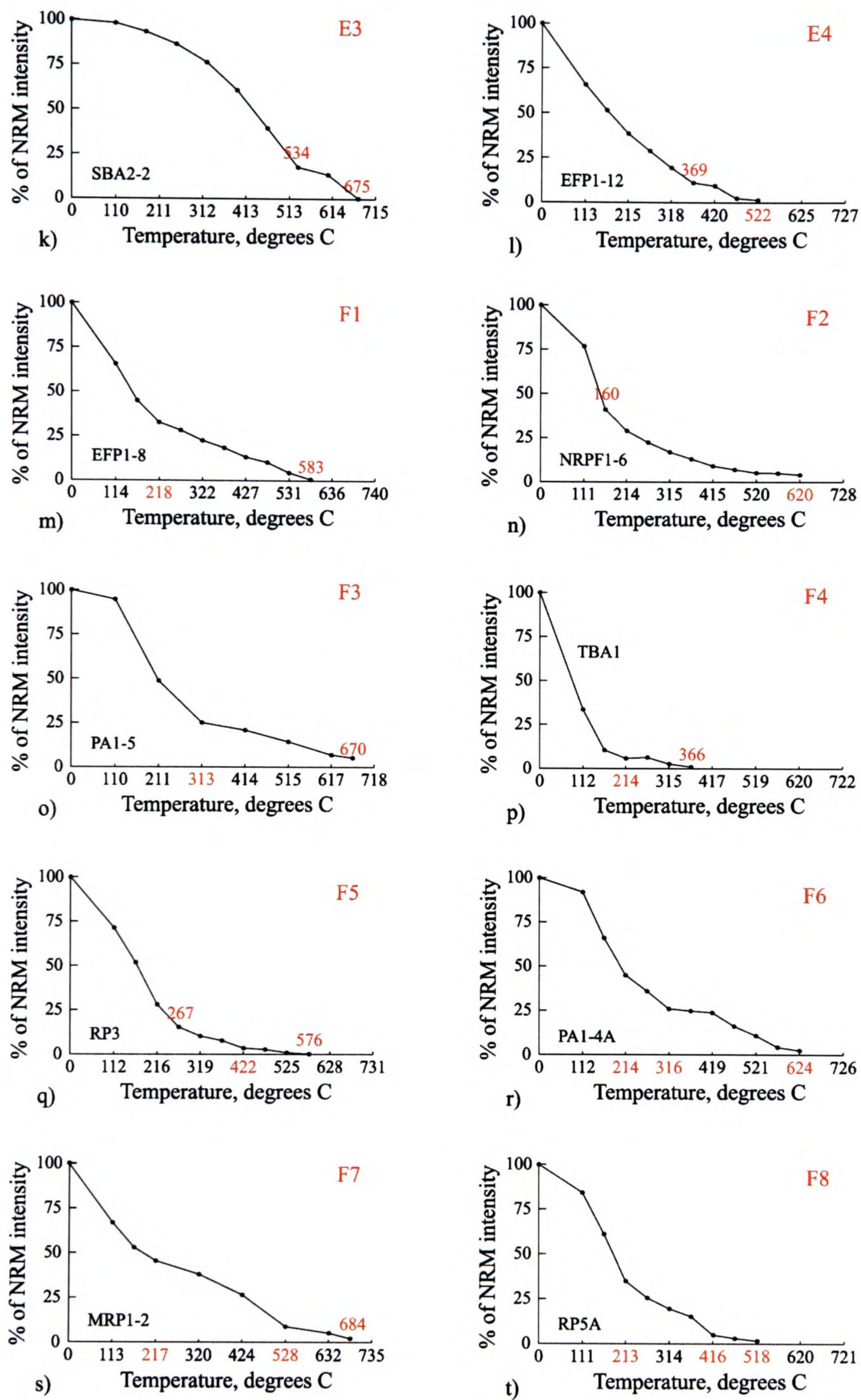


Figure 3.16 continued: Examples of the different types of blocking temperature spectra exhibited by clasts from deposits sampled on Ascension Island. Spectra are labelled (in red) according to the classification shown in Table 3.3. Curie temperatures are shown in red and sample names in black. Temperatures have been corrected to account for the thermal gradient of the demagnetising furnace.

type	T _b spectra description	sub-type	description	interpretation
A	1-phase curve; T _c ≈ 580°C	1	sharp decrease to T _c	magnetite (mag)
		2	gradual decrease to T _c	
B	1-phase curve; T _c ≈ 590°C-675°C	1	sharp decrease to T _c	maghaemite (maghaem)
		2	gradual decrease to T _c	
C	1-phase curve; T _c ≈ 675°C	1	sharp decrease to T _c	haematite (haem)
		2	gradual decrease to T _c	
D	1-phase curve; T _c < 580°C	1	sharp decrease to T _c	titanomagnetite (timag)
		2	gradual decrease to T _c	
E	2-phase curve	1	T _{c1} < 580°C, T _{c2} ≈ 580°C	mag
		2	T _{c1} < 580°C, T _{c2} ≈ 590°C-675°C	timag + maghaem
		3	T _{c1} < 580°C, T _{c2} ≈ 675°C	timag + haem
		4	T _{c1} < 580°C, T _{c2} < 580°C	timag
F	drop in intensity between 0°C and ~200°C (T _{c1}) plus:	1	T _{c2} ≈ 580°C	mag
		2	T _{c2} ≈ 590°C-675°C	timag + maghaem
		3	T _{c2} ≈ 675°C	timag + haem
		4	T _{c2} < 580°C	timag
		5	T _{c2} < 580°C, T _{c3} ≈ 580°C	mag
		6	T _{c2} < 580°C, T _{c3} ≈ 590°C-675°C	2 timags + maghaem
		7	T _{c2} < 580°C, T _{c3} ≈ 675°C	2 timags + haem
		8	T _{c2} < 580°C, T _{c3} < 580°C	timag
G	3-phase/more complex curve			3+ mineral phases

Table 3.3: Classification of T_b spectra for clasts from pyroclastic deposits sampled on Ascension, according to shape and T_c. T_c = Curie temperature. T_{c1} = lowest temperature T_c, T_{c3} = highest temperature T_c.

3.6.3.1 Magnetic mineralogy and VRM

In many cases (and commonly in clasts from pyroclastic deposits sampled on Ascension), it is difficult to distinguish a low-temperature thermoremanent magnetism (TRM) from a viscous remanent magnetism (VRM) acquired through prolonged exposure to the earth's magnetic field. Work by McClelland and Bardot (2000) on pyroclastic deposits from Taupo and Ruapehu volcanoes (New Zealand) suggests that the presence or absence of VRM in a sample is controlled, to some degree, by its magnetic mineralogy. They have shown that samples in which remanence is carried by *high-titanium titanomagnetite* (i.e. TM55, T_c ≈ 200°C) do *not* tend to display a VRM, whereas samples in which *magnetite* (or low-titanium titanomagnetite) is the main remanence carrier commonly *do* display a VRM. McClelland and Bardot (2000) also show that where samples have a mixed mineralogy (e.g. titanomagnetite plus magnetite), the sample may display a VRM that deviates from the expected GAD mean direction, as the direction of the VRM component may be 'biased' towards that of the non-VRM carrying component. Discriminating between TRM and VRM components is complicated further where the low-temperature component is carried by multidomain (MD) grains, because a VRM carried by MD grains may persist to higher temperatures than a VRM carried by single-domain grains.

3.6.4 Secular variation and magnetic polarity

The direction and intensity of the Earth's magnetic field is known to change with time. Relatively small changes that occur over time periods between 1 and 10^5 years make up what is called *geomagnetic (palaeo)secular variation* (Butler 1992). When observed at a single location, secular variation is seen as an oscillation of the geomagnetic field around the geocentric axial dipole (GAD) direction for that location (Figure 3.17). Samples from hot pyroclastic deposits (and lavas) of different ages are therefore expected to exhibit some variation in the inclination and declination of their low-temperature components. Hence it may be possible to correlate different units by comparing the mean directions of their low-temperature components.

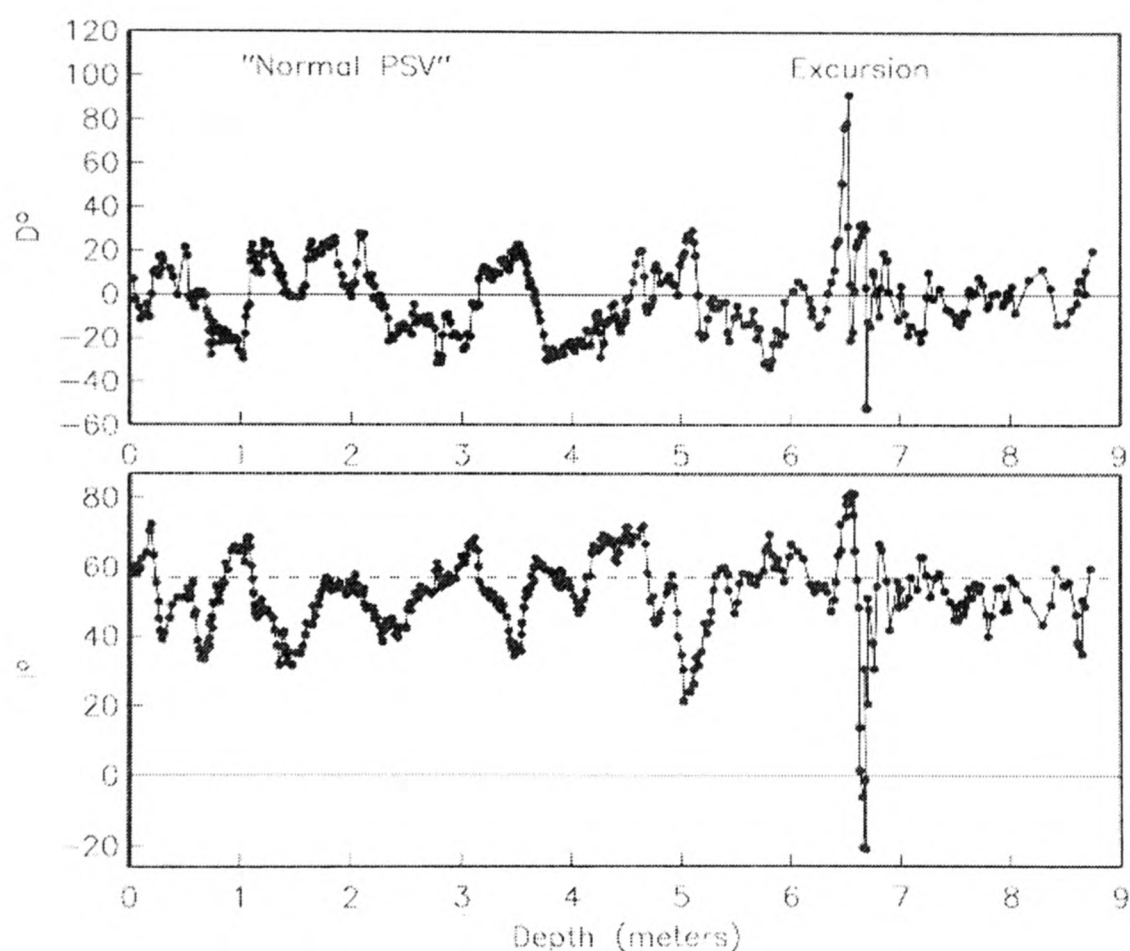


Figure 3.17: Example of palaeosecular variation, showing the variation in declination (D) and inclination (I) with depth (age) in lake sediments that surround Mono Lake. Data shown represent ~23 kyr of time. The expected inclination from the geocentric axial dipole mean is shown as the dashed line, and the expected declination is zero (from Tauxe, 2000).

Over longer time scales, the polarity of the geomagnetic field has been seen to completely reverse. Reversals of the geomagnetic field can be recorded on a magnetostratigraphic timescale (Figure 3.18). The most recent major magnetic reversal is dated at ~0.78Ma and marks the boundary between the normal Brunhes and reversed Matuyama polarity *chrons* (Figure 3.18). The major polarity *chrons* can be further divided into a number of more short-lived polarity intervals called *events* (Figure 3.18). Occasionally, the geomagnetic

field appears to undergo an 'incomplete' reversal. Here, the change in field tends towards 180°, but either the field does not fully reach this direction, or it does not remain locked in the reversed direction for a measurable amount of time. These episodes are generally only localised phenomena and are called *excursions* (see Figure 3.18).

The magnetic polarity of a hot pyroclastic deposit can be determined by demagnetisation of its juvenile or lithic clasts. These are expected to record of the local direction of the geomagnetic field at the time of deposition, which may be normal or reversed. Polarity data can be used to correlate deposits and yield relative dates for them, where dating of the surrounding stratigraphy (for example intercalated lavas, which are typically less problematic to date than pyroclastic deposits) has been carried out.

3.7 NEW ZEALAND PILOT STUDY

A palaeomagnetic pilot study was carried out at Ruapehu volcano (Figure 3.19) central North Island, New Zealand in autumn 1996. The aim of this study was to gain an insight into the nature of some of the recent pyroclastic deposits erupted from this volcano, whilst learning the technique of palaeomagnetic sampling. Juvenile and lithic clasts were sampled from two volcanoclastic deposits situated within the ring plain surrounding Ruapehu, for palaeomagnetic analysis. Thermal demagnetisation was subsequently carried out on clasts to provide emplacement temperature estimates for the deposits and hence determine their origins (i.e. as primary hot pyroclastic deposits or secondary cold reworked deposits). The majority of the ring plain deposits are thought to be reworked (i.e. of laharc and epiclastic origin) with only a minor component of primary pyroclastic material (Hackett and Houghton, 1989; Palmer et al., 1993; Donoghue et al., 1997).

The results of this study have provided information on the nature of acquisition of remanence in pumices, as well as challenging the previous interpretation of some of the deposits as primary pyroclastics. This work is partly published in Donoghue et al. (1999).

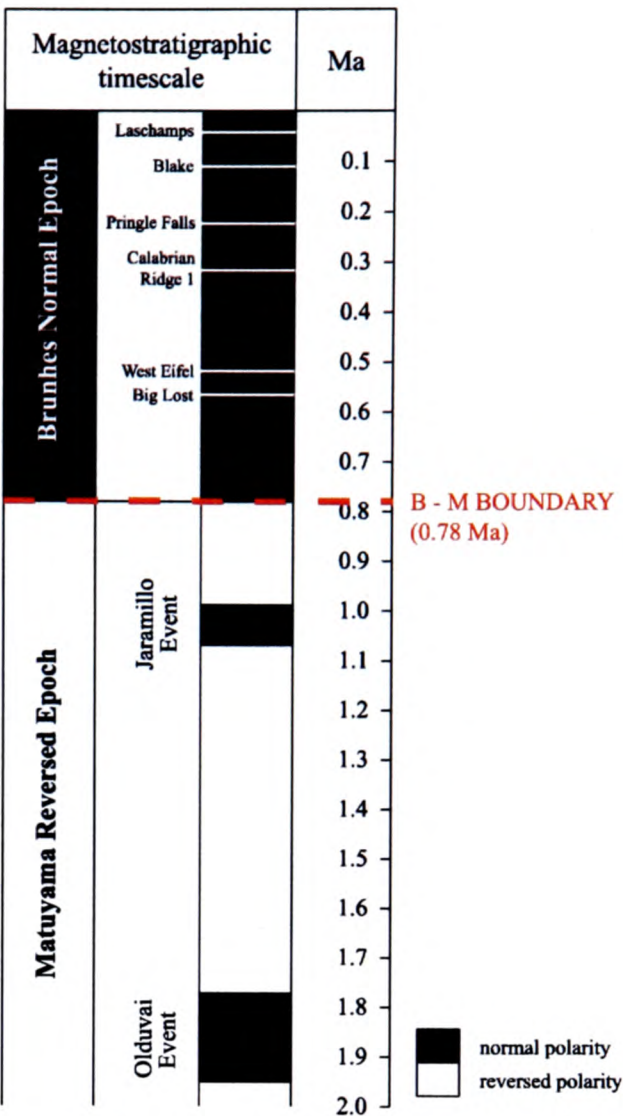


Figure 3.18: Magnetostigraphic timescale for the last ~2Ma showing some of the excursions identified within the Brunhes chron, normal events within the Matuyama chron, and the position of the Brunhes-Matuyama reversal boundary (red dashed line). Data from Cande and Kent (1995), Opdyke and Channell (1996), Gubbins (1999).

3.7.1 Ruapehu and the Taupo Volcanic Zone

Ruapehu is a large, highly active andesitic stratovolcano situated within the Tongariro National Park at the southern end of the Taupo Volcanic Zone (TVZ), North Island, New Zealand (Figures 3.19, 3.20). The TVZ is highly active volcanic arc, which lies parallel to the Kermadec subduction system in the Pacific Ocean and is a result of the subduction of the Pacific plate beneath the North Island of New Zealand. The TVZ covers



Figure 3.19: View of Ruapehu volcano.

a total area of ~300km in length and 60km in width. On land however, it is manifested as a northeast – southwest trending belt, stretching 200km across the North Island, from

Ohakune in the south to White Island in the north. The volume of the volcanic succession that comprises the Taupo Volcanic Zone is unknown due to the indeterminate nature of the sub-volcanic basement. Estimates from gravity modelling have inferred a minimum depth to basement of 2-2.2km and volumes of over 15,000km³ of volcanic deposits (Wilson et al., 1984). To the east and west of the zone, greywackes of mainly Mesozoic age can be found cropping out in the Hauhungaroa and axial mountain ranges. The same lithology is thought to underlie the offshore Bay of Plenty area (Wilson et al., 1984) and is known to crop out further north. It has therefore been

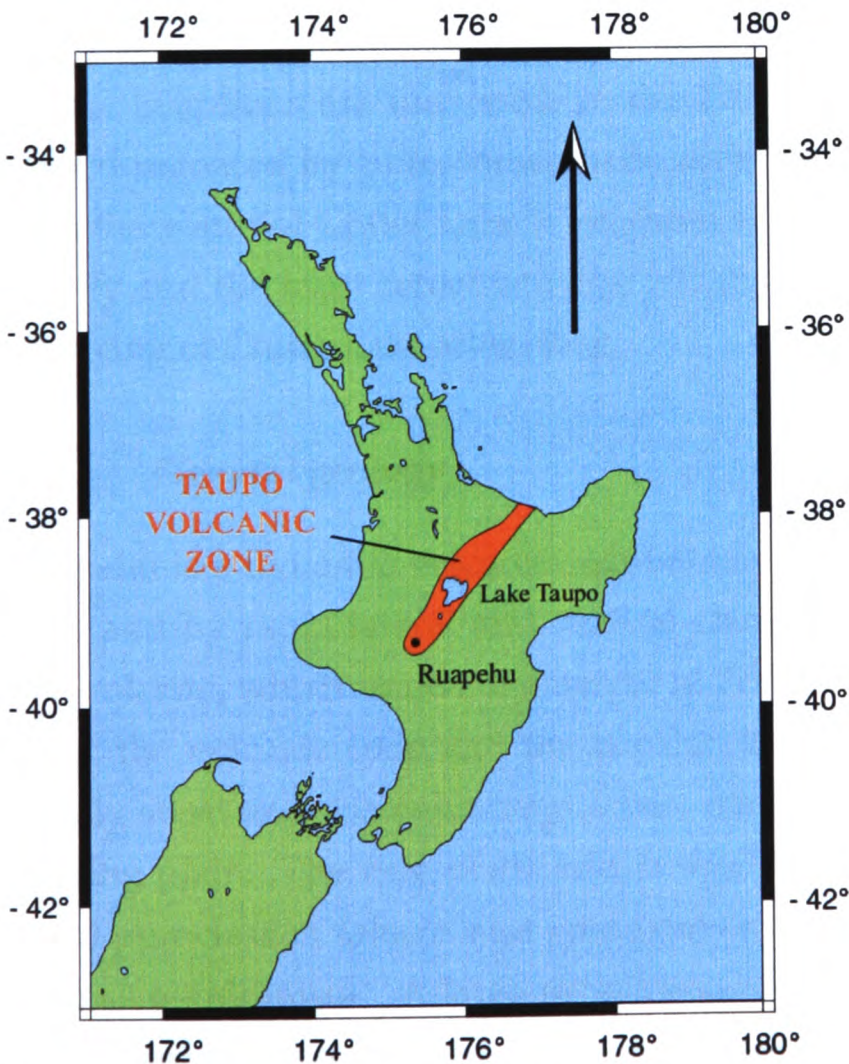


Figure 3.20: Topographic map of North Island, New Zealand showing the locations of the Taupo Volcanic Zone, Lake Taupo and Ruapehu volcano.

inferred that this same lithology comprises the sub-volcanic basement of the Taupo Volcanic Zone (Wilson et al., 1984).

The Taupo Volcanic Zone has been the major region of volcanic activity in New Zealand since around 2Ma. Since that time, it has produced more than 10,000km³ of magma making it the most productive silicic volcanic system on earth (Houghton et al., 1995). Activity in this area has involved eruptions from both andesitic stratovolcanoes such as Ruapehu and rhyolitic caldera-forming volcanoes such as Taupo. The central part of the TVZ has played host to rhyolitic activity, whilst the northern and southern ends of the zone comprise regions of andesitic stratovolcanoes. Rhyolitic activity is dominant and eight rhyolitic caldera centres have been identified within the 125km long central region, which are inferred to have produced thirty-four caldera ignimbrite eruptions (Wilson et al., 1984).

Between 0.9Ma and 0.34Ma, uplift in the area brought about the onset of rifting along the zone, which continues in the modern day at a rate of 7-18mm per year.

3.7.2 Eruption history

Modern Ruapehu was constructed in four distinct cone building episodes spanning 250ka, involving both summit and flank vents. Holocene activity has included sub-Plinian and Strombolian activity, eruption of aa and block lavas, debris avalanches and large lahars. The youngest deposits of these cone-building phases have been dated at approximately 25ka³. Eruptions are numerous in the 120-year historical record of Ruapehu and have been dominated by phreatomagmatic activity caused by interaction of andesite magma with the water of Crater Lake (Houghton et al., 1987). Levels in the lake have fluctuated greatly and the most recent activity, which took place in September 1996, resulted in the emptying of Crater Lake altogether.

3.7.3 General geology

Ruapehu is a dynamic volcanic-sedimentary system, characterised by high accumulation rates and by rapid lateral and vertical changes in facies (Hackett and Houghton, 1989). The volcano, which stands at a height of 2797m, can be stratigraphically divided into two parts: the volcanic cone and the surrounding ring plain. The volcanic cone consists of mainly sheet and autobrecciated lavas, which, in general, do not extend into the area of the ring plain. The ring plain, which was the focus of study, comprises over 100 km³ of distal pyroclastics, laharic and epiclastic deposits, the primary and reworked products of explosive volcanism. A large proportion of the ring plain deposits are laharic in origin. Lahars are easily initiated at Ruapehu due to the presence of Crater Lake, summit snow and ice and intense regional rainstorms, and material is very rapidly reworked and quickly aggrades on the ring plain. Debris avalanche and fluvial deposits can also be

found in the area and in some places are interbedded with tephra from Ruapehu and other volcanic centres further north (Palmer et al., 1993).

In their paper of 1989, Hackett and Houghton outline four lithofacies associations at Ruapehu, including a distal (ring plain) association. This includes fall deposits from Ruapehu, Tongariro and Taupo, but the main facies found on the Ruapehu ring plain are lenses of coarse-grained volcanoclastic material of laharic or fluvial origin. Within these, Hackett & Houghton have identified three main lithofacies: 1) muddy, matrix-supported gravel with no stratification or imbrication, 2) clast supported gravel, usually with poorly defined, sub-horizontal bedding, and 3) trough and planar cross-bedded sand.

More detailed accounts of the general geology and eruption history of the volcano can be found in Hackett and Houghton (1989), Donoghue et al. (1997, 1999) and Palmer et al. (1989). In addition, Cronin et al. (1997), Palmer and Neall (1989), Topping (1973) and Topping and Kohn (1973) describe different aspects of the stratigraphy of the volcano. An account of magma mingling in the Pourahu Formation is given in Donoghue et al. (1995).

3.7.4 Fieldwork

Work for this study centred on part of the ignimbrite unit of the Pourahu Member, which has been dated at between c. 11,850-10,000 years B.P. The Pourahu Member plus an airfall unit comprise part of the (upper) Bullott Formation, a sequence of airfall tephras erupted from Mount Ruapehu (Donoghue et al., 1995). Samples were taken from two localities on the western flanks of the volcano, which were inferred to represent proximal (unit 1) and distal (unit 2) parts of the pumiceous ignimbrite. Unit 1 has been identified previously as a primary hot material (Vince Neall, pers. comm.).

3.7.4.1 Sampling techniques

The units sampled were identified from existing data on the surrounding tephra stratigraphy (Donoghue et al., 1995; Vince Neall, pers. comm.). Where possible, fist-size or smaller lithic and pumice clasts were sampled from each deposit. In the case of RRP18 samples were also taken from volcanic bombs within the deposit. Each clast was oriented using the palaeomagnetic sampling technique (see Appendix A). Where appropriate, the stratigraphic height of the clast within the unit was recorded along with the overall unit thickness at that point (to allow for effects of thermal overprinting by stratigraphically higher units). The nature of the surrounding matrix was also recorded where this was variable. The clasts were then removed and stored in sample bags. In all cases the relatively small clast sizes and unconsolidated nature of the units sampled avoided the need to drill sample cores.

3.7.4.2 Field observations

Unit 1 (RRP15-17)

Unit 1 is located on the Mangaturuturu River, 500m downstream from Mangaturuturu Hut, on the western flanks of Ruapehu (Figure 3.21). At the sampling location, it is a medium-grained yellow-brown breccia, composed dominantly of yellowy (andesitic or dacitic) pumice clasts. Pumice clasts are crystal rich and subrounded and some display colour banding, which is inferred to reflect magma mingling prior to eruption (Donoghue et al., 1995). The unit also contains some scoriaceous (mafic) clasts. Lithic clasts are abundant and are typically cm-size to dm-size. Little variation in lithic type is seen. The unit comprises three distinct layers: an upper (50cm thick), predominantly pumice layer, a middle layer comprised of both pumice and lithic clasts and a lower layer that is also dominantly composed of pumice. Within the lower layer is a pocket of much coarser, lithic material, which contains boulders more than 1m in diameter. The upper surface of the deposit has an erosional nature and the deposit is overlain by a coarse laharic deposit. Lithic clasts were sampled from the lithic-rich pocket at the base of the deposit (RRP15) and from the upper pumice-rich layer of the deposit (RRP17). Pumice clasts were also sampled from same upper layer (RRP16).

Field characteristics such as the highly pumiceous nature of the deposit, its colour and the crystal-rich nature of pumice clasts, suggest that the deposit is likely to be a hot primary pyroclastic deposit, although unequivocal evidence such as the presence of carbon or gas-escape pipes is not observed. However a 'hot' origin concurs with previous interpretations of the deposit as part of the ignimbrite unit of the Pourahu Member (Vince Neall, pers. comm.), based on measurements of the deposit's overall magnetism using a portable fluxgate magnetometer in the field. This method gives a uniform direction of magnetization for the deposit that is parallel to the present field direction at Ruapehu (Vince Neall, pers. comm.) implying that clasts have been remagnetised and have therefore travelled in a hot (pyroclastic) flow.

Unit 2 (RRP18)

Unit 2 is situated on Highway 4, south of Mangaturuturu River (Figure 3.21). It is a highly pumiceous breccia, which is similar in appearance to unit 1, however here, pumice clasts show a greater degree of rounding and the unit contains a number of lenses of fine gravel to sand.

The rounded nature of pumice clasts implies that unit 2 has a reworked origin. Moreover, the sandy lenses seen within the deposit are interpreted as the products of hyperconcentrated stream flow (Vince Neall, pers. comm.), suggesting that the unit has been fluvially reworked.

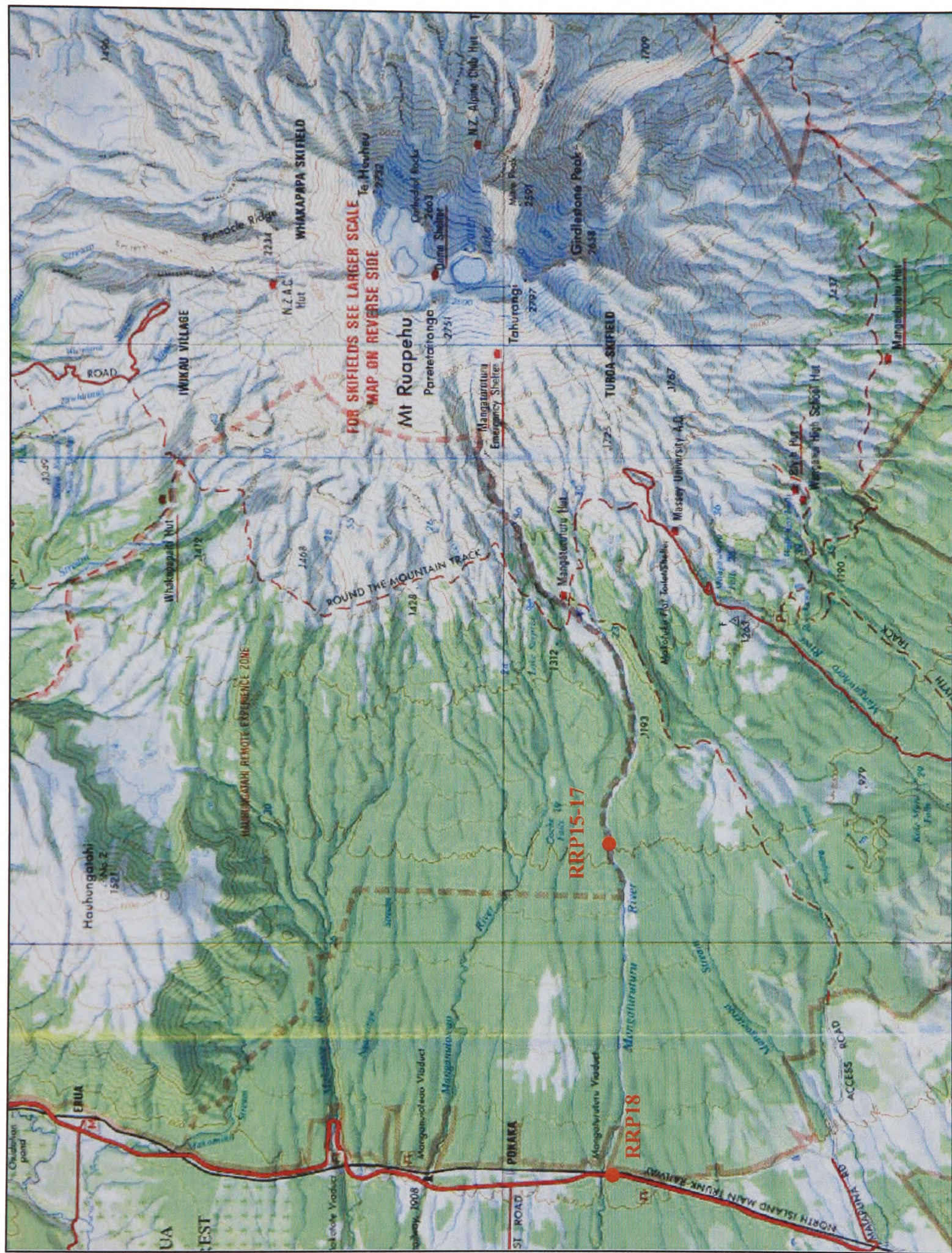


Figure 3.21: Topographic map of the western flanks of Ruapehu volcano, showing the locations of unit 1 (RRP15-17) and unit 2 (RRP18). Grid squares = 1km x 1km.

3.7.4.3 Palaeomagnetic observations

In the majority of cases, the remanence characteristics exhibited by clasts are directly linked to their mineralogy. The magnetic mineralogy of clasts was determined through analysis of blocking temperature spectra and temperature-dependent susceptibility. In

general, clasts display either a single-phase (titanomagnetite or magnetite) mineralogy (e.g. Figure 3.22a) or a mixed mineralogy comprising titanomagnetites of two (or three) different compositions or titanomagnetite(s) plus magnetite; e.g. Figure 3.22b). Some clasts display a more complex mineralogy, for example RRP15-4 (Figures 3.22c, 3.24), which contains four mineral phases; three titanomagnetite phases of different compositions (Curie temperatures $\sim 200^{\circ}\text{C}$, $\sim 310^{\circ}\text{C}$ and $\sim 500^{\circ}\text{C}$ respectively), and a magnetite phase with a Curie temperature (T_c) of $\sim 580^{\circ}\text{C}$.

In most clasts, a 'characteristic remanence' (ChRM) can be identified in clasts (usually the low-temperature component), which is inferred to be carried by titanomagnetite (e.g. Figures 3.23a,b). Many clasts also exhibit a high-temperature component, which is inferred to be carried by low-titanium titanomagnetite or magnetite (e.g. Figure 3.23c,d). Some clasts display a low-T 'overprint' component, which is distinct from the ChRM component (e.g. Figure 3.24). Table 3.4 shows mean declination and inclination directions (plus Fisher statistics) for the principal components of magnetism calculated for RRP15 to RRP18. Table 3.5 shows a summary of the different types of blocking temperature spectra (T_b spectra) that are displayed by clasts from these units.

RRP15 – lithic clasts only (ten clasts)

Lithic clasts from RRP15 typically display type 2 remanence behaviour (Table 3.2); i.e. low-temperature (low-T) components lie in a direction distinct from the expected geocentric axial dipole mean direction (GAD) for Ruapehu (e.g. Figure 3.23). In addition, directions of low-T components are randomly orientated between clasts from the same deposit (Figure 3.23e). Forty percent of clasts display a single-component remanence

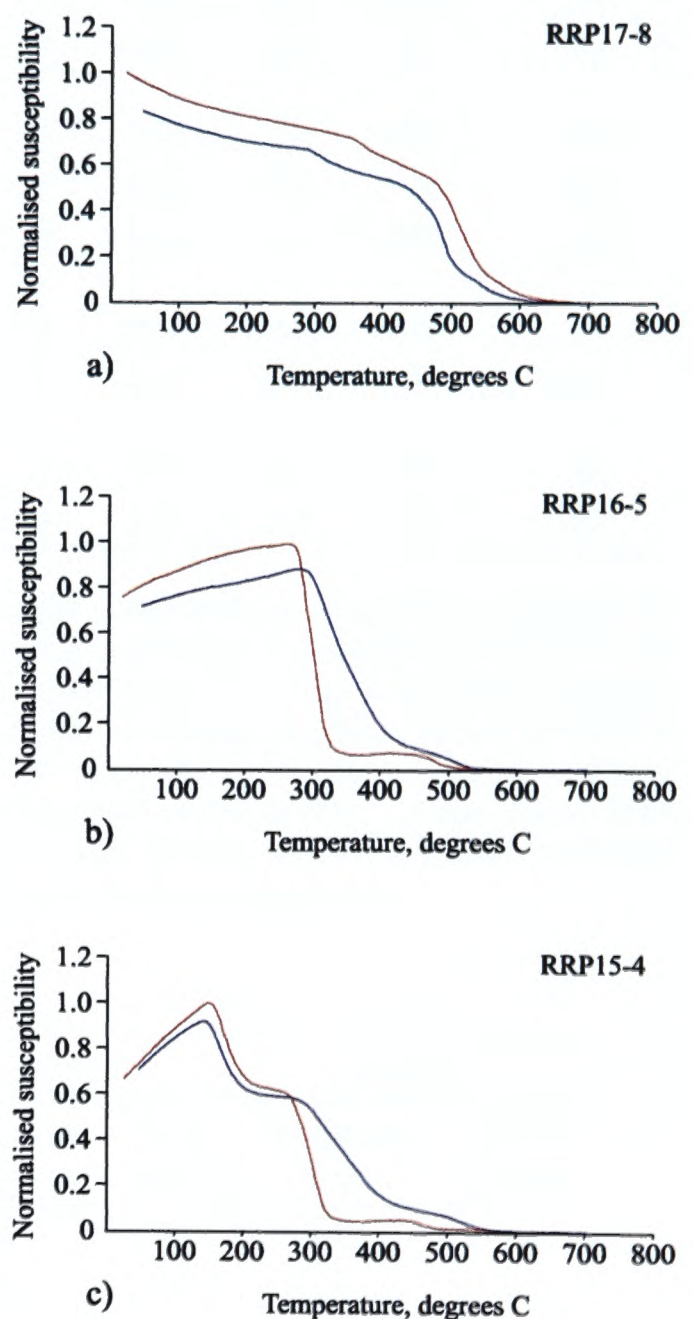


Figure 3.22: Examples of temperature-dependent susceptibility data for clasts sampled at Ruapehu. Plot a) shows a clast with a single-phase magnetite mineralogy with a T_c of $\sim 580^{\circ}\text{C}$ (although the clast displays a 'tail' of maghaemite, probably a result of alteration on heating). Plot b) shows a clast with a two-phase mineralogy, comprising two titanomagnetites with T_c s of $\sim 310^{\circ}\text{C}$ and $\sim 500^{\circ}\text{C}$ and plot c) shows a clast with a three or four-phase mineralogy, comprising three titanomagnetites with T_c s of $\sim 200^{\circ}\text{C}$, $\sim 310^{\circ}\text{C}$ and $\sim 500^{\circ}\text{C}$, plus a minor magnetite phase with a T_c of $\sim 580^{\circ}\text{C}$. Red and blue lines represent heating and cooling curves respectively. Runs were carried out in air and the slight increase in T_c s seen on the cooling curve in plots b) and c) is inferred to result from alteration (oxidation) of the clasts on heating.

unit	component	D	I	α_{95}	N	R	k	$3R^2/N$	grouped?
RRP15 (lithics)	overprint	4.0	-46.8	180.0	3	1.45	1.3	2.10	no
	ChRM	254.4	-60.1	70.2	10	3.74	1.4	4.20	no
	high-T	352.0	29.3	180.0	3	1.85	1.7	3.42	no
RRP16 (pumices)	ChRM	331.7	-36.5	20.8	10	8.59	6.4	22.14	yes
	high-T	unconstrainable		n/a	8	n/a	n/a	n/a	no
RRP17 (lithics)	overprint	47.2	-45.9	180.0	3	1.41	1.3	1.99	no
	ChRM	91.0	-37.2	90.0	7	2.75	1.4	3.24	no
	high-T	60.3	-19.7	180.0	7	1.46	1.1	0.91	no
RRP18 (pumices)	ChRM	233.2	8.4	41.0	5	4.10	4.4	10.09	yes
	high-T	337.9	18.1	180.0	4	1.34	1.1	1.35	no
RRP18 (lithics)	ChRM	244.5	22.5	122.5	5	2.10	1.4	2.65	no
	high-T	211.6	-17.9	180.0	4	1.43	1.2	1.53	no

Table 3.4: Mean directions and Fisher statistics for the principal components of magnetism calculated for units sampled in the New Zealand pilot study. D = declination, I = inclination, N = number of clasts, R = the vector resultant of N vectors, k = the best estimate of the precision parameter, κ , α_{95} = the 95% confidence limit and $3R^2/N$ is a statistical test of randomness for a population of samples (Rayleigh 1919); if $3R^2/N > 7.18$, the population can be considered to be non-random. See Appendix C for full description of Fisher statistics and tests of randomness. RRP15 = lithic clasts from lithic-rich pocket, RRP16 = pumice clasts from main deposit, RRP17 = lithic clasts from pumice-rich layer of main deposit, RRP18 = pumice and lithic clasts from ‘reworked’ deposit, downstream. ChRM = characteristic remanent magnetism.

RRP15		RRP16		RRP17		RRP18	
T_b spectra type	% of clasts	T_b spectra type	% of clasts	T_b spectra type	% of clasts	T_b spectra type	% of clasts
A	0	A	0	A	20	A	10
B	0	B	0	B	0	B	0
C	0	C	0	C	10	C	0
D	10	D	10	D	0	D	0
E	80	E	60	E	60	E	50
F	0	F	20	F	0	F	20
G	0	G	10	G	10	G	20

Table 3.5: Summary of T_b spectra types for clasts sampled for the New Zealand pilot study.

(type 2a behaviour, Table 3.2; e.g. Figure 3.23a), whilst 60% display a two-component remanence (type 2b behaviour, Table 3.2; e.g. Figure 3.23d). In most clasts, a characteristic remanent magnetism (ChRM) can be identified, which demagnetises over a temperature range of ~166°C–322°C and is inferred to be carried by titanomagnetite with compositions ranging from TM42 to TM56 (see Figure 3.8; e.g. Figure 3.23a). Directions of ChRM components are interpreted as random following the criterion outlined in Watson, 1955

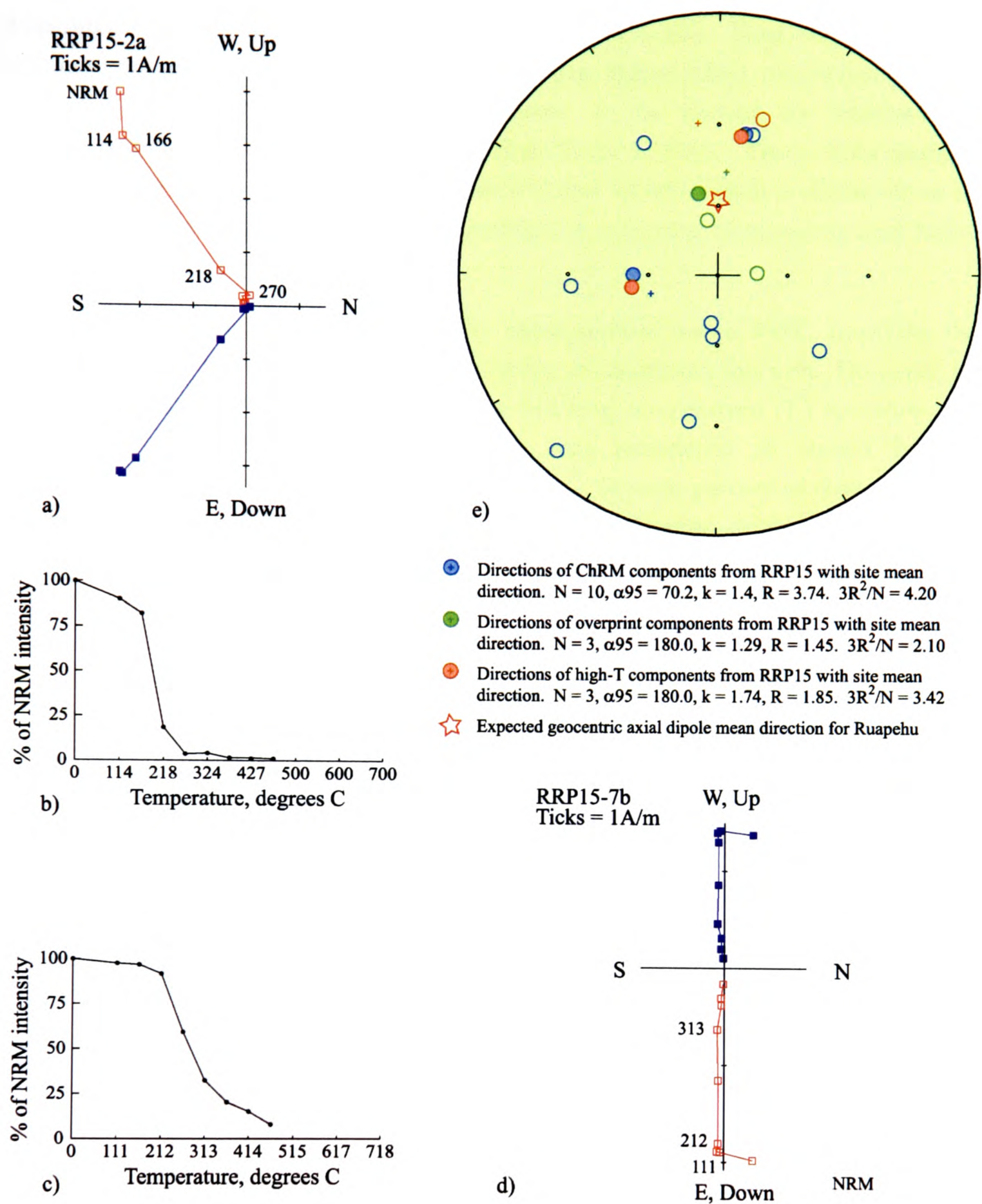


Figure 3.23: Zijderveld plots (z-plots), T_b spectra and equal area stereoplot for typical clasts from RRP15. RRP15-2a displays a single-component remanence in a direction distinct from the expected geocentric axial dipole (GAD) mean direction for Ruapehu (000/-59); i.e. type 2a remanence behaviour (Table 3.2; plot a). The T_b spectrum for RRP15-2a (plot b) is two-phase (type F4; Table 3.3), with a sharp decrease in intensity (to ~5% of the NRM intensity) seen between ~166°C and ~218°C followed by a gradual decrease to <1% of the NRM intensity from ~270°C to ~479°C below 580°C, suggesting that remanence is carried by two titanomagnetites. RRP15-7b displays a two-component remanence; the low-T component persists to 313°C and both low-T and high-T components lie in a direction distinct from the expected GAD for Ruapehu (i.e. type 2b remanence behaviour; Table 3.2; plot d). The T_b spectrum for RRP15-7b (plot c) is similar to that of RRP15-2a, with an initial decrease in intensity between ~212°C and ~313°C followed by a more gradual decrease to ~5% of the NRM intensity by ~465°C, suggesting that remanence is carried by two titanomagnetites. Plot e) shows the distribution of individual ChRM, overprint and high-T directions for clasts from RRP15, with site mean directions (small crosses). Directions of all components are random. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

(Appendix A; hereafter referred to as 'random'; Figure 3.23e). Four clasts display an additional high-temperature (high-T) component (e.g. Figure 3.23c), which demagnetises between $\sim 350^{\circ}\text{C}$ and $\sim 483^{\circ}\text{C}$ and is inferred to be carried by titanium-poor titanomagnetite, with compositions ranging from TM17 to TM21. Three clasts display a low-T component that demagnetises between 0°C and $\sim 200^{\circ}\text{C}$, which is distinct from the ChRM component (e.g. Figure 3.24). Directions of overprint components and high-T components are random (Figure 3.23e).

All clasts except two from RRP15 are fully demagnetised before 580°C , implying that titanomagnetite is the dominant remanence carrier in clasts from this unit. However, the majority of clasts (80%) display a two-phase blocking temperature (T_b) spectrum (e.g. Figures 3.23b,c; see Table 3.5), suggesting that remanence is carried by two titanomagnetite phases with different compositions. Seventy percent of clasts display a discrete T_b spectrum (i.e. the greater part of demagnetisation occurs over a narrow temperature range, resulting in a sharp drop on the T_b spectrum; e.g. Figure 3.22b), suggesting that the clasts contain magnetic grains with a narrow range of sizes. In these

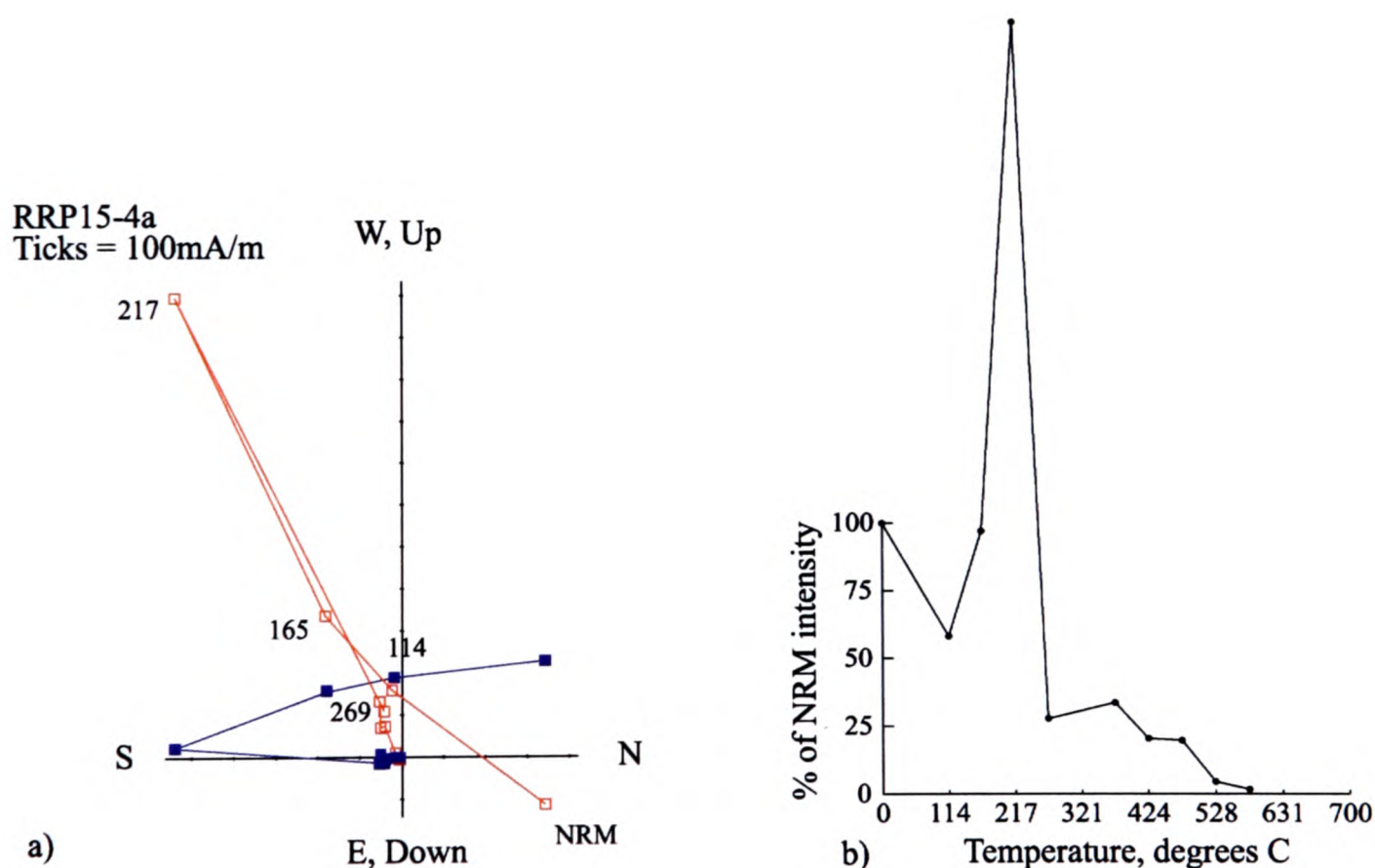


Figure 3.24: Zijdeveld plot and T_b spectrum for a clast from RRP15 that displays a low-T overprint (distinct from the ChRM component). RRP15-4a displays a two-component remanence, with the low-T overprint component demagnetising between 0°C and 217°C and the high-T component demagnetising between 217°C and $\sim 580^{\circ}\text{C}$ (plot a). Both low-T and high-T components lie in directions distinct from the expected geocentric axial dipole (GAD) mean direction for Ruapehu (type 2b remanence behaviour; Table 3.2). The T_b spectrum for RRP15-4a (plot b) is complex, with a decrease in intensity from 0°C to 114°C and a sharp apparent increase to 217°C as the low-T component tracks away from the centre of the z-plot, followed by a sharp decrease to 25% of the NRM value at 269°C and a gradual decrease to $<1\%$ of the NRM value at $\sim 580^{\circ}\text{C}$, suggesting that remanence is carried by three mineral phases. This concurs with high-T $\square$ data for this RRP15-4 (Figure 3.22), which shows the mineralogy more clearly. Points in a) (and on z-plots in 3.23) represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace.

clasts, the drop in intensity typically corresponds to the removal of the ChRM component. A summary of the demagnetisation behaviour that is displayed by clasts from RRP15 is shown in Table 3.5.

RRP16 – pumice clasts only (ten clasts)

The mineralogies of clasts from RRP16 are dominated by titanomagnetite with a T_c of $\sim 350^\circ\text{C}$ (e.g. Figure 3.22b). The majority of clasts also contain some magnetite or low-titanium titanomagnetite component, which has a higher T_c (e.g. Figure 3.25b,c). A characteristic remanent magnetism (ChRM) can be identified in all clasts, which typically demagnetises over a temperature range of $\sim 100^\circ\text{C}$ – 350°C and is inferred to be carried by titanomagnetite with compositions ranging from TM35 to TM43. ChRM directions are interpreted as grouped, following the criterion outlined in Watson, 1955 (Appendix A; hereafter referred to as 'grouped') and their mean direction approximates the expected GAD for Ruapehu; i.e. clasts display type 1 remanence behaviour (Table 3.2; Table 3.4; e.g. Figures 3.25a,d,e).

Eight clasts display an additional high-temperature (high-T) component (i.e. they display type 1b remanence behaviour; Table 3.2; e.g. Figure 3.25a,d). These components cannot be constrained but can be identified from vector plots, where the trajectories of ChRM components do not reach the origin (e.g. Figures 3.25a,d). Blocking temperature spectra and temperature-dependent susceptibility data (Figures 3.25b,c, 3.22b) suggest that these clasts contain a significant magnetite or low-titanium titanomagnetite (TM19 to TM21) phase. High-T components are interpreted as primary TRMs. To attempt to constrain the directions of high-T components, great circle paths were defined over the ChRM 100°C – 350°C interval for each clast, and were subsequently superimposed (Figure 3.26a). Paths show a random distribution, but intersect at a point close to the mean ChRM direction. This implies that directions of high-T components are randomly orientated between clasts. If directions of high-T components were similar between clasts, a swathe of great circles would be seen, with an intersection point denoting the mean *high-T component* direction. The 'random distribution' of high-T directions can be shown more simply, by plotting the demagnetisation path – from the ChRM direction towards the high-T component direction – for individual clasts on a stereoplot (Figure 3.26b). This shows that demagnetisation trajectories are different for each clast, whereas they would describe a similar path if the directions of high-T components were similar.

RRP17 – lithic clasts only (nine clasts)

The majority of lithic clasts from RRP17 (60%) exhibit a mixed titanomagnetite–magnetite mineralogy. Most clasts exhibit a ChRM, which demagnetises between $\sim 100^\circ\text{C}$ and $\sim 335^\circ\text{C}$ and is inferred to be carried by titanomagnetite (TM41 to TM58), plus or minus an additional high-temperature (high-T) component, which typically demagnetises between $\sim 350^\circ\text{C}$ and $\sim 600^\circ\text{C}$ and is inferred to be carried by low-titanium titanomagnetite (TM10

to TM27) or magnetite. Some clasts are not fully demagnetised until >600°C, suggesting that they have some haematite component (e.g. Figure 3.27d). Both ChRM and high-T

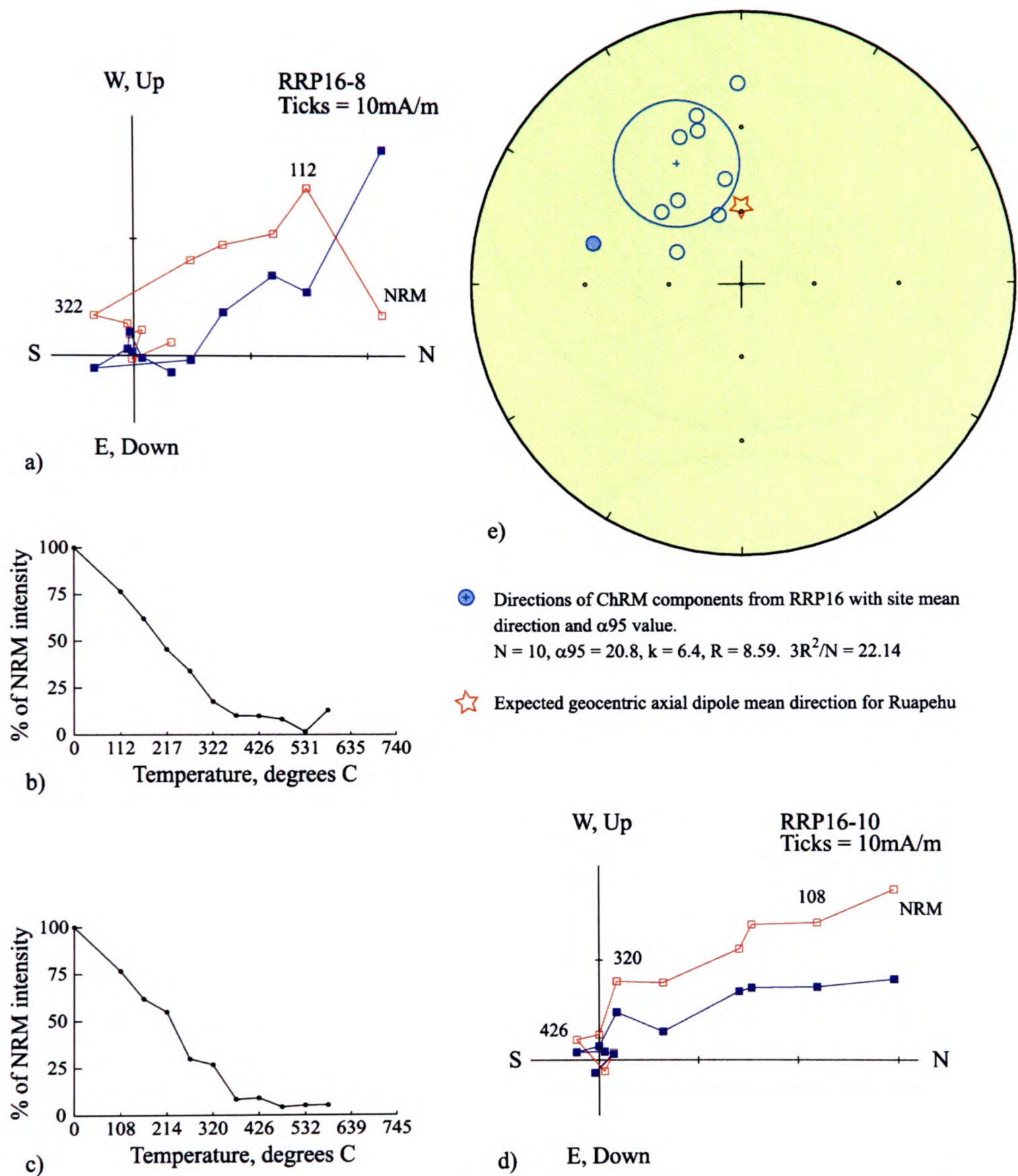


Figure 3.25: Zijderveld plots (z-plots), T_b spectra and equal area stereonet for two clasts from RRP16. Clasts typically display a two-component remanence, with a low-T component that lies sub-parallel to the expected (GAD) for Ruapehu, but does not tend toward the origin, and a high-T component that carries only a small fraction of the remanence and cannot be isolated (i.e. type 1b remanence behaviour; Table 3.2; plots a,d). The T_b spectra for clasts from RRP16 are typically two-phase (type E4; Table 3.3), with an initial decrease in intensity at ~350°C and a subsequent decrease to <1% of the NRM intensity before 580°C, suggesting that remanence is carried by two titanomagnetites. Plot c) shows the distribution of individual ChRM component directions for clasts from RRP16 with the site mean direction (small cross) and α_{95} value (large circle). Directions are grouped and the mean direction lies close to the expected GAD for Ruapehu. Open and filled shapes represent points on the upper and lower hemispheres of the stereonet respectively. Points on z-plots represent heating steps of 50°C (except where otherwise indicated) and temperatures in z-plots and T_b spectra have been corrected to account for the thermal gradient of the demagnetising furnace.

component directions are random and are distinct from the expected GAD for Ruapehu, i.e. clasts display type 2(b) remanence behaviour (Table 3.2; Table 3.4; Figure 3.27e).

Unit 2: RRP18 – pumice (five) and lithic (five) clasts

Pumice clasts from RRP18 all display a mixed titanomagnetite–magnetite mineralogy. A ChRM component can be identified in all clasts, which typically demagnetises between ~100°C and ~360°C and is inferred to be carried by titanomagnetite (TM36 to TM57; e.g. Figure 3.28c). ChRM directions are grouped, however, their site mean direction is distinct from the expected GAD for Ruapehu, i.e. they display type 2 remanence behaviour (Table 3.2; Table 3.4; Figure 3.28). Four clasts display an additional high-temperature (high-T) component, which demagnetises between ~300°C and ~580°C and is inferred to be carried by low-titanium titanomagnetite (TM10 to TM12) or magnetite (e.g. Figure 3.28d). Directions of high-T components are distinct from the expected GAD for Ruapehu and are randomly orientated between clasts (Figure 3.28e).

Lithic clasts from RRP18 typically display a mixed titanomagnetite–magnetite (or maghaemite) mineralogy. A ChRM component can be identified in all clasts, which demagnetises between 0°C and

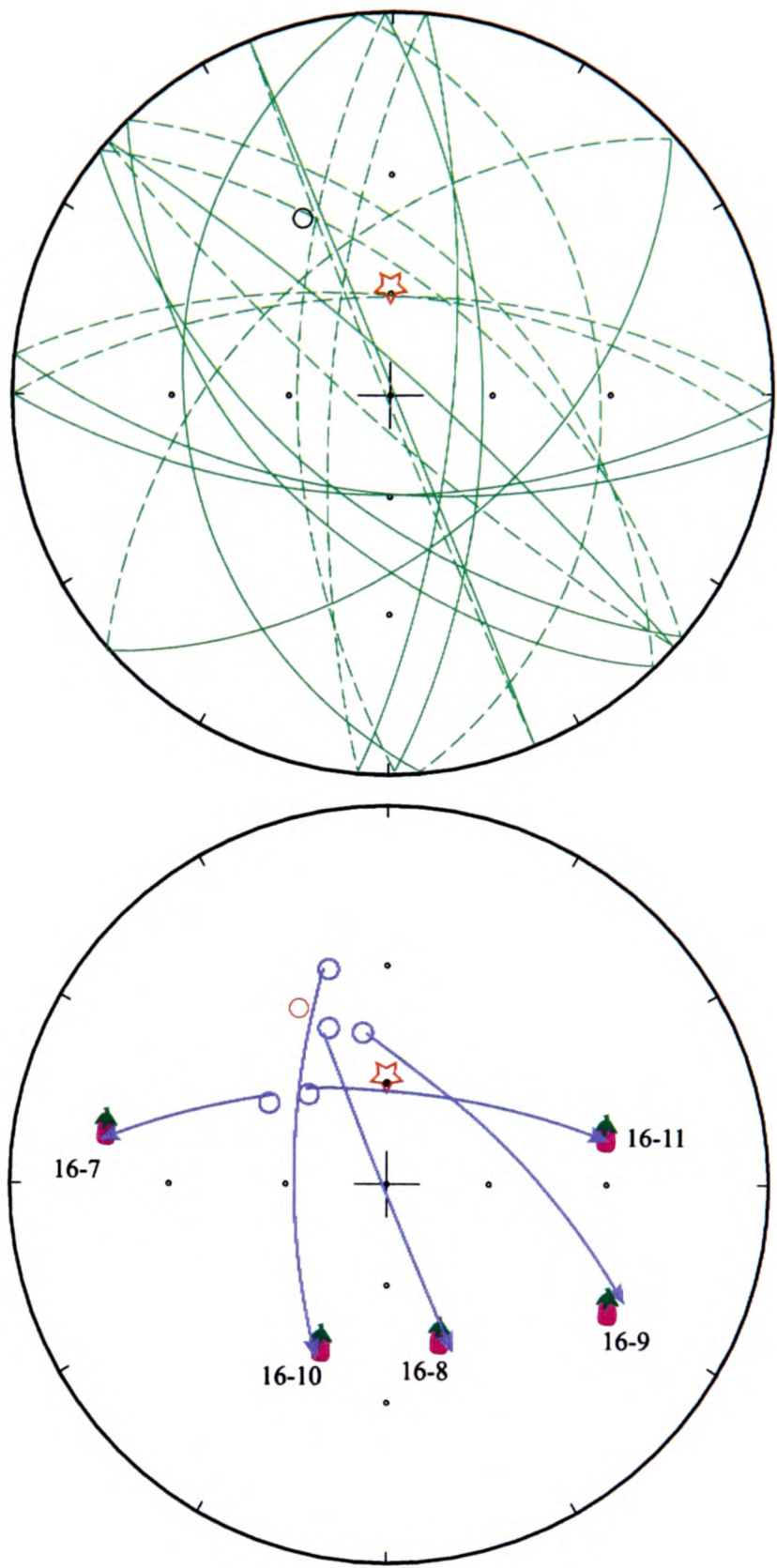


Figure 3.26: Equal area stereoplots showing: a) great circle paths, defined over the ChRM 100°C–350°C interval, for all clasts from RRP16. Paths show a random distribution, but intersect at a point close to the mean ChRM direction (small circle), suggesting that directions of high-T components are randomly orientated between clasts. Dashed and solid lines represent the intersection of the plane with the upper and lower hemispheres of the stereoplot respectively, and b) sketch of demagnetisation trajectories from the ChRM direction (blue circles) toward high-T component directions (aubergines) for clasts from RRP16. ChRM directions are similar for each clast and grouped around the ChRM mean direction (red circle), but the demagnetisation path from the ChRM to the high-T direction is different for each clast, showing that high-T components have a random distribution. The expected GAD mean direction for Ruapehu is shown as the red star.

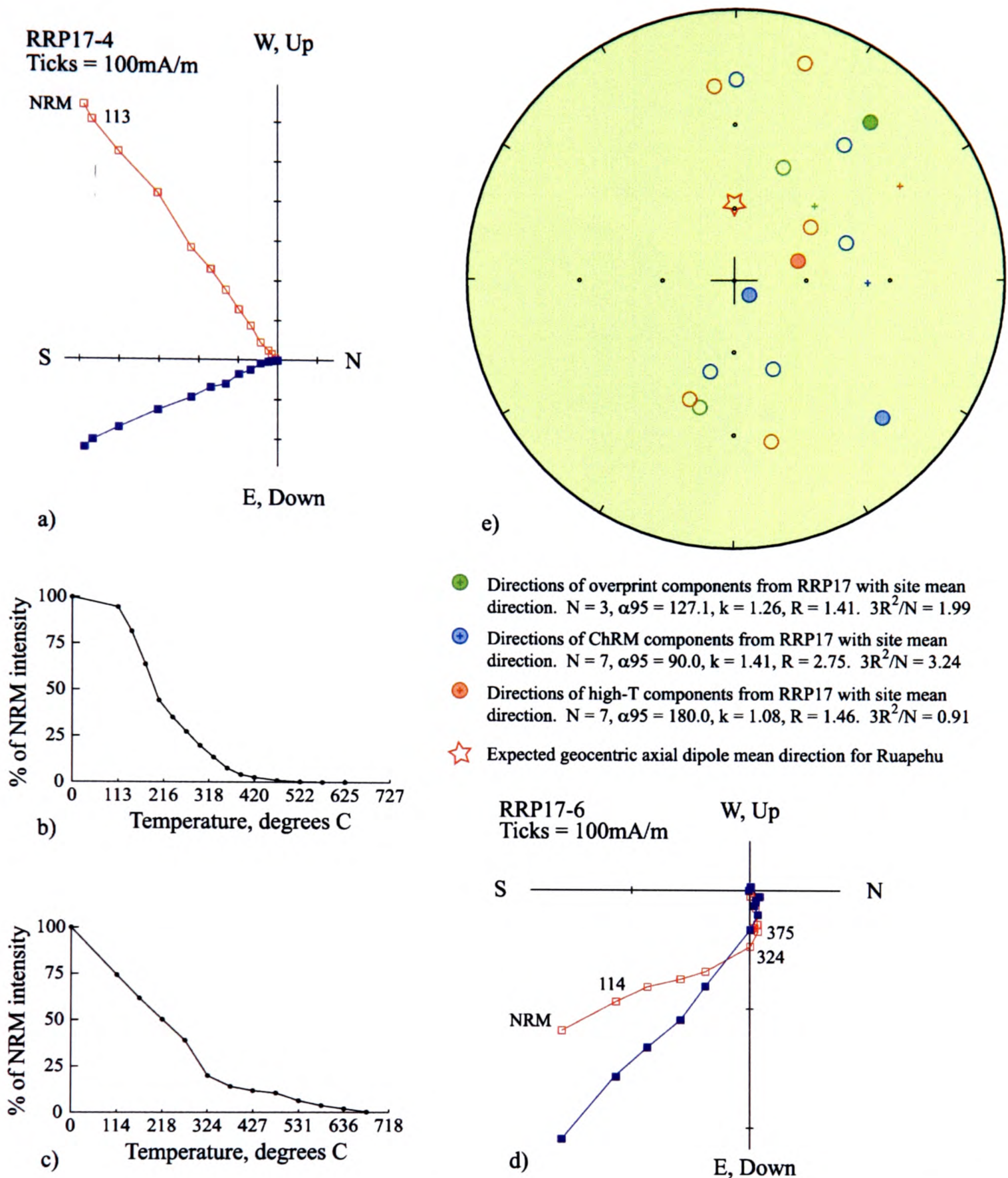


Figure 3.27: Zijderveld plots (z-plots), T_b spectra and equal area stereoplot for typical clasts from RRP17. RRP17-4 displays a single-component remanence in a direction distinct from the expected geocentric axial dipole (GAD) mean direction for Ruapehu (i.e. type 2a remanence behaviour; Table 3.2; plot a). The T_b spectrum for RRP17-4 (plot b) is two-phase (type E4; Table 3.3), with an initial decrease in intensity seen between $\sim 113^\circ\text{C}$ and $\sim 205^\circ\text{C}$ followed by a more gradual decrease to $<1\%$ of the NRM intensity from $\sim 205^\circ\text{C}$ to $\sim 522^\circ\text{C}$, suggesting that remanence is carried by two titanomagnetites. RRP17-6 displays a two-component remanence and both low-T and high-T components lie in directions distinct from the expected GAD for Ruapehu (type 2b remanence behaviour; Table 3.2; plot d). The low-T component persists to between $\sim 324^\circ\text{C}$ and 375°C . The T_b spectrum for RRP17-6 (plot c) is two-phase (type E2; Table 3.3) and displays decreases in intensity between 0°C and $\sim 324^\circ\text{C}$ and between 324°C and 688°C , suggesting that remanence is carried by titanomagnetite plus haematite. Plot c) shows the distribution of individual ChRM and overprint directions for clasts from RRP17, with site mean directions (small crosses). Directions of all components are random. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively. Points on z-plots represent heating steps of 50°C (except where otherwise indicated) and temperatures in z-plots and T_b spectra have been corrected to account for the thermal gradient of the demagnetising furnace.

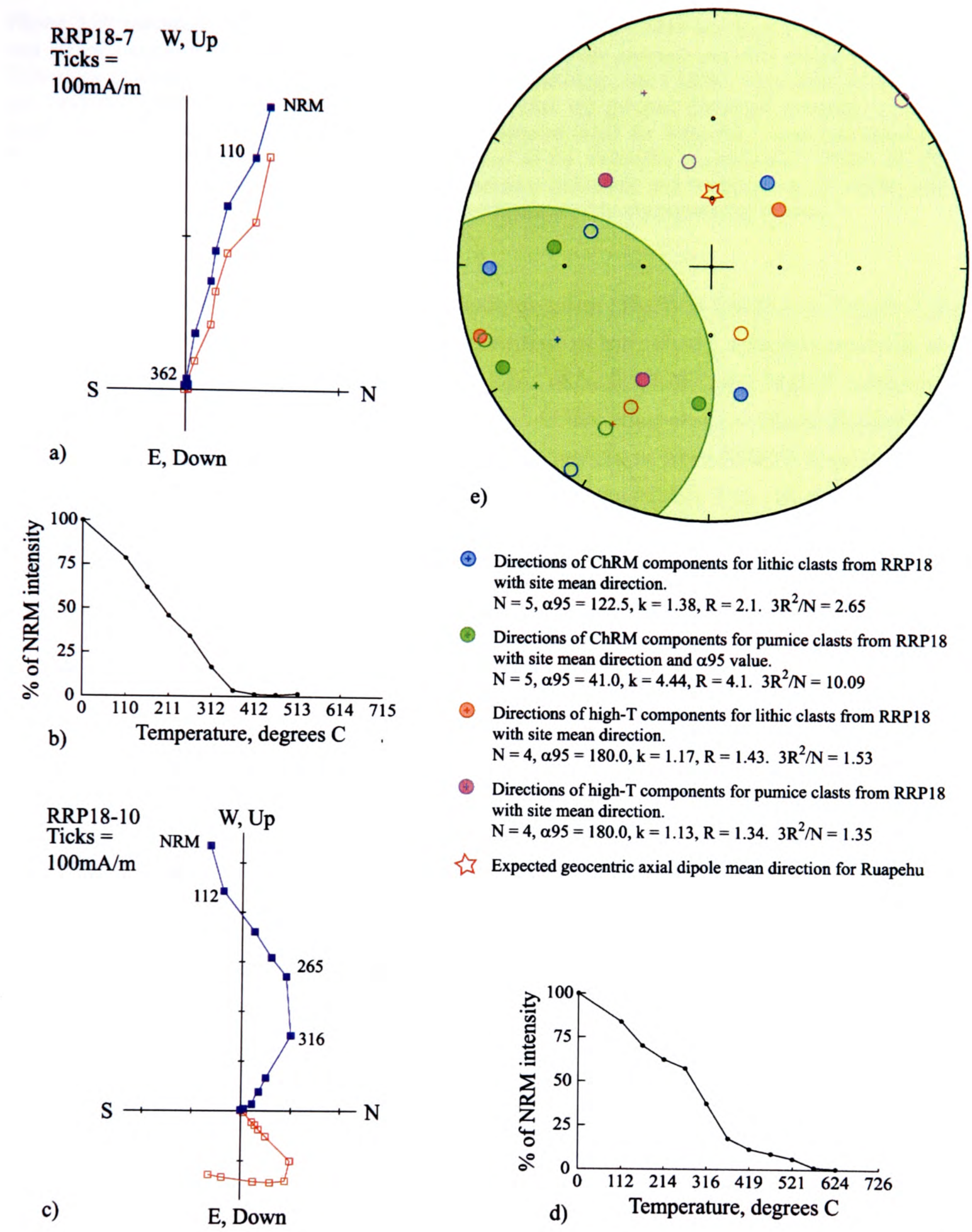


Figure 3.28: Zijderveld plots (z-plots), T_b spectra and equal area stereoplot for a typical lithic clast and juvenile (pumice) clast from RRP18. RRP18-7 is a lithic clast and displays a single-component remanence in a direction distinct from the expected geocentric axial dipole (GAD) mean direction for Ruapehu (i.e. type 2a remanence behaviour; Table 3.2; plot a). The T_b spectrum for RRP15-2a (plot b) is single-phase (type D2; Table 3.3), with intensity decreased to ~1% of the NRM intensity by ~412°C, suggesting that remanence is carried by titanomagnetite. RRP18-10 is a pumice clast and displays a two-component remanence (plot c); the low-T component persists to between 265°C 316°C and the apparent middle-T component is interpreted as a feature of overlapping T_b spectra of low-T and high-T components. Both low-T and high-T components lie in directions distinct from the expected GAD for Ruapehu (i.e. the clast displays type 2b remanence behaviour; Table3.2). The T_b spectrum for RRP18-10 (plot d) is three-phase (type G; Table 3.3) with decreases in intensity seen at ~316°C, 368°C and a decrease to <1% of the NRM intensity at ~580°C, suggesting that remanence is carried by two titanomagnetites plus magnetite. See over for rest of caption.

Figure 3.28 continued: Plot c) shows the distribution of individual ChRM and high-T directions for lithic and juvenile clasts from RRP18, with site mean directions (small crosses) and α_{95} values (large circles). Directions of high-T components for both lithic and juvenile clasts, and ChRM components for lithic clasts are random. ChRM directions for juvenile (pumice) clasts are grouped (although grouping is relatively poor), but their mean direction is distinct from the expected GAD for Ruapehu. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively. Points on z-plots represent heating steps of 50°C (except where otherwise indicated) and temperatures in z-plots and T_b spectra have been corrected to account for the thermal gradient of the demagnetising furnace.

~360°C and is inferred to be carried by titanomagnetite (TM36 to TM43; e.g. Figure 3.28a). An additional high-T component can be identified in four clasts, which is inferred to be carried by magnetite or maghaemite. Directions of both ChRM and high-T components are random and are distinct from the expected GAD for Ruapehu, i.e. clasts display type 2 remanence behaviour (Table 3.2; Figure 3.28e). Two clasts from RRP18 display a three-component remanence (i.e. type 2c remanence behaviour; Table 3.2). In these clasts, the low-T and medium-T components are inferred to be carried by titanomagnetites of two different compositions and the high-T component is inferred to be carried by magnetite or maghaemite.

3.7.4.4 Discussion

Unit 1 – lithic clasts

Lithic clasts from RRP15 and RRP17 typically display type 2 remanence behaviour (Table 3.2), i.e. directions of ChRM (or overprint) components are random and distinct from the expected GAD for Ruapehu (e.g. Figures 3.23, 3.27). This suggests that the unit was *not* deposited hot, but was reworked at ambient temperature. Moreover, many clasts display more than one component of magnetism, which indicates that the unit was reworked from a pre-existing (hot) pyroclastic deposit.

Unit 1 – pumice clasts

Most pumice clasts from unit 1 display type 1b remanence behaviour (Table 3.2). Low-temperature (low-T) components are grouped and their site mean direction approximates the expected GAD for Ruapehu, however they do not trend toward the origin on vector component plots (e.g. Figure 3.25a,c). They are inferred to be carried by titanomagnetite. High-temperature (high-T) components typically lie in a direction distinct from the expected GAD for Ruapehu and directions are random (e.g. Figure 3.25e). They are inferred to be carried by low-titanium titanomagnetite or magnetite.

The fact that pumice clasts display type 1 remanence behaviour (Table 3.2; i.e. a ChRM sub-parallel to the expected GAD for New Zealand) suggests initially that these clasts (and hence the unit) were emplaced hot, contradicting the results from lithic clasts (which suggest that the unit has a reworked origin). However, Sparks et al. (1999) have suggested that pumice is chemically unstable and alters readily. The type 1 (ChRM) components exhibited by pumice clasts from unit 1 are therefore interpreted to be

chemical remanent magnetisations (CRMs), formed by post depositional alteration of the unit, and not TRMs formed through a heating event. The high-T components exhibited by pumice clasts from unit 1 are interpreted to be remnants of the clasts' original TRMs (formed on cooling after eruption) that have been incompletely overprinted by CRM components. The random distribution of high-T directions suggests that clasts were reworked prior to the acquisition of CRM components, substantiating the interpretation of the unit as reworked (from lithic clast data).

The data from pumice clasts from unit 1 is enigmatic as it suggests that in these clasts, titanomagnetite (which is inferred to carry the ChRM component) is an alteration product. This is in contrast to the usual assumption, which is that in volcanic rocks, titanomagnetite is a primary mineral, which commonly alters to magnetite. However, this behaviour may be explained by the homogenisation of titanium-rich grains within the clast because of alteration. Such grains may be produced by deuteric oxidation, which typically occurs in volcanic rocks after eruption (on cooling) and involves the exsolution of intermediate composition titanomagnetite grains into low-titanium magnetite and high-titanium phases (Dunlop and Özdemir, 1997).

Unit 2

Both pumice clasts and lithic clasts from unit 2 typically display type 2 remanence behaviour (Table 3.2). Most clasts display a two-component remanence and directions of both low-T (ChRM) and high-T components are distinct from the expected GAD for Ruapehu (e.g. Figure 3.28a,c). ChRM directions for pumice clasts from unit 2 are grouped, but grouping is poor and the site mean direction is distinct from the expected GAD for Ruapehu (Figure 3.28e). The significance of this grouping is not certain, but it may be the result of the imbrication of clasts during fluvial transport and deposition. Directions of all other components (in pumice clasts and lithic clasts) are random (Figure 3.28e). The fact that clasts typically display type 2 remanence behaviour, and a multi-component remanence concurs with field evidence (such as the rounded nature of pumice clasts), to suggest that the unit is reworked in origin. Moreover, some lithic clasts display a three-component remanence, which suggests that this unit was derived from a pre-existing *reworked* pyroclastic deposit, possibly unit 1.

3.7.5 Conclusions

The major implications of this study are that: a) thermal demagnetisation can be used effectively to distinguishing primary (hot) pyroclastic material from reworked (cold) pyroclastic material, b) lithic clasts should be used in preference to (or as well as) juvenile (pumice) clasts in palaeomagnetic studies, as juvenile clasts may not provide a reliable record of the deposit's history, c) care must be taken when using the fluxgate technique to interpret pyroclastic deposits, as it is possible for a deposit to retain an overall record of

the geomagnetic field direction, even if it has been deposited cold and d) titanomagnetite can occur as an alteration product (carrying a CRM) in pyroclastic deposits.

Fluxgate measurements suggested that unit 1 was a primary (hot) pyroclastic flow deposit and field evidence (although not unequivocal) concurred with this suggestion. However, thermal demagnetisation of clasts from units 1 and 2 has shown that neither unit was deposited by a primary pyroclastic flow. Directions of magnetic components from lithic clasts are randomly orientated between clasts from the same unit, implying that the units were deposited at ambient temperature (i.e. cold). Moreover, the remanence characteristics displayed by lithic and juvenile clasts suggest that unit 1 was reworked from a pre-existing hot pyroclastic deposit (possibly a more proximal part of the Pourahu Formation) and was subsequently reworked and deposited downstream as unit 2.

Pumice clasts within volcanic deposits tend to be chemically unstable and can alter quickly after deposition (Sparks et al., 1999), forming new magnetic minerals. With the formation of new magnetic minerals, these clasts can acquire a (new) chemical remanent magnetism (CRM) that will record the direction of the geomagnetic field at the time of alteration. In these deposits, the CRM component is typically carried by titanomagnetite. The acquisition of CRM can cause erroneous interpretation of pyroclastic deposits when using the fluxgate technique because: 1) the method does not take in to account the different magnetic properties of pumice and lithic material, and 2) the method allows no distinction between a primary TRM (formed by a heating event, e.g. transport within a pyroclastic flow) and a CRM that may be formed without heating. Hence thermal demagnetisation of lithic (and juvenile) clasts is the preferred palaeomagnetic technique to ensure accurate interpretation of pyroclastic deposits.

Chapter 4

AIRFALL DEPOSITS

Airfalls comprise 37% of the deposits sampled on Ascension Island for palaeomagnetic analysis. Seventy-eight percent of the airfalls sampled are felsic in composition and the remaining 22% are mafic in composition. Samples were taken from thirty-six individual locations (Figure 4.1). At most localities, between four and eight clasts of juvenile material were sampled to determine magnetic polarity. Additional lithic clasts were taken from thirteen airfall units, to determine emplacement temperature.

The units sampled were categorised as airfall deposits based on field evidence. This chapter describes the palaeomagnetic characteristics (remanence, emplacement temperature, magnetic mineralogy and secular variation) displayed by the Ascension airfall deposits. Palaeomagnetic and field evidence are combined with geochemical data to refine interpretations of these deposits.

4.1 REMANENCE CHARACTERISTICS

A classification of remanence characteristics for clasts from volcanoclastic deposits is provided in Table 3.2 (Chapter 3). **Type 1** clasts display a low-temperature (low-T) component in a direction sub-parallel to the expected geocentric axial dipole mean direction (GAD) for Ascension (000/-15). Low-T components are similarly directed between individual clasts from the same unit. Medium-temperature (med-T) or high-temperature (high-T) components, where present, show no preferred orientation between clasts from the same unit (hereafter referred to as *randomly orientated*). **Type 2** clasts display a low-T component in a direction distinct from the expected GAD for Ascension. Low-T components *and* med-T and high-T components (where present) are randomly

orientated between individual clasts from the same unit. Remanence sub-types a, b and c refer to clasts with a single, two or three-component remanence respectively. In this and the following chapters, VRM components are not included in the classification of remanence according to Table 3.2 (except where stated otherwise). A sample that displays two TRM components and an additional VRM is therefore referred to simply as two-component (sub-type b, Table 3.2). Descriptions of remanence behaviour in this section apply to both felsic and mafic airfalls (as they display similar remanence characteristics).

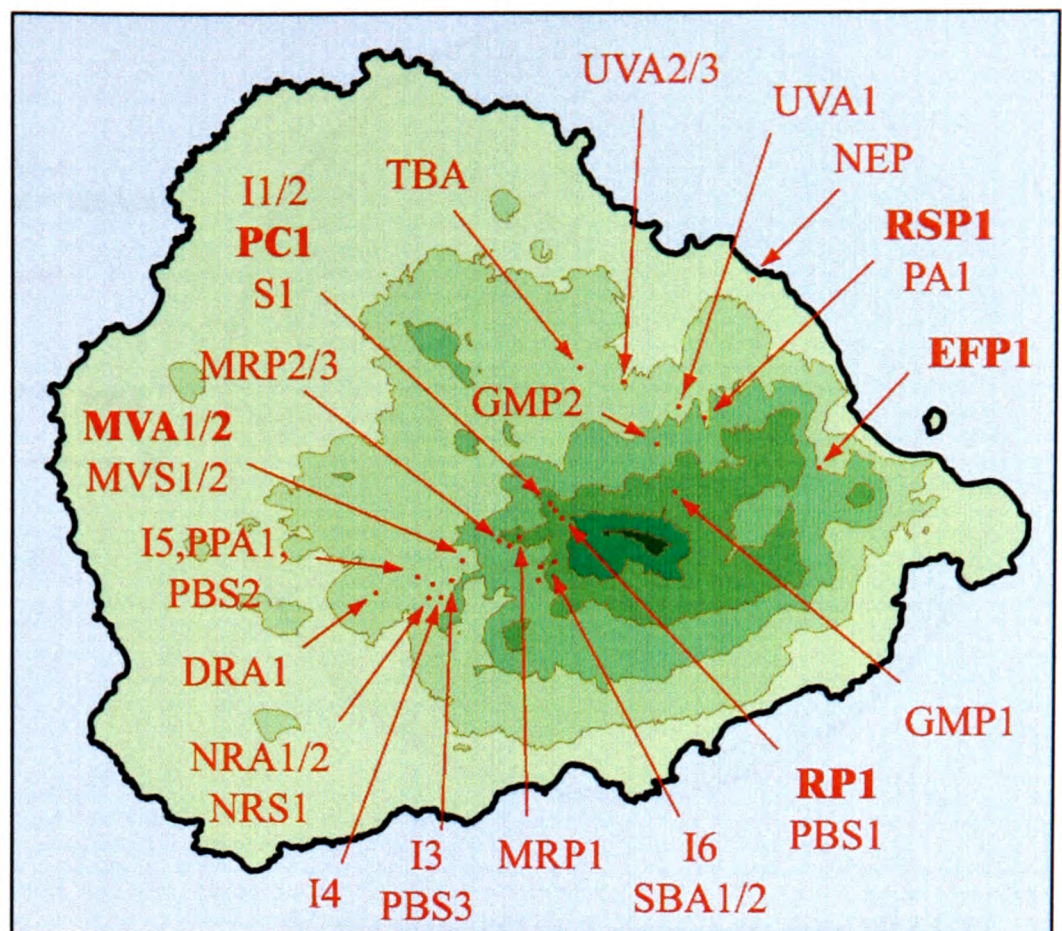


Figure 4.1: Topographic map of Ascension Island showing individual palaeomagnetic sampling locations of airfall deposits. Sites shown in bold exhibit palaeomagnetic characteristics that are not typical of airfalls. Shading represents contours of 500ft.

4.1.1 Juvenile clasts

In the descriptions of the airfall deposits in this and following chapters, the term 'juvenile' is used to denote primary *vesicular* material, i.e. pumice and scoria, as opposed to non-vesicular juvenile material (which may also be referred to as 'cognate lithic' material).

Pumice or scoria clasts from airfall deposits on Ascension typically exhibit a single-component remanence, in a direction sub-parallel to the expected geocentric axial dipole mean direction (GAD) for Ascension (i.e. type 1a remanence behaviour, Table 3.2; e.g. Figures 4.2a,c). Directions of type 1a components in typical juvenile clasts from felsic airfalls are interpreted as grouped following the criterion outlined in Watson, 1956 (Appendix A; hereafter referred to as 'grouped'; e.g. Figures 4.2c, 4.3c). This type of remanence behaviour is expected from juvenile clasts from pyroclastic deposits (Section 3.6.1.1) and is interpreted as a CRM (Zlotnicki, 1984; McClelland and Druitt, 1989). CRMs are thought to be acquired by juvenile clasts because of chemical alteration due to the resorption of volatiles (Sparks et al., 1999; Section 3.6.1.1). The CRM acquired will record the direction of the ambient field at the time of alteration and will typically overprint any

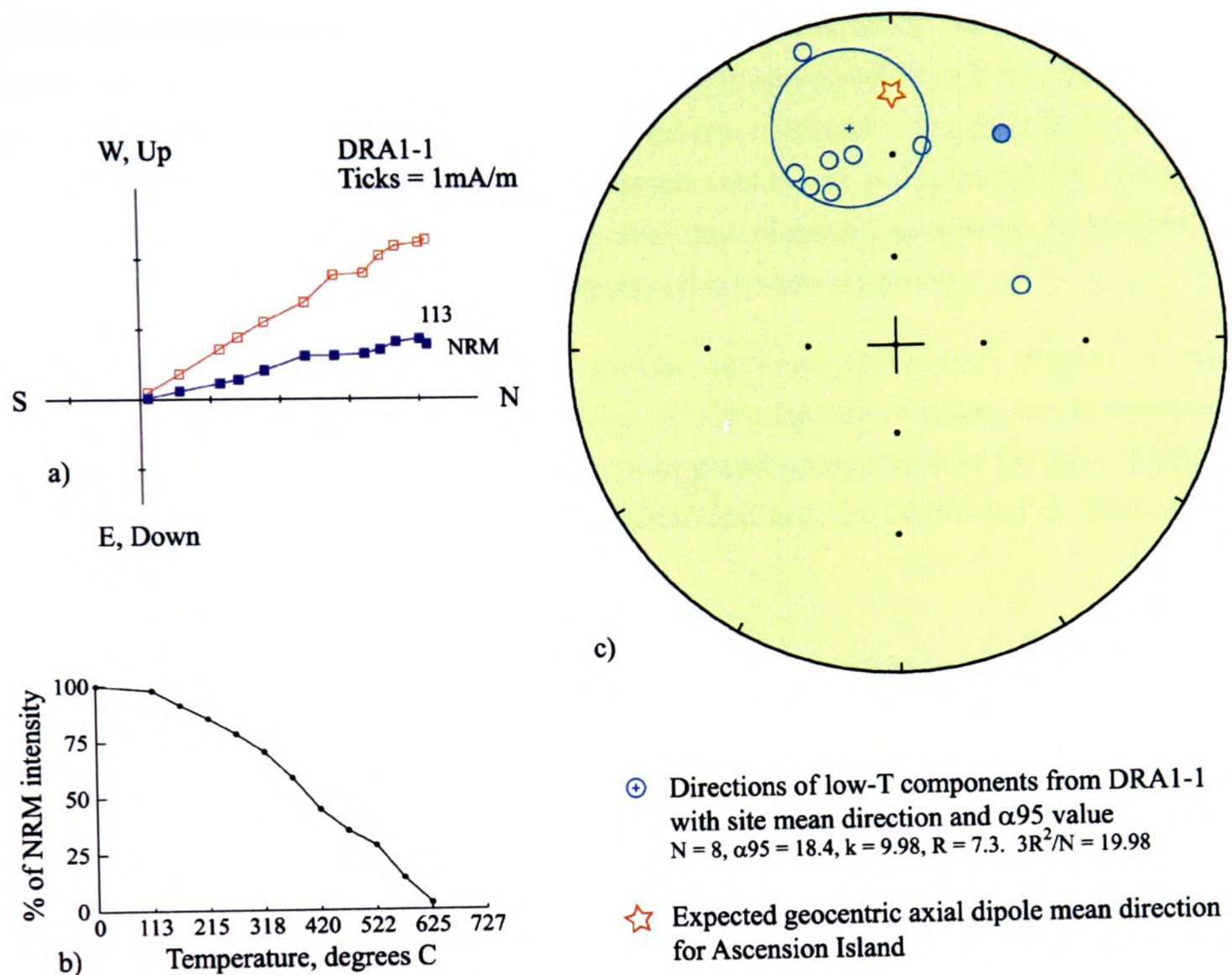


Figure 4.2: Zijderveld plot (z-plot), T_b spectra and equal area stereoplot for juvenile clasts from a typical airfall deposit from Ascension Island (DRA1). DRA1-1 displays type 1a remanence behaviour (Table 3.2; plot a). Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for DRA1-1 (plot b) is two-phase (type E2; Table 3.3), with decreases in intensity seen at ~420°C and ~625°C, implying that remanence is carried by titanomagnetite plus maghaemite. Plot c) shows the distribution of individual low-T components for clasts from DRA1, with site mean direction (small cross) and α_{95} value (large circle). Low-T directions are tightly grouped and the site mean direction approximates the expected GAD for Ascension. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

original TRM components. However, such alteration is expected to occur minutes to hours after deposition (Sparks et al., 1999), meaning that the CRM direction is not expected to differ from the original TRM direction.

Several of the juvenile clasts sampled on Ascension show poorly constrained linear components (seen as considerable scatter of vector points on the Zijderveld plot). This may be the result of inhomogeneities of magnetisation (i.e. where individual magnetic grains are magnetised in slightly different directions), or of the manual positioning of samples during laboratory measurements (see Appendix A). Slight changes in sample position between measurements will affect the direction of magnetism that is measured at each step, producing scatter on the vector component plot. The amount of scatter will increase with decreasing intensity as the total intensity of the sample approaches the noise

level of the magnetometer. Hence, this scatter of points tends to be exacerbated in juvenile samples, which are typically more weakly magnetised than lithic clasts. Where scatter is extreme, it may not be possible to isolate any magnetic components (no magnetic components can be resolved). Intensity measurements are *not* affected by changes in sample position and hence it should be noted that blocking temperature spectra (e.g. Figure 4.2b) will be reliable even where directional data are scattered.

Over 50% of the airfall units sampled contain juvenile clasts that display a multi-component remanence (e.g. Figures 4.3a, 4.4a). In the majority of cases, this is interpreted as the result of the rotation of clasts during cooling and compaction of the unit (Hoblitt et al, 1985), although a multi-component remanence can only be attributed to clast rotation

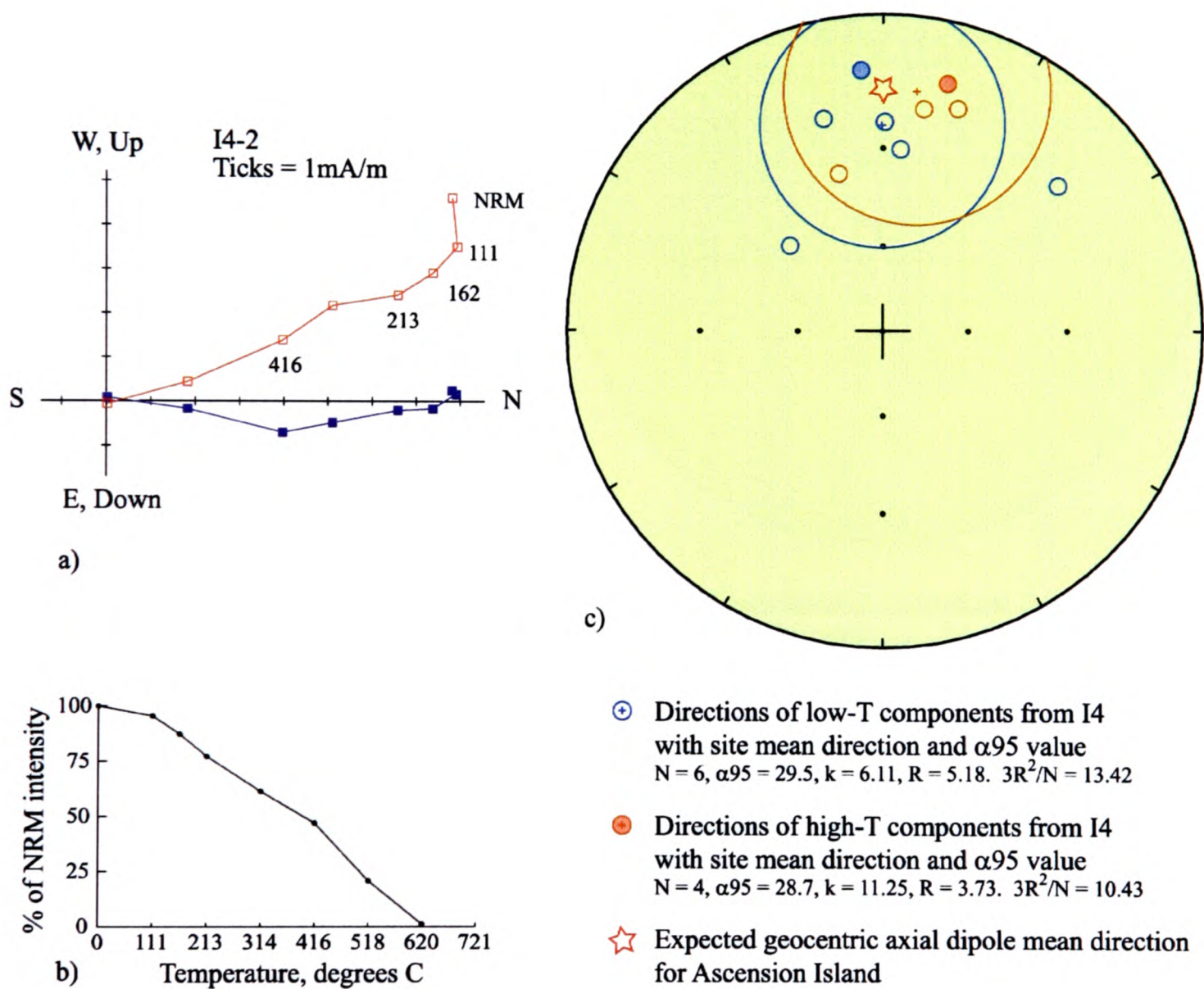


Figure 4.3: Zijderveld plot (z-plot) and T_b spectra for a juvenile clast that shows signs of rotation during cooling (I4-2), plus equal area stereoplot showing low-T and high-T directions for all clasts from I4. I4-2 displays type 1b remanence behaviour (Table 3.2; plot a), but low-T and high-T components are sub-parallel. Points represent heating steps of 100°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for I4-2 (plot b) is single-phase (type B2 behaviour; Table 3.3), with intensity reduced to ~1% of the NRM value at ~620°C, suggesting that remanence is carried by maghaemite. Plot c) shows the distribution of individual low-T and high-T components for all clasts from I4, with site mean directions (small crosses) and α_{95} values (large circles). Both low-T and high-T directions are grouped, with similar site mean directions that approximate the expected GAD for Ascension. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

where the clast displays sub-parallel low-temperature (low-T) and high-temperature (high-T) components (e.g. Figure 4.3a). In the remaining multi-component clasts, the low-T component is sub-parallel to the expected GAD for Ascension, but the high-T component is distinct from the expected GAD (type 1b remanence behaviour, Table 3.2; e.g. Figure 4.4a). In these clasts, the high-T component is typically isolated only in the last steps of demagnetisation and carries only a small fraction of the remanence. These clasts are interpreted as 'secondary' juvenile clasts, i.e. pre-existing pyroclastic material that has been incorporated into a subsequent eruption in the same way as lithic clasts (such clasts should not strictly be referred to as juvenile, but the term is applied here to distinguish

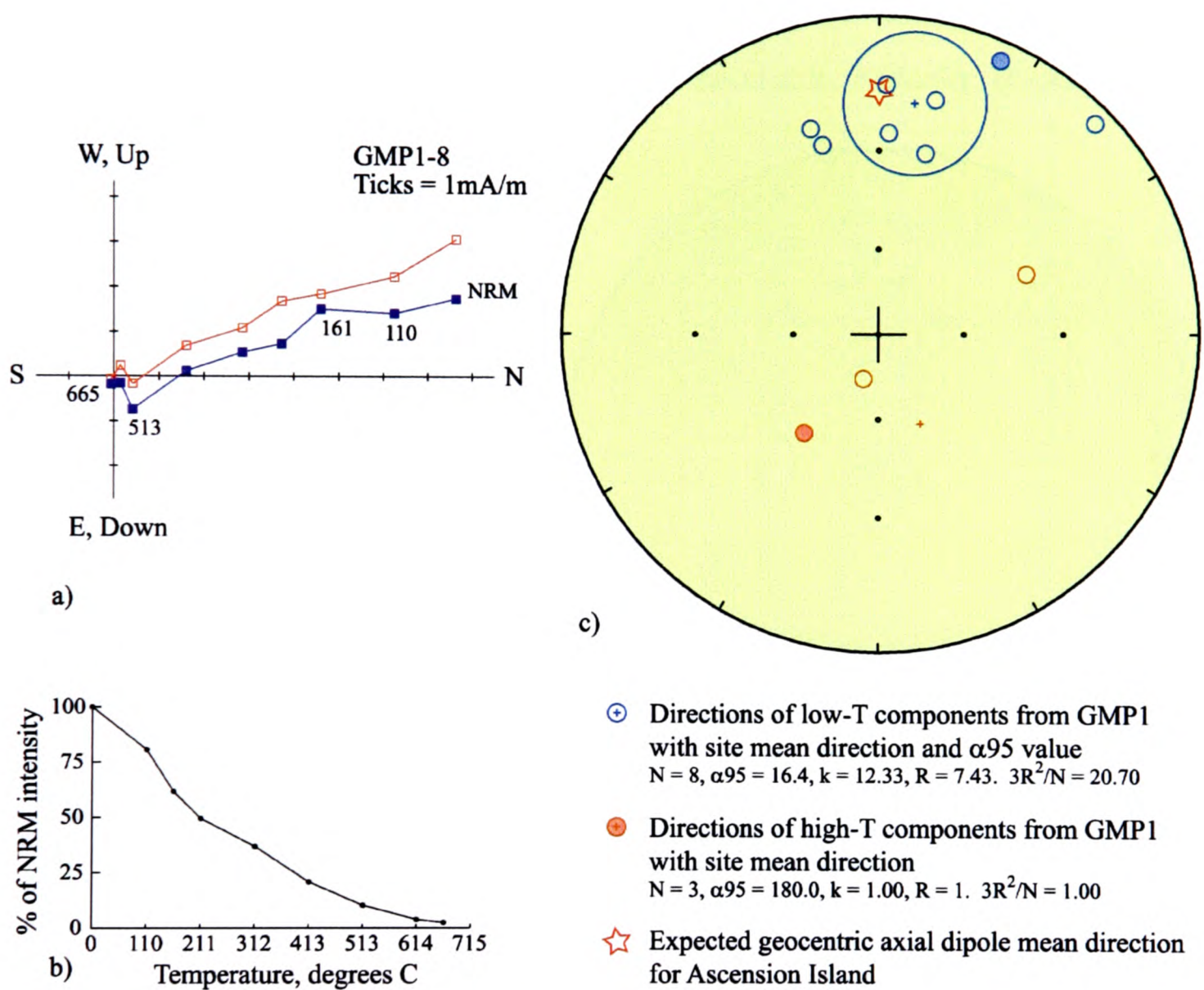


Figure 4.4: Zijderveld plot (z-plot), T_b spectra for a juvenile clast that shows a two-component remanence (GMP1-8), plus equal area stereoplot showing low-T and high-T directions for all clasts from GMP1. GMP1-8 displays type 1b remanence behaviour (Table 4.1; plot a); the low-T component (inferred to be a CRM overprint) lies in a direction sub-parallel to the GAD for Ascension and persists to 513°C. The high-T component (inferred to be a pre-existing TRM or CRM) is isolated only in the last few demagnetisation steps and carries only a small fraction of the remanence. Points represent heating steps of 100°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for GMP1-8 (plot b) is two-phase (type E2 behaviour; Table 4.2), with a decrease in intensity seen at ~211°C and full demagnetisation occurring at ~665°C. Remanence is inferred to be carried by titanomagnetite plus maghaemite or haematite. Plot c) shows the distribution of individual low-T and high-T components for all clasts from GMP1, with site mean directions (small crosses) and α_{95} value (large circle). Low-T directions are tightly grouped and their mean direction approximates the expected GAD for Ascension. High-T directions are random. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

such clasts from lithic material). High-T components are interpreted as pre-existing TRMs (acquired on eruption and cooling) or CRMs, which have been incompletely overprinted by later CRMs (formed soon after deposition as described). Type 1b remanence behaviour may also be displayed by secondary juvenile clasts from *epiclastic* deposits that have acquired an *in-situ* CRM due to post-depositional alteration. However, in this case, *all* (secondary juvenile) clasts from the same unit are expected to display type 1b remanence behaviour (Table 3.2). This type of remanence behaviour is exhibited by pumice clasts sampled from reworked parts of the Pourahu deposit, Ruapehu volcano, New Zealand (Donoghue et al, 1999; Section 3.7).

4.1.2 Lithic clasts

Lithic clasts sampled from airfall deposits on Ascension typically display a multi-

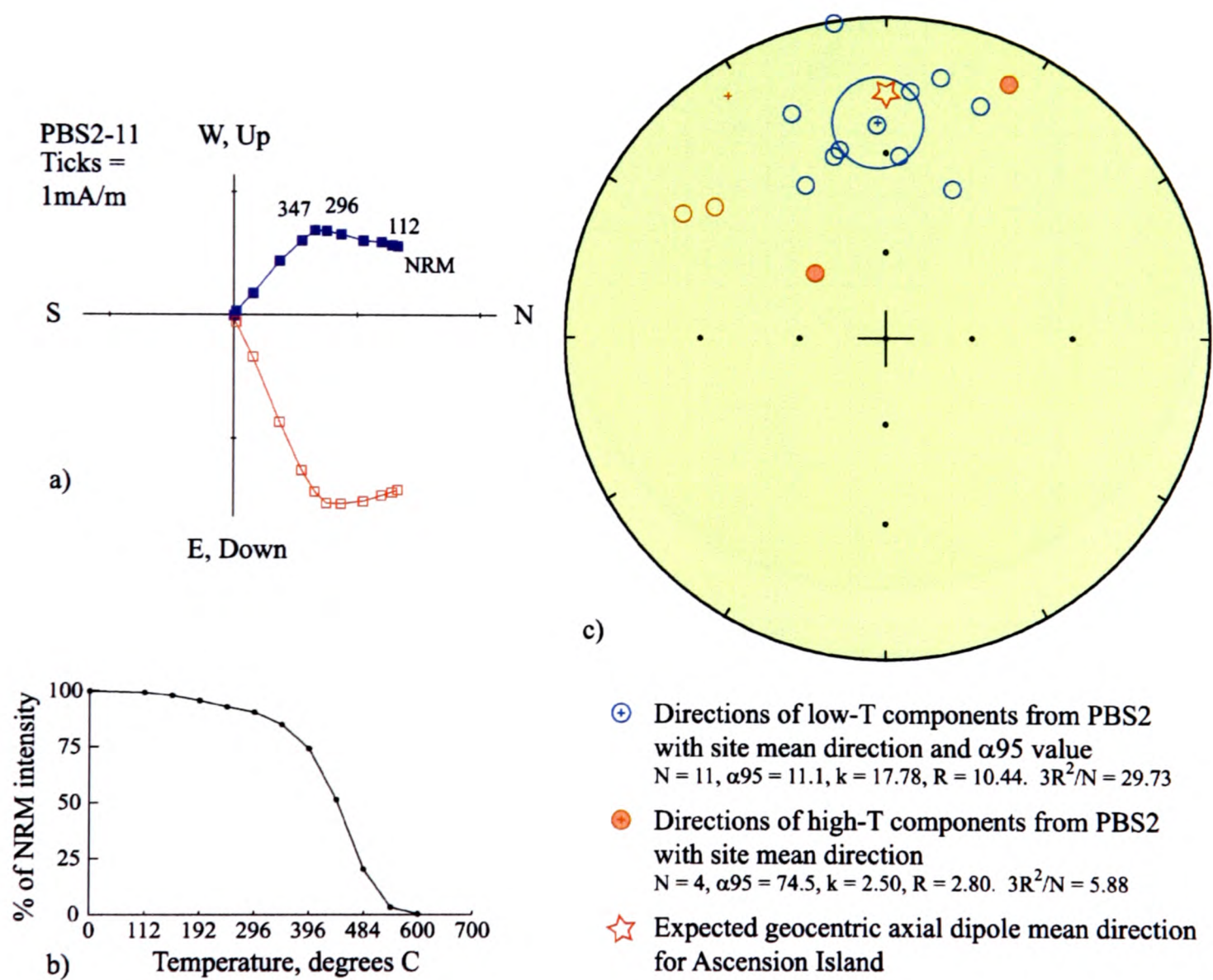


Figure 4.5: Zijderveld plot (z-plot), T_b spectra for a typical lithic clast from an Ascension airfall deposit (PBS2-11), plus equal area stereoplot showing low-T and high-T directions for all clasts from PBS2, with site mean directions and α_{95} value. PBS2-11 displays type 1b remanence behaviour (Table 3.2; plot a). T_c for PBS2-11 is between 296°C and 347°C. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for PBS2-11 (plot b) is single-phase (type A1; Table 3.3), with the major decrease in intensity occurring at ~580°C, implying that magnetite is the remanence carrier. Plot c) shows the distribution of individual low-T and high-T components for all clasts from PBS2, with site mean directions (small crosses) and α_{95} value (large circle). Low-T directions are tightly grouped and their mean direction approximates the expected GAD for Ascension. High-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

component remanence, with a low-T component that lies sub-parallel to the expected GAD for Ascension and high-T or med-T components (where present) that are distinct from the expected GAD and are randomly orientated between clasts from the same unit (i.e. type 1 remanence behaviour, Table 3.2). This behaviour is expected from lithic clasts from airfall deposits (see Section 3.6.1.2). The majority of clasts from Ascension airfall deposits display a two-component remanence (i.e. type 1b remanence behaviour, Table 3.2; e.g. Figure 4.5a). Eight lithic clasts display a three-component remanence (i.e. type 1c remanence behaviour, Table 3.2; e.g. Figure 4.6a). Type 1c clasts are inferred to have been sourced from a pre-existing (primary) pyroclastic deposit. This type of remanence behaviour may also be produced by clast rotation during cooling, however this

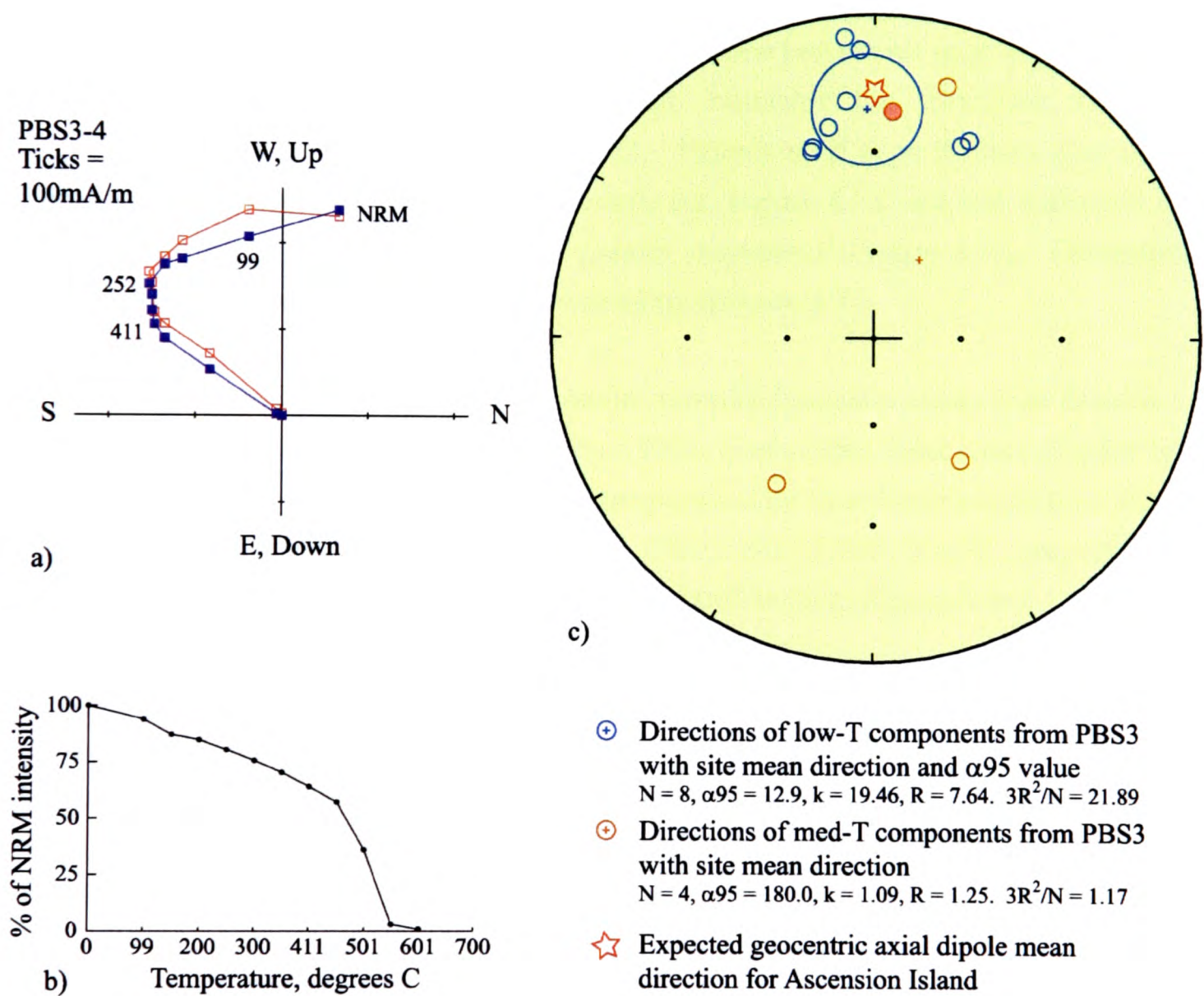


Figure 4.6: Zijderveld plot (z-plot), T_b spectra for a lithic clast from an Ascension airfall deposit (PBS3-4) that displays a three-component remanence, plus equal area stereoplot showing low-T and high-T directions for clasts from PBS3. PBS3-4 displays type 1c remanence behaviour (Table 3.2; plot a). T_{e1} for PBS3-4 is ~252°C and T_{e2} (the 'relict' T_e from a previous heating episode) is ~411°C. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for PBS3-4 (plot b) is single-phase (type A1; Table 3.3), with the major decrease in intensity seen at ~580°C, implying that remanence is carried by magnetite. Plot c) shows the distribution of individual low-T and high-T and components for all clasts from PBS3, with site mean directions (small crosses) and α_{95} value (large circle). Statistics cannot be calculated for med-T components due to small population size. Low-T directions are tightly grouped and their mean direction approximates the expected GAD for Ascension. High-T directions are random. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

mechanism can only be invoked if low-T and medium-T (med-T) components are sub-parallel (behaviour seen in relatively few clasts from Ascension airfall deposits).

Directions of low-T components from typical lithic clasts from felsic airfalls are interpreted as tightly grouped following the criterion outlined in Watson, 1956 (Appendix A; hereafter referred to as 'tightly grouped'; e.g. Figures 4.5c, 4.6c). Site mean directions for low-T components approximate the expected GAD for Ascension (e.g. Figure 4.6c). Directions of med-T and high-T components (where present) are interpreted as randomly orientated following the criterion outlined in Watson, 1956 (Appendix A; hereafter referred to as 'random'; e.g. Figures 4.5c, 4.6c).

Unit PC1 (Figure 4.1) differs from other airfall units sampled. The majority of lithic clasts (and juvenile clasts) from PC1 display type 1 remanence behaviour (e.g. Figure 4.7d) and directions of low-T components are grouped, however the grouping is poor in comparison to other airfall units (Figure 4.7c). However, if type 2 clasts (i.e. clasts in which all components are randomly orientated, e.g. Figure 4.7a) are not included in the analysis, grouping of low-T directions is greatly improved (Figure 4.7c). Directions of high-T components for clasts from PC1 are random (Figure 4.7c).

Units EFP1, RP1 and RSP1 (Figure 4.1) contain juvenile (pumice) clasts that display type 1a remanence behaviour (Table 3.2). However, lithic clasts from these units display type 2 remanence behaviour (Table 3.2), i.e. low-T components lie in a direction distinct from the expected GAD for Ascension (e.g. Figure 4.8). Directions of both low-T components and high-T components from EFP1, RP1 and RSP1 are random (e.g. Figure 4.8c).

Unit MVA2 (Figure 4.1) contains juvenile (pumice) clasts that display a normal low-T component and a reversed high-T component (e.g. Figure 4.9a), though in the majority of clasts, components are poorly constrained. Low-T directions for juvenile clasts are tightly grouped, with a mean direction that approximates the expected GAD for Ascension (Figure 4.9c). High-T components are grouped and their mean direction approximates the expected reversed GAD for Ascension (Figure 4.9c). Directions of low-T components for lithic clasts from MVA2 are random, however in most lithic clasts, bulk susceptibility increases significantly on heating, suggesting that they have unstable mineralogies.

Units MRP2, MRP3 and MVA1 are comprised mainly of clasts for which no magnetic components can be resolved and hence statistics cannot be calculated for these units. Bulk susceptibility for these clasts increases significantly on heating, suggesting that they have unstable mineralogies.

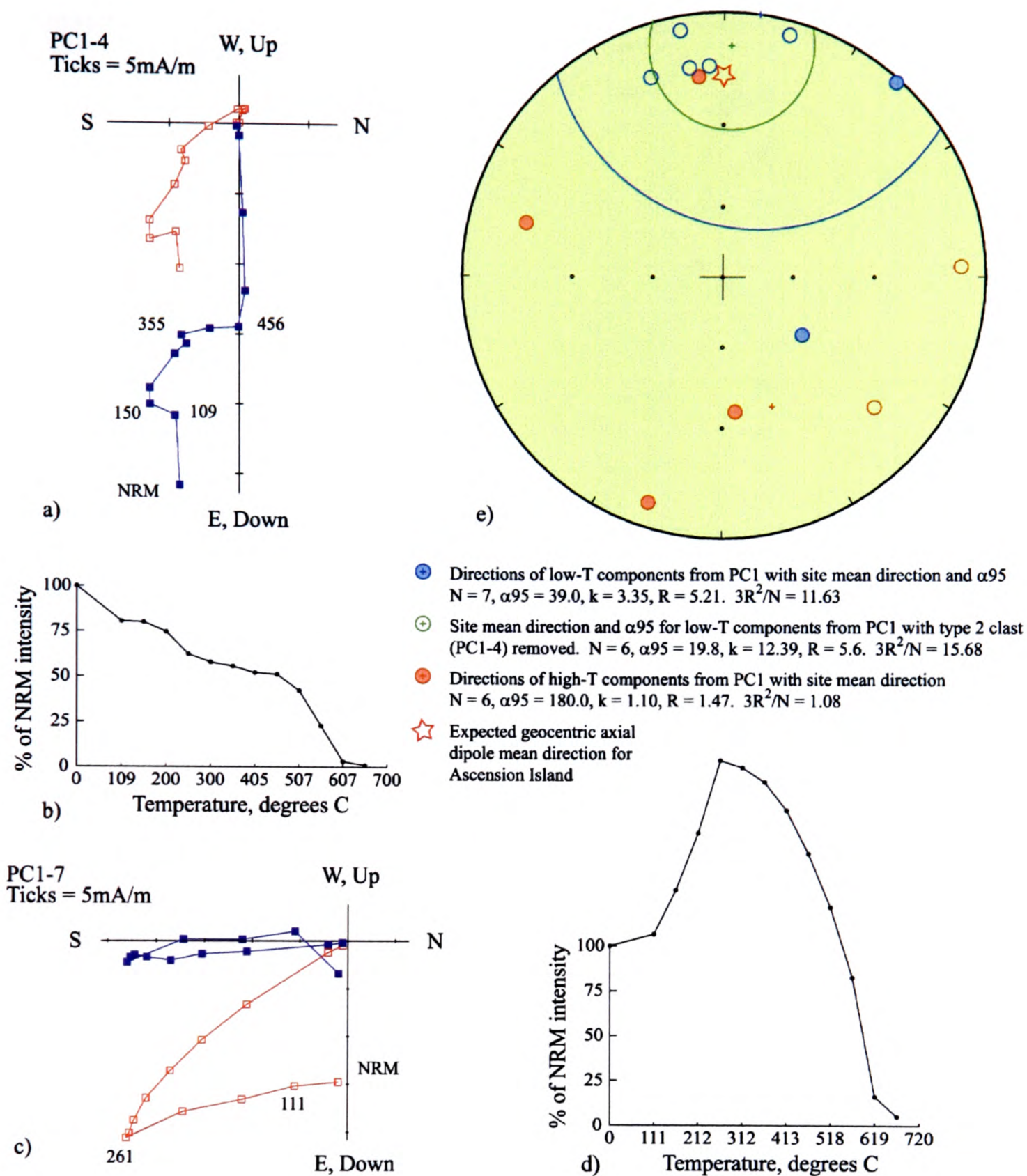


Figure 4.7: Zijderveld plots, T_b spectra and equal area stereoplot for lithic clasts from PC1. PC1-7 displays type 1b remanence behaviour (Table 3.2, plot c), which is typical of clasts from PC1. T_e for PC1-7 is $\sim 261^\circ\text{C}$. PC1-4 displays atypical (type 2c) behaviour (plot a). Points represent heating steps of 50°C except where indicated otherwise and temperatures have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for PC1-7 (plot d) shows an apparent increase in intensity from 0°C to 261°C , but this is due to the tracking of the low-T component away from the origin (see c). The major decrease in intensity occurs at $\sim 675^\circ\text{C}$, suggesting that remanence is carried by haematite (type C1 behaviour, Table 3.3). The T_b spectrum for PC1-4 (plot b) is two-phase (type E2; Table 3.3), with decreases in intensity seen at 250°C and 607°C , suggesting that remanence is carried by titanomagnetite and maghaemite. The decrease in intensity between 0°C and 100°C is inferred to represent the removal of a lab-induced VRM and does not therefore reflect the mineralogy of the clast. Plot c) shows the distribution of individual low-T and high-T components for clasts from PC1, with site mean directions (small crosses) and $\alpha 95$ values (large circles). Low-T directions are grouped, but grouping is poor. However, if the type 2 clast (PC1-4) is excluded from the analysis, grouping is significantly tighter and the site mean direction approximates the expected GAD for Ascension. Directions of high-T components are random. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

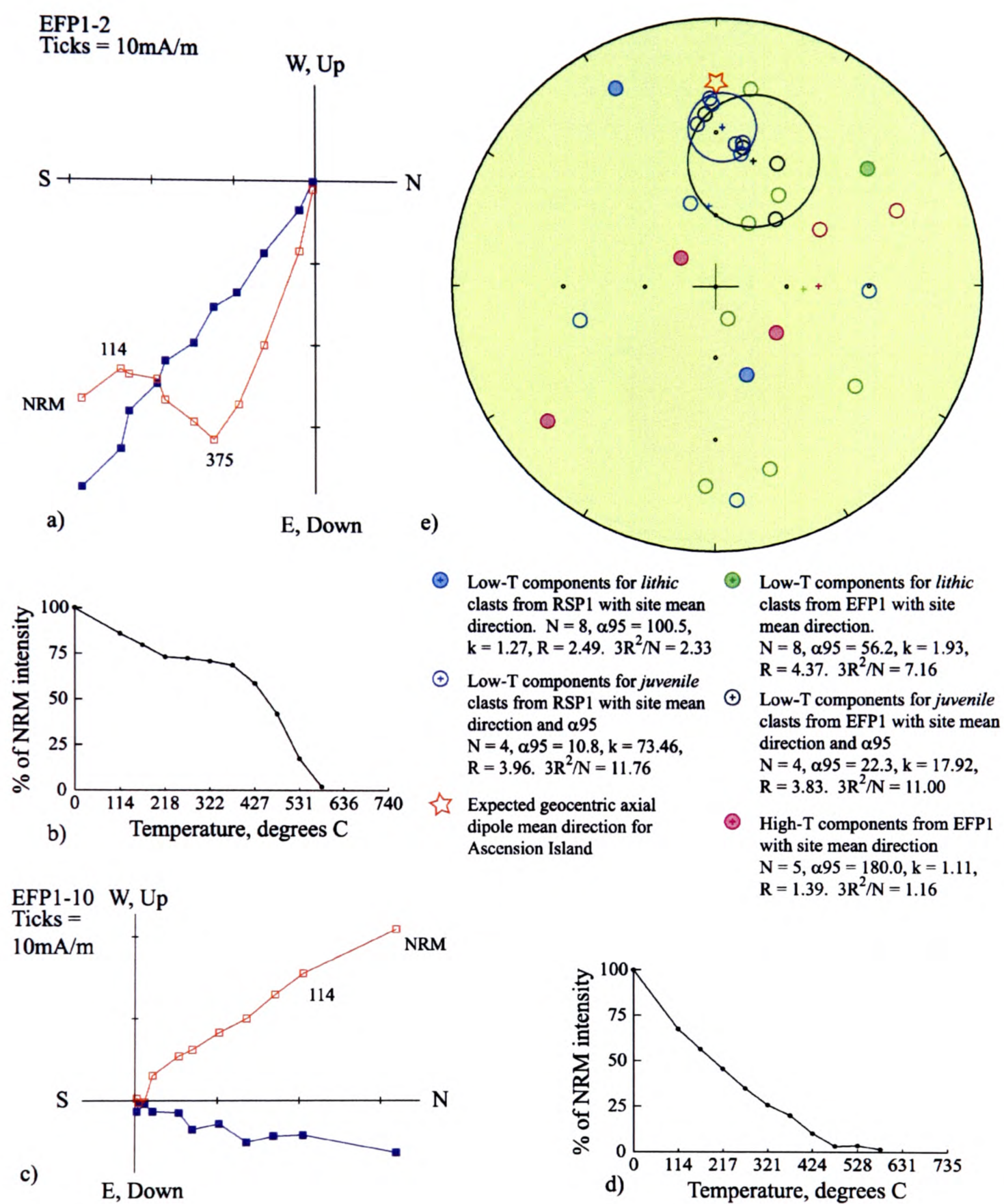


Figure 4.8: Zijderveld plots, T_b spectra and equal area stereoplot for airfall deposits (EFP1 and RSP1) in which lithic clasts display type 2 remanence behaviour and juvenile clasts display type 1 remanence behaviour (Table 3.3). EFP1-2 (a lithic clast) displays type 2b remanence behaviour (Table 3.2; plot a). The 'relict' T_e for EFP1-2 is $\sim 375^\circ\text{C}$. EFP1-10 (a pumice clast) displays type 1a remanence behaviour (Table 3.2; plot c). Points represent heating steps of 50°C except where indicated otherwise and temperatures have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for EFP1-2 (plot b) is two-phase, with decreases in intensity at $\sim 218^\circ\text{C}$ and $\sim 580^\circ\text{C}$, suggesting that remanence is carried by titanomagnetite and magnetite. The T_b spectrum for EFP1-10 (plot d) is single-phase and intensity is reduced to $\sim 1\%$ of the NRM value at $\sim 470^\circ\text{C}$, suggesting that remanence is carried by titanomagnetite (type D2 behaviour; Table 3.3). Plot c) shows the distribution of low-T and high-T components from lithic and juvenile clasts from EFP1 and RSP1, with site mean directions (small crosses) and α_{95} values (large circles). Low-T directions for lithic clasts are random, however low-T directions for juvenile clasts are grouped. Directions of high-T components for lithic clasts are random. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

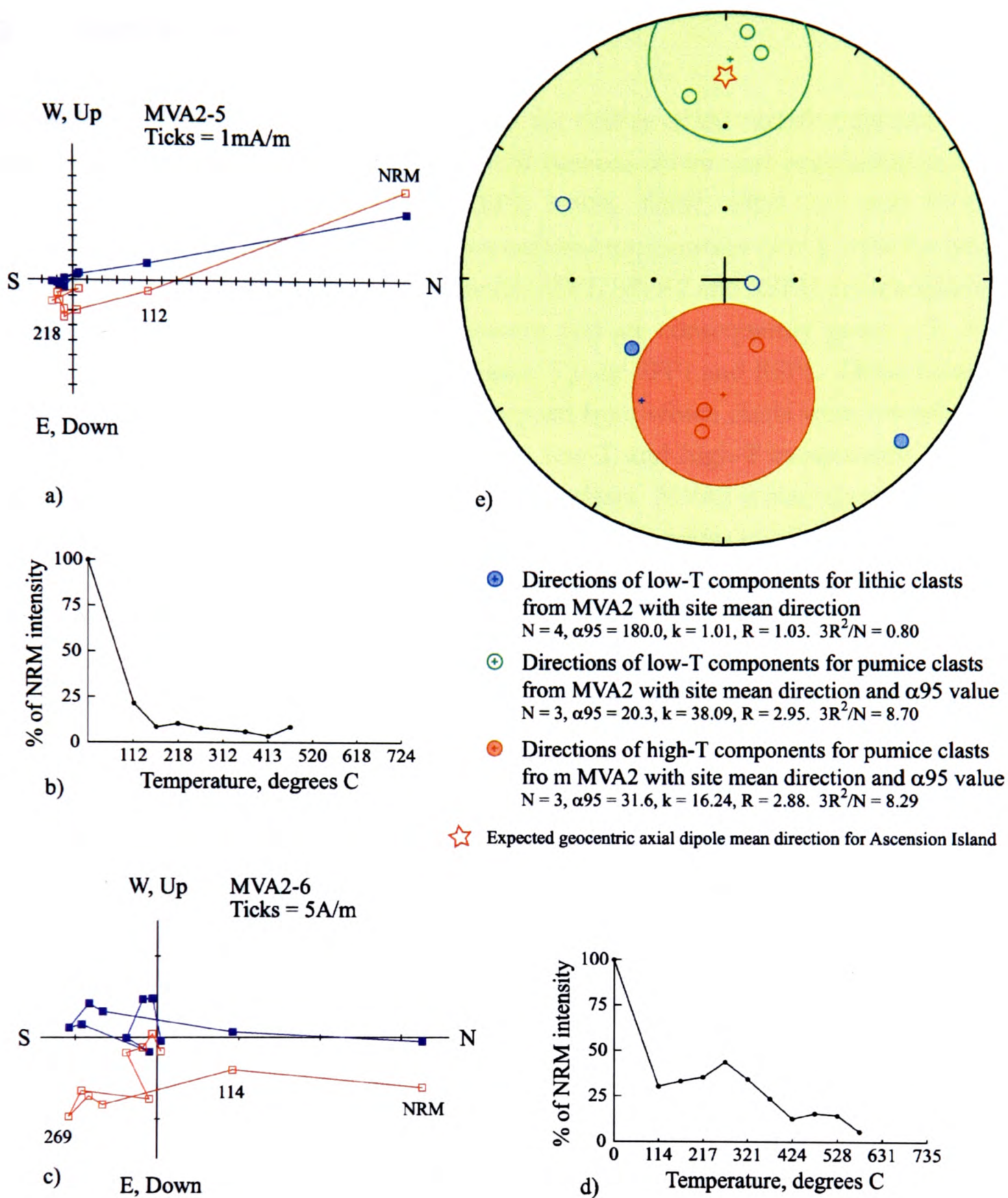


Figure 4.9: Zijderveld plot, T_b spectra and equal area stereoplot for clasts from MVA2. Plots a) and c) show juvenile clasts from MVA2, which exhibit a normal polarity low-T component that persists to ~218–260°C (inferred to be a CRM overprint), and a reversed polarity high-T component (inferred to be the primary component). High-T components are poorly developed and are typically almost entirely overprinted by the low-T component. Points represent heating steps of 50°C except where indicated otherwise and temperatures have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for MVA2-5 (plot b) displays type E3 behaviour (Table 3.3), with a sharp drop in intensity seen between 0°C and 165°C followed by a gradual decrease to ~1% of the NRM value by ~413°C. Remanence is inferred to be carried by titanomagnetites of two different compositions. The T_b spectrum for MVA2-6 is complex (type G, Table 3.3), suggesting that remanence is carried by a number of phases. Plot c) shows the distribution of individual low-T and high-T components for lithic and pumice clasts from MVA2, with site mean directions (small crosses) and α_{95} values (large circles). Low-T directions for pumice clasts are tightly grouped and the site mean direction approximates the expected GAD for Ascension. High-T directions for pumice clasts are grouped and their mean direction approximates the reverse of the expected GAD for Ascension. Low-T directions for lithic clasts are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

4.2 EMPLACEMENT TEMPERATURES

Emplacement temperatures can be estimated for twelve of the airfall units sampled on Ascension (no estimate can be made for unit S1 because of low clast population and noisy data). Eight of these units (GMP1, NEP1, MVS1, NRS1, PBS1/2/3 and PC1) are interpreted as having been emplaced above ambient temperature ('hot'), with T_e s ranging from 175°C to >580°C (Table 4.1). Three units (EFP1, MVA2 and RSP1) are interpreted as having been emplaced at ambient temperature and are consequently given a T_e of 0°C (Table 4.1). Values in brackets represent 'relict' T_e s for EFP1 and RSP1. These values are inferred to represent the average T_e of the deposit from which clasts were reworked and are calculated from the break-points between low-T and high-T components in multi-component type 2 (randomly orientated, i.e. cold) clasts. MVA2 is also given a secondary T_e , which represents the temperature to which CRM overprints persist in juvenile clasts. Two possible values for T_e are given for RP1: 1) 0°C, which assumes that the low-T components from RP1 are VRMs and hence that the unit was emplaced cold, and 2) 190°C, which assumes that low-T components are TRMs and hence that the unit was emplaced hot and was subsequently disrupted (after deposition and cooling).

FELSIC AIRFALLS		MAFIC AIRFALLS	
site	average T_e , °C	site	average T_e , °C
EFP1	0 (211)	MVS1	>580
GMP1	210	NRS1	350
MVA2	0, 211 ^c	PBS1	418
NEP1	175	PBS2	322
RP1	0/190	PBS3	273
RSP1	0 (326)	PC1	325

Table 4.1: Estimates of equilibrium emplacement temperature for airfall deposits sampled on Ascension. Units that are inferred to have been emplaced at ambient temperature are given a T_e of 0° (although *sensu stricto* T_e should = ambient temperature). Values in brackets represent relict T_e s (i.e. the T_e of the source deposit). ^c represents the temperature to which CRM overprints persist in MVA2. Two possible values for T_e are shown for RP1, reflecting the two possible origins for low-T components (and hence for the unit).

Emplacement temperatures for the (hot) felsic airfall units shown in Table 4.1 are similar (only 35°C difference is seen between the hottest and coolest units) and are relatively low. However, it is likely that higher T_e s are displayed by some of the felsic airfall units on Ascension, especially close to the volcanic vent, where partial welding may be displayed (Section 2.2.1.2). The extent of welding in airfall deposits increases with column height, grain size and magmatic temperature, but proximal welding of silicic and intermediate deposits is only developed where magmatic temperature is >850°C (Thomas and Sparks,

1992). Assuming the felsic airfall deposits on Ascension were erupted at similar temperatures, significant cooling must have occurred to result in emplacement temperatures as low as those recorded in Table 4.1 (however, it should be noted that felsic airfalls may weld more easily than silicic airfalls because of their more alkaline composition).

The hot mafic airfall units shown in Table 4.1 typically display higher T_e s than their felsic equivalents, reflecting the higher eruption temperature of mafic magmas. Over 300°C difference is seen in the T_e s of the hottest and coolest units (Table 4.1), suggesting that the individual mafic eruptions may have been more variable than felsic eruptions (e.g. in terms of column height).

4.3 MAGNETIC MINERALOGY

Clasts from Ascension airfall deposits display varied magnetic mineralogies. Blocking temperature (T_b) spectra for the majority of clasts are well distributed (e.g. Figure 4.3b), allowing all magnetic components to be isolated. However, in some clasts, demagnetisation occurs over a narrow temperature range, producing a *discrete* T_b spectrum. In these clasts, the isolation of all magnetic components may not be possible.

In this thesis, magnetic mineralogy is determined using mainly T_b spectra. T_b spectra have been classified according to their shape and to the temperature(s) at which the major decreases in intensity are seen, i.e. the T_c (s) that they display (see Table 3.3, Section 3.6.3). Spectra **types A to D** are single-phase, with T_c s of ~580°C (magnetite), 590°C-675°C (maghaemite), •675°C (haematite) and <580°C (titanomagnetite) respectively. **Type E** spectra are two-phase, with a lower T_c (titanomagnetite) phase plus one or two higher T_c phase(s). **Type F** spectra exhibit a sharp drop in intensity (T_{cl}) in the first few demagnetisation steps (i.e. over the temperature range 0°C to ~200°C), followed by one or two higher T_c phases. **Type G** spectra are three-phase or more complicated. A summary of the different types of T_b spectra displayed by clasts from felsic and mafic airfall deposits from Ascension is shown in Table 4.2.

Comparison of T_b spectra with temperature-dependent susceptibility (high-T χ) data for clasts from pyroclastic deposits sampled on Ascension suggests that in most cases, the T_b spectrum provides a reliable estimate of magnetic mineralogy (Section 3.6.3). Many clasts from Ascension airfall deposits display multi-phase T_b spectra (types E, F or G; Table 3.3, Table 4.2) and in general, these are inferred to reflect multi-phase magnetic mineralogies.

4.3.1 Felsic airfalls

One hundred and sixty-seven clasts from felsic airfalls were thermally demagnetised in the laboratory. Eighty-four percent of clasts display distributed T_b spectra, whilst 16%

FELSIC AIRFALLS		MAFIC AIRFALLS		INTERPRETATION
T _b spectra type	% of clasts	T _b spectra type	% of clasts	(mineralogy)
A	12	A	21	single-phase magnetite
B	14	B	7	single-phase maghaemite
C	1	C	5	single-phase haematite
D	6	D	13	single-phase titanomagnetite
E	35	E	30	two-phase
F	19	F	21	two/three phase (low T _c)
G	4	G	0	three+ phase

Table 4.2: Summary of T_b spectra types for clasts from felsic and mafic airfall deposits sampled on Ascension (with basic interpretation).

display discrete T_b spectra. NRM intensities range from 0.5mA/m to 9.4A/m for lithic clasts and from 0.01mA/m to 140mA/m for pumice clasts. Maximum unblocking temperatures range from 211°C to 690°C, however the most common maximum unblocking temperature is 580°C, suggesting that magnetite is the most ubiquitous magnetic mineral in clasts from felsic airfall deposits.

A summary of the different types of T_b spectra displayed by clasts from felsic airfalls is shown in Table 4.2. Thirty-three percent of clasts display single-phase T_b spectra (demagnetisation types A, B, C and D, Table 4.2), suggesting that they have single-phase mineralogies. In 58% of clasts, T_b spectra are multi-phase (demagnetisation types E, F and G, Table 4.2), suggesting that remanence is carried by more than one mineral phase. In the remaining 9% of clasts, demagnetisation spectra cannot be classified due to noisy data.

The most common demagnetisation behaviour displayed by clasts from felsic airfalls is type E (Table 3.3; e.g. Figure 4.2b; 35% of clasts). The two-phase nature of T_b spectra for these clasts suggests that remanence is carried by two mineral phases: a titanomagnetite phase, plus magnetite (type E1; 27 clasts), maghaemite (type E2; 20 clasts), a second titanomagnetite (type E4; 6 clasts) or haematite (type E3; 5 clasts). The composition of the titanomagnetite phase can be approximated from its T_c using a graph of T_c v titanium content (see Section 3.5.1, Figure 3.9). According to T_b spectra data, high-titanium (low T_c) titanomagnetites have T_cs ranging from 534°C to 114°C, suggesting compositions of TM08 to TM69. Low-titanium (high T_c) titanomagnetites have T_cs ranging from 552°C to 211°C, suggesting compositions of TM05 to TM57 (from Figure 3.9).

Next most common is type F demagnetisation behaviour (Table3.3), which is displayed by 19% of clasts (e.g. Figure 4.9b). These clasts display a multi-phase T_b spectrum, with a sharp decrease in intensity in the first few steps of demagnetisation (between 0°C and ~200°C). This behaviour can generally be attributed to the removal of a high-titanium (low T_c) titanomagnetite phase (composition TM58 to ~TM70; estimated from Figure 3.9).

However, alteration products such as goethite may also demagnetise over this temperature range (see Table 3.1). In some cases, the drop in intensity may simply represent the removal of a lab-induced viscous component that does not correspond to the magnetic mineralogy of the sample (e.g. Figure 4.7b, see Section 3.6.3).

In most type F clasts, comparison of T_b spectra, high-T χ and vector component plots substantiates the presence of a high-titanium titanomagnetite phase. In these clasts, the initial sharp decrease in intensity typically corresponds to the removal of a low-T CRM overprint. This suggests that CRM overprints are carried by high-titanium titanomagnetite in these clasts. This behaviour is also displayed by clasts from reworked parts of the Pourahu deposit, Ruapehu volcano, New Zealand (Section 3.7.4.3).

Type A and B demagnetisation behaviour (Table 3.3) are displayed by 12% and 14% of clasts respectively (e.g. Figure 4.5b). These clasts display a single-phase T_b spectrum with intensity reduced to ~1% of the NRM value at ~580°C (A), suggesting that remanence is carried by magnetite, or between ~590°C and 675°C (B), suggesting that remanence is carried by maghaemite.

Type D demagnetisation behaviour (Table 3.3) is displayed by 6% of clasts (e.g. Figure 4.8d). These clasts display a single-phase T_b spectrum with intensity reduced to ~1% of the NRM value before 580°C, suggesting a titanomagnetite mineralogy.

Four percent of clasts display a three-phase or more complex T_b spectra (type G demagnetisation behaviour; Table 3.3; e.g. Figure 4.9d). This is inferred to reflect a three-phase or more complex mineralogy.

Type C demagnetisation behaviour (Table 3.3) is displayed by just 1% of clasts from felsic airfalls. These clasts display single-phase T_b spectra with intensity reduced to ~1% of the NRM value at or above 675°C (e.g. Figure 4.7d). Remanence in these clasts is inferred to be carried by haematite.

4.3.2 Mafic airfalls

Sixty-one clasts from mafic airfalls were demagnetised in the laboratory. Sixty-seven percent of these display distributed T_b spectra, whilst 34% display discrete T_b spectra. NRM intensities range from 8mA/m to 9A/m for lithic clasts and from 8.5mA/m to 11.6A/m for scoria clasts. Maximum unblocking temperatures range from 404°C to 680°C, however full demagnetisation of clasts most commonly occurs at ~580°C, suggesting that magnetite is the most ubiquitous magnetic mineral in these clasts.

Table 4.2 summarises the different types of T_b spectra displayed by clasts from mafic airfalls (according to the classification shown in Table 3.3). Forty-six percent of clasts

display single-phase T_b spectra and 51% display multi-phase T_b spectra. In 3% of clasts, noisy data preclude the classification of T_b spectra.

Type E demagnetisation behaviour (Table 3.3) is most common in clasts from mafic airfalls (30% of clasts; Table 4.2; e.g. Figure 4.4b). These clasts display a two-phase T_b spectrum comprising a low T_c phase ($T_c < 580^\circ\text{C}$) plus a higher T_c phase, which is inferred to reflect a two-phase mineralogy, with remanence carried by a titanomagnetite phase plus magnetite, maghaemite, haematite or an additional titanomagnetite phase. T_b spectra data suggest that titanomagnetite phases have T_c s ranging from 522°C to 199°C , suggesting titanomagnetite compositions of TM11 to TM58 (estimated from Figure 3.9).

Next most common demagnetisation behaviours are type A and type F (Table 3.3), each displayed by 21% of clasts. T_b spectra for type A clasts are single-phase and clasts fully demagnetise at $\sim 580^\circ\text{C}$ (e.g. Figures 4.5b, 4.6b), suggesting a magnetite mineralogy. T_b spectra for type F clasts are multi-phase, displaying a sharp decrease in intensity between 0°C and $\sim 200^\circ\text{C}$, and clasts are inferred to possess a low-T CRM overprint, carried by high-titanium titanomagnetite (plus further magnetite, maghaemite, haematite or titanomagnetite phases).

Type D demagnetisation behaviour (Table 3.3) is displayed by 13% of clasts. Type D T_b spectra are single-phase and are fully demagnetised before 580°C , suggesting that remanence is carried by titanomagnetite. T_b spectra data suggest that titanomagnetite phases have Curie temperatures ranging from 548°C to 404°C , suggesting titanomagnetite compositions of TM06 to TM30 (estimated from Figure 3.9).

Type B and C demagnetisation behaviour (Table 3.3) are displayed by 7% and 5% of clasts respectively (Table 4.2). Both types of T_b spectra are single-phase. Type B clasts fully demagnetise between $\sim 590^\circ\text{C}$ and $\sim 675^\circ\text{C}$, suggesting that remanence is carried by maghaemite and type C clasts fully demagnetise only at or above $\sim 675^\circ\text{C}$, suggesting that remanence is carried by haematite.

4.3.3 Magnetic mineralogy and VRM

Over 50% of clasts from Ascension airfall deposits display a mixed mineralogy. Only a small number of clasts possess a high-titanium titanomagnetite mineralogy (i.e. $T_c \leq 200^\circ\text{C}$). These typically do not show a VRM component.

4.4 SECULAR VARIATION

Site mean directions for the felsic and mafic airfall units sampled on Ascension for palaeomagnetic analysis are shown in Figures 4.10 and 4.11. Felsic units are divided over two plots because of the large number of sites.

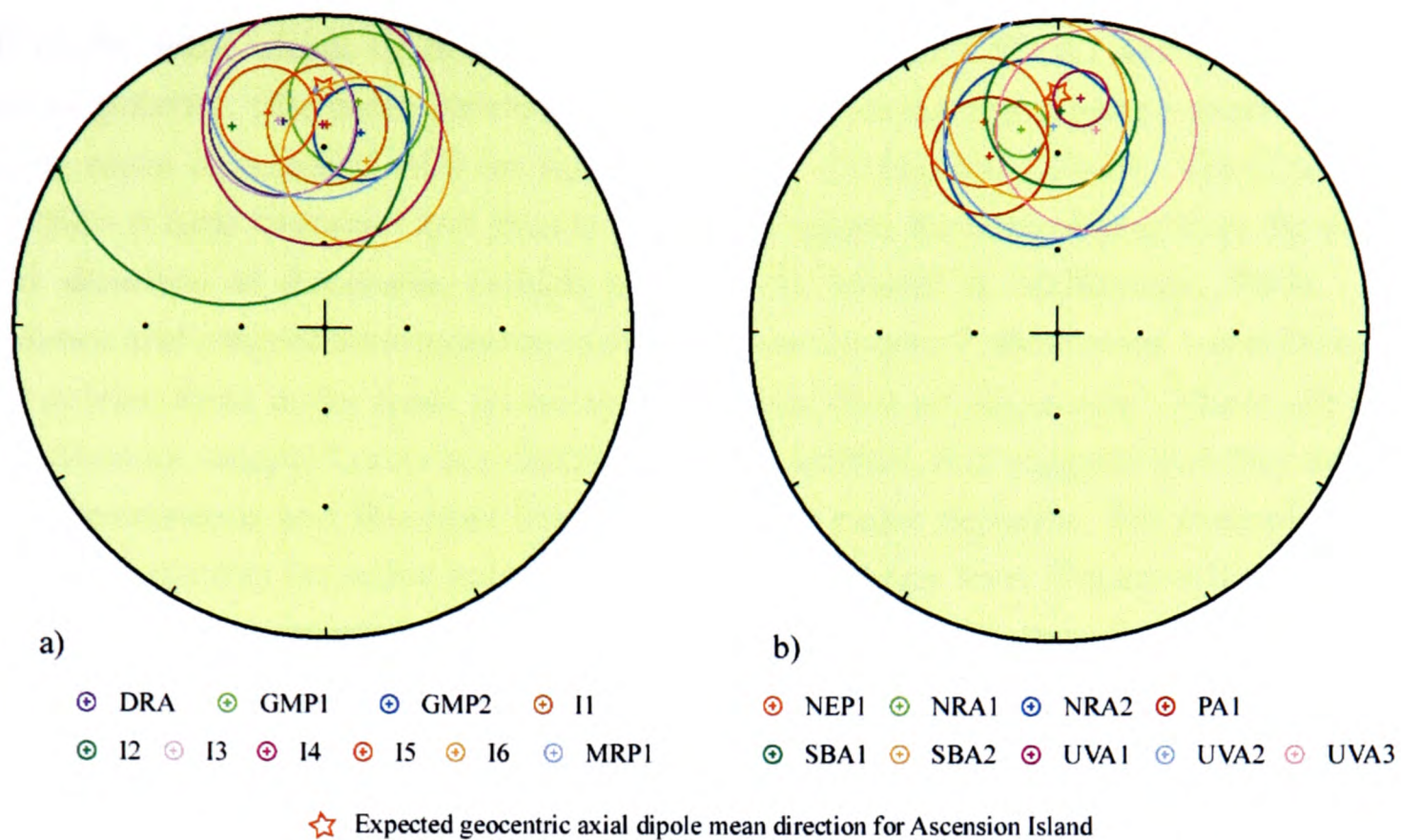


Figure 4.10: Equal area stereoplots showing (low-T) site mean directions (small crosses) for felsic airfall deposits sampled on Ascension for palaeomagnetic analysis, with α_{95} values (circles). Units are divided into two groups for ease of presentation. Mean directions for most sites approximate expected GAD for Ascension. Large α_{95} values mean that few sites can be distinguished from one another at the 95% confidence level. All shapes represent points on the upper hemispheres of the stereoplots.

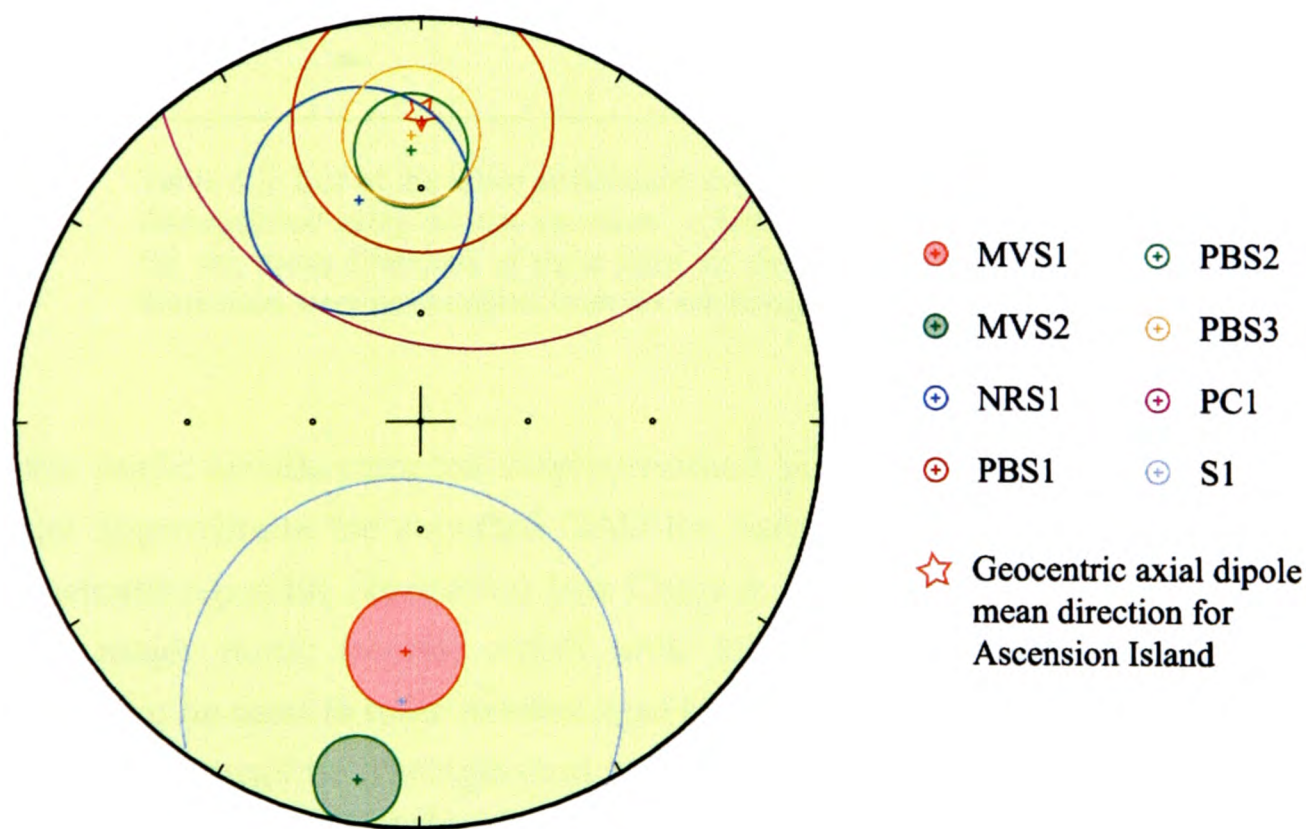


Figure 4.11: Equal area stereoplots showing (low-T) site mean directions (small crosses) for the mafic airfall deposits sampled on Ascension for palaeomagnetic analysis, with α_{95} values (circles). Mean directions for normally magnetised units approximate the expected GAD for Ascension and cannot be distinguished from one another at the 95% confidence level. Mean directions for reversed sites deviate from the expected reversed GAD for Ascension by up to 15°. Units MVS1 and MVS2 are distinct from one another but not from S1. Open and filled circles represent areas on the upper and lower hemispheres of the stereoplots respectively.

All of the felsic airfall units sampled on Ascension except MVA1 and MVA2 display normal polarity. Site mean directions typically approximate the expected geocentric axial dipole mean direction (GAD) for Ascension (000/-15; Figures 4.10a,b). The GAD mean direction is time averaged and thus is more appropriate for comparison than the present field direction at Ascension (which is ~017/-35; Merrill & McElhinny, 1983). Field evidence and magnetostratigraphic correlation (see Chapter 7, Enclosures 1 and 2) suggest that at least three major felsic (pumice) airfall units exist on Ascension. Where site mean directions for sampled units are distinct from one another, this suggests that they are non-contemporaneous and therefore belong to separate major deposits. For example, GMP2 and I5 are distinct from one another at the 95% confidence level (Figure 4.10a; Table 4.3) and are therefore interpreted *not* to belong to the same major deposit. Similarly, GMP2 and UVA1 are distinct from NRA1 and from PA1, and UVA1 from NEP1 (Table 4.3). However, in many cases, secular variation cannot be used to distinguish between felsic airfall units as their site mean directions *cannot* be distinguished from one another.

unit	≠	unit	≠	unit	≠	unit	≠	unit
				I5	≠	UVA1		
		GMP2	≠	I5				
NRA1	≠	GMP2				UVA1	≠	NRA1
		GMP2	≠	PA1				
				PA1	≠	UVA1		
						UVA1	≠	NEP1

Table 4.3: List of the felsic airfall units sampled on Ascension that can be distinguished using secular variation. ≠ between two units indicates that the site mean directions of these units are distinct from one another (i.e. these units were not sampled from the same major deposit).

Five of the mafic airfalls sampled display normal polarity and site mean directions for these units approximate the expected GAD for Ascension (Figure 4.11). Field evidence and magnetostratigraphic correlation (see Chapter 7, Enclosures 1 and 2) suggest that at least three major mafic (scoria) airfall units exist on Ascension. However, secular variation cannot be used to infer relative ages for the normal mafic units sampled, as their mean directions cannot be distinguished at the 95% confidence level. Three of the mafic airfall units sampled display reversed polarity (Figure 4.11), suggesting that they were deposited before the most recent magnetic reversal (~0.78Ma; Cande and Kent, 1995). An alternative explanation is that they were deposited during a short-lived reversal event within the normal Brunhes chron (see Section 3.6), however magnetostratigraphic correlation (Chapter 7) suggests that the reversal recorded in the stratigraphy represents the Brunhes-Matuyama boundary and hence that the reversed polarity mafic airfall units sampled on Ascension are older than 0.78Ma. Unit S1 cannot be distinguished from

MVS1/2 at the 95% confidence level, but MVS1 and MVS2 are distinct from one another implying that they belong to individual scoria units. This concurs with field evidence that shows that MVS1 lies stratigraphically above MVS2, within the pyroclastic sequence of Middleton's Valley (see Section 5, Enclosure 1) and is hence younger.

4.5 GEOCHEMISTRY

Pumice airfall units are exposed at several different locations on Ascension Island. Field evidence suggests that each of these units belong to one of a number of *major* pumice deposits that are exposed across the island (see Enclosure 1). Samples were taken for XRF analysis from thirty individual airfall units on Ascension, in order to differentiate between and categorise them as part of one of these major deposits, on the basis of their geochemistry. Major element analysis (from whole rock data) suggests that the majority of the felsic airfall units sampled are trachytic in composition (Figure 4.12; see Appendix E for XRF data). This concurs with the work of previous authors such as Nielson and Sibbett (1996), Weaver et al. (1996) and Kar et al. (1998). Scoria airfalls have basaltic or trachybasalt compositions (see Figure 4.12; Appendix E).

The felsic airfall units sampled for XRF can be divided into two categories on the basis of their trace element geochemistry: units that display relatively low Ba and Sr values (the majority) and units that display higher Ba and Sr values (the 'atypical' pumices). Figure 4.13 shows trace element signatures for units that display relatively low Ba and Sr values (values have been chondrite normalised using chondrite values of McDonough and Sun, 1995 and Sun and McDonough, 1989). All of the units display similar trace element signatures (Figure 4.13) and hence cannot be distinguished further using geochemistry. However, field relationships (see

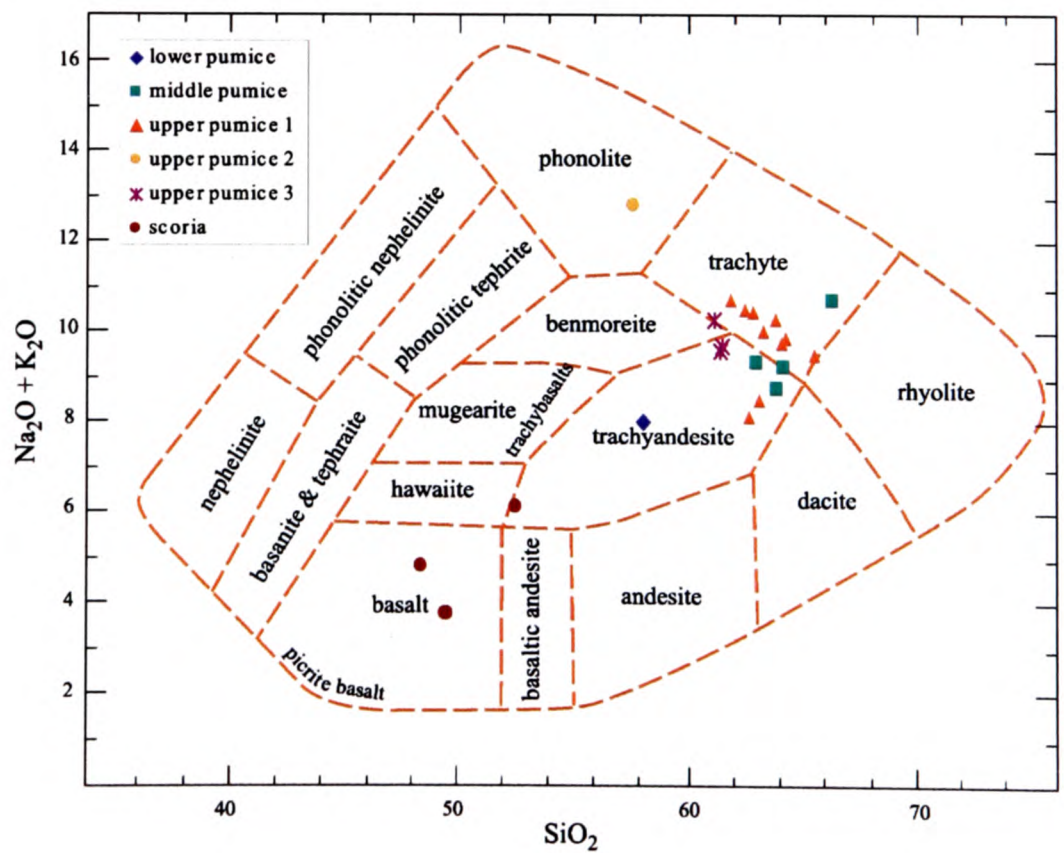


Figure 4.12: Silica v total alkalis diagram showing fields in which different types of volcanic rock plot (after Cox et al., 1979). Superimposed are compositions of some of the mafic (scoria) and felsic (pumice) airfall deposits sampled on Ascension for XRF analysis. The majority of felsic airfalls lie in or close to the trachyte field and the scoria airfalls are basaltic or trachybasaltic in composition. Field areas are approximate.

Enclosure 1) suggest that these units were sampled from two major airfall deposits: the *Upper Pumice 1* (Figure 4.13a) and the *Middle Pumice* (Figure 4.13b). Some of the units that are interpreted as part of the Upper Pumice 1 deposit (e.g. DRA, I4 and I6) display slightly higher Ba values than the rest of the units and variation is also seen in values of Sc, Co

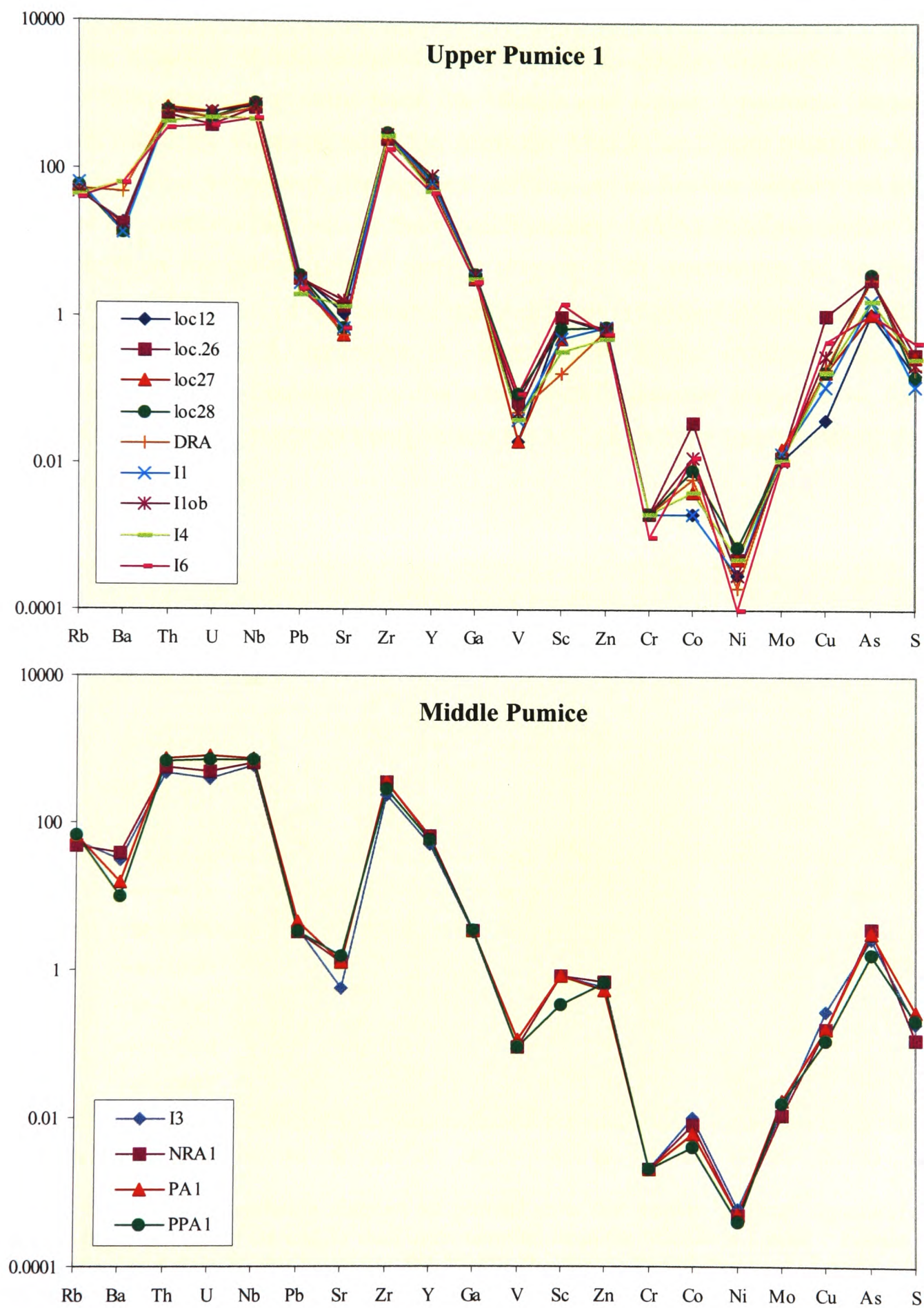


Figure 4.13: Trace element variation diagram for airfall units sampled on Ascension that are inferred to belong to: a) the Upper 1 Pumice and b) Middle Pumice deposits. Units from both major deposits display similar trace element signatures. Some variation is seen in the values of Ba, Sc, Co and Cu between samples from the same major deposit. Values are in ppm and have been chondrite-normalised using chondrite values of McDonough and Sun (1995) and Sun and McDonough (1989).

and Cu between samples (Figure 4.13a). The Ba content of samples may vary according to their alkali feldspar content, however the variation in Ba (and other elements) observed in Upper Pumice 1 samples is in keeping with field evidence (such as variation in lithic content and grain size with height, stratification, and the presence of ash layers; see Chapter 2) that suggests that both the Middle Pumice and Upper Pumice 1 are comprised of several individual fall units (which may vary slightly in geochemistry).

The remaining 'atypical' airfalls sampled for XRF analysis display distinctly higher values of Ba and Sr than are seen in units from the Middle and Upper 1 pumices (Figure 4.14). This suggests that they were *not* sampled from the Middle or Upper pumices, but from other major deposits. Moreover, the 'atypical' airfalls can be further subdivided into three further major deposits on the basis of their geochemistry: MVA2 displays higher V and Sr and lower Sc than the other atypical airfalls (Figure 4.14) supporting its interpretation from field evidence as part of the *Lower Pumice* deposit (reversed polarity pumice airfall seen in Sections 4, 5 and 8, Enclosure 1). In addition, MVA2 exhibits a similar trace element pattern to those displayed by the scoria airfall deposits sampled on Ascension (see Figure 4.15), and the major element values for MVA2 plot between those of the scoria

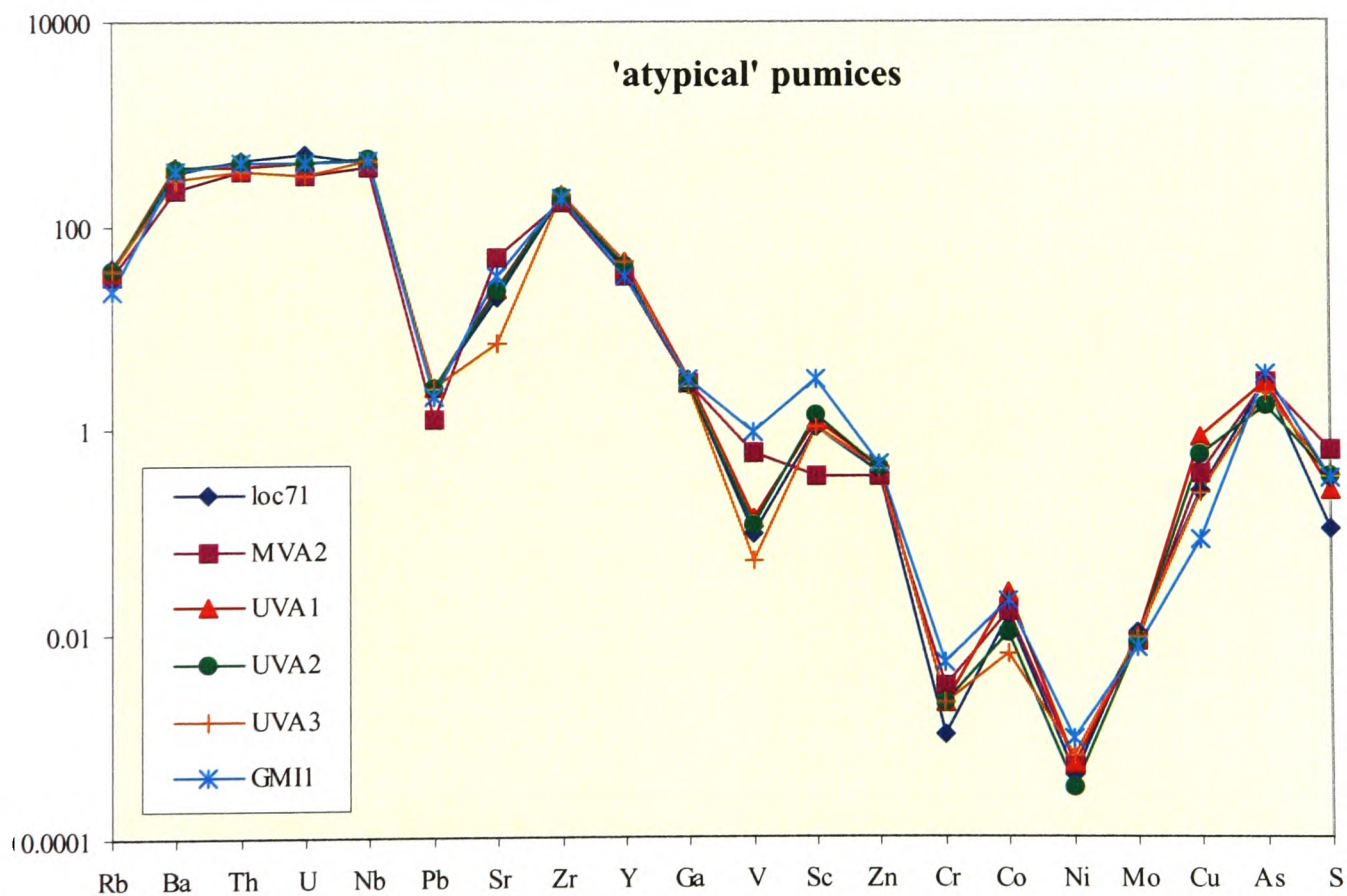


Figure 4.14: Trace element variation diagram for pumice units that display 'atypical' signatures. These units display higher values of Ba and Sr than units sampled from the Middle or Upper 1 Pumice (Figure 4.13), suggesting that they do *not* belong to the Middle Pumice or Upper Pumice 1 deposits, but were sampled from distinctly different pumice airfall deposits. These are interpreted as: the *Lower Pumice*, represented by MVA2 (which displays a slightly different signature to the other units here; higher V and Sr and lower Sc), the Upper Pumice 2, represented by UVA1, UVA2 and loc. 71, and the Upper Pumice 3, represented by UVA3, which also displays a slightly different signature to the other units (i.e. lower Sr). Also included here is the trace element signature for unit GM11 (Green Mountain ignimbrite), which is similar to that of the units interpreted as the Upper Pumice 2. Values are in ppm and have been chondrite-normalised using chondrite values of McDonough and Sun (1995) and Sun and McDonough (1989).

airfalls and the Middle/Upper 1 pumices, suggesting that MVA2 has an intermediate, trachyandesite composition. The ignimbrite unit GMI1 (which is included in Figure 4.14) shows a similar trace element pattern and hence may also be transitional in composition. Units UVA1, UVA2 and loc.71 (which was sampled at Turtle's Back; see Figure 1.8) display similar patterns to one another (but lower V and Sr and higher Sc than MVA2; Figure 4.14), suggesting that they represent a fourth individual major airfall deposit: the *Upper Pumice 3* (see Enclosure 2). UVA3 displays distinctly lower Sr (and slightly lower V and Co) than any of the other atypical airfall units (Figure 4.14) and is therefore interpreted to represent a fifth major airfall unit: the *Upper Pumice 2*. These data also support field evidence that shows that UVA3 lies stratigraphically below UVA1/2 (i.e. the *Upper Pumice 3*; see Sections E and F; Enclosure 2).

The scoria airfall units sampled on Ascension can be divided into three categories based on variations in their trace element geochemistry (Figure 4.15). Units TBLS and loc. 74 exhibit almost identical trace element patterns (Figure 4.15), suggesting that they were sampled from the same major scoria airfall deposit. However, PBS1 and TBUS have higher values of Th, U, Nb (and slightly higher values of Zr and Y) and lower values of Cr, Ni and As (than TBLBS and loc. 74; Figure 4.15), suggesting that they were sampled

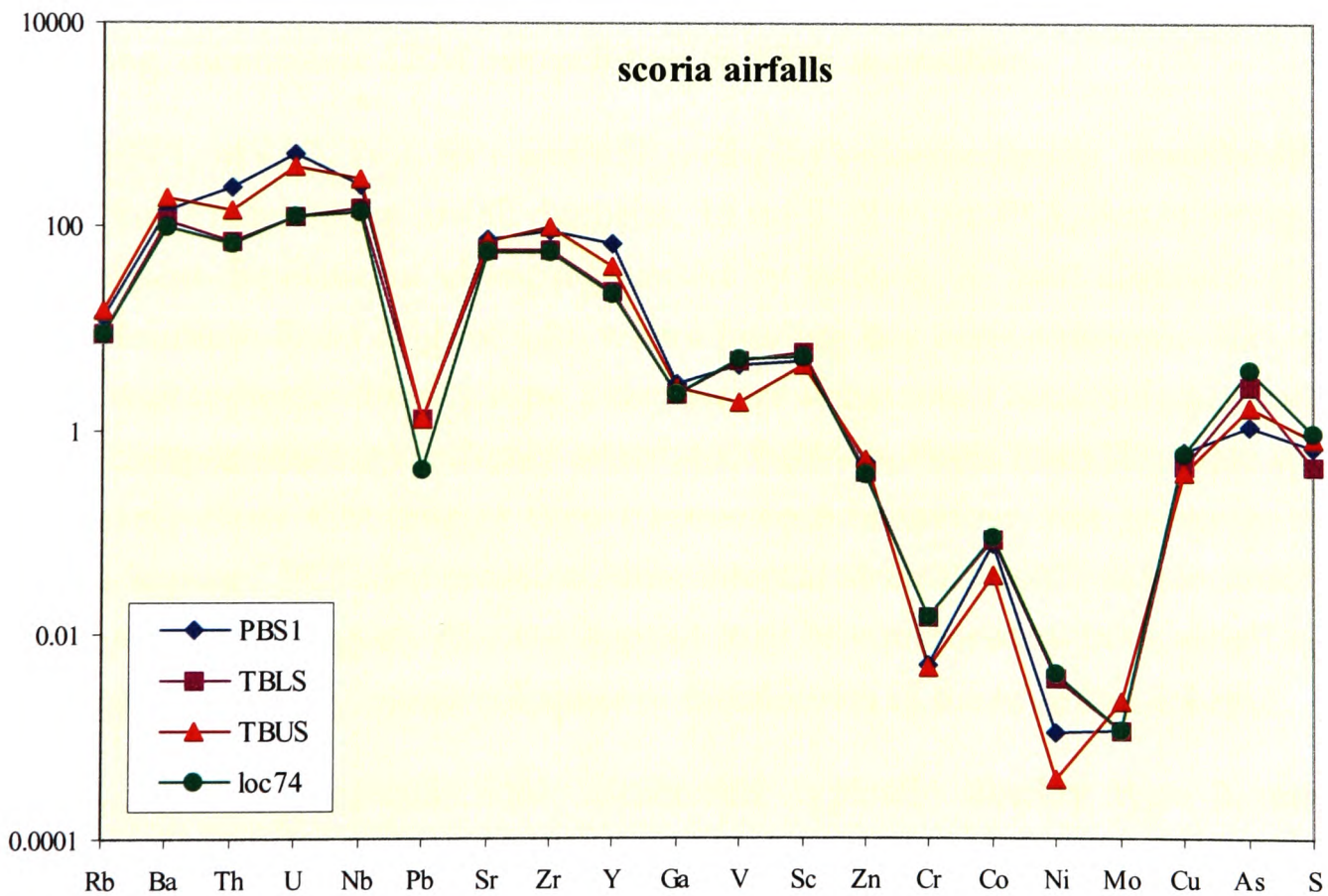


Figure 4.15: Trace element variation diagram for scoria airfall units sampled on Ascension. The units can be divided into three groups according to slight variations in their trace element signatures, suggesting that they represent three distinct major airfall deposits (see Enclosures 1 and 2). TBLS and loc. 74 comprise one group, having almost identical trace element signatures, PBS1 comprises a second group, displaying higher values of Th, U and Nb and lower values of Cr, Ni and As, and TBUS comprises the third group with higher Th, U and Nb but lower V, Co and Ni than PBS1. Values are in ppm and have been chondrite-normalised using chondrite values of McDonough and Sun (1995) and Sun and McDonough (1989).

from different major deposits. Furthermore, TBUS displays lower V, Co and Ni than PBS1 (and the other units), suggesting that TBUS and PBS1 represent two further (separate) major deposits. These data support field evidence that suggests that these units were sampled from three individual major deposits: the pumice-based scoria deposit seen in Enclosure 1 (Sections 2–4 and 8) and the two upper scoria units seen in Enclosure 2 (Section D).

4.6 CONCLUSIONS

4.6.1 Palaeomagnetic interpretations

The units discussed in this chapter were originally categorised as airfall deposits solely according to field evidence. The palaeomagnetic data presented in this chapter enable clarification of the origins of these units. In the majority of cases, palaeomagnetic data substantiate field interpretations of these units as airfall deposits. Lithic clasts typically display type 1b remanence behaviour (Table 3.2); i.e. a two-component remanence, with the low-T component lying sub-parallel to the expected (normal or reversed) GAD for Ascension and the high-T component displaying no preferred orientation. Juvenile clasts typically display type 1a remanence behaviour (Table 3.2); i.e. a single-component remanence sub-parallel to the (normal or reversed) GAD. Any deviations from type 1a remanence behaviour (in juvenile clasts) can generally be attributed to clast rotation during cooling, incomplete CRM overprinting or VRM acquisition.

Five units (EFP1, MVA2, PC1, RP1 and RSP1) display palaeomagnetic characteristics that differ from those expected of airfall deposits. In units RP1 and PC1, this is interpreted as the result of post-depositional slumping caused by faulting, as both units are located on the Green Mountain Road (Figure 1.8), where faulting has been common. RP1 contains lithic clasts that typically display type 2 remanence behaviour (Table 3.2); i.e. both low-T and high-T components are randomly orientated between clasts from the same unit. PC1 contains mainly clasts that display type 1 remanence behaviour, but grouping of low-T components is poor. PC1 also contains some internal stratification that was attributed to flow processes. This suggests that the deposit may be composed of both airfall and flow units, the latter formed by minor collapses or instabilities of the eruption column.

Units EFP1 and RSP1 contain lithic clasts that typically display type 2 remanence behaviour (Table 3.2); i.e. directions of low-T components are random between lithic clasts from the same site. This suggests that they have been reworked at ambient temperature, and they are hence re-interpreted as epiclastic deposits. Unit MVA2 also contains type 2 lithic clasts, however this is interpreted to be the result of rotation of clasts due to faulting (which has affected the sampling area) and contamination of the magnetic signal by CRM (as most clasts from MVA2 are inferred to have undergone alteration). Juvenile (pumice) clasts from MVA2 display type 1 remanence behaviour (Table 3.2), with a normal low-T

component and a reversed high-T component. The high-T reversed components displayed by pumice clasts from MVA2 are interpreted as original TRMs or CRMs, acquired soon after the deposition of MVA2 and before the most recent magnetic reversal (Brunhes-Matuyama; ~0.78Ma). This concurs with field evidence, which shows that MVA2 lies within a sequence of pyroclastic deposits that display reversed polarity (See Enclosure 1). Low-T normal components in juvenile clasts are interpreted as secondary CRMs, acquired at a much later date, i.e. some time after the B-M reversal.

4.6.1.1 Ability of juvenile material to record palaeomagnetic signals

Comparisons of palaeomagnetic data from scoria and pumice clasts sampled from Ascension airfalls suggests that pumice is a more reliable material than scoria for recording a coherent component of magnetism. Juvenile clasts of either composition are typically more weakly magnetised than lithic clasts and a large number of both pumice and scoria clasts display scattered directional data. However, comparison of juvenile clasts alone suggests that pumice clasts typically carry a more reliable signal than scoria clasts. Many scoria clasts also display a discrete blocking temperature spectrum, which can make the resolution of magnetic components difficult.

These data imply that scoriaceous material may be more readily altered than pumiceous material, causing contamination of the magnetic signal and possible loss of information. The fact that 5% of clasts from mafic airfalls contain haematite (see Table 4.2) supports this.

4.6.2 Emplacement temperatures

Analysis of emplacement temperatures of the Ascension airfall deposits reveals information about the distance travelled by the deposits and the height of the eruption column from which they were produced. Proximal deposits undergo the least amount of cooling during transport and hence are expected to have the highest T_e s, and T_e is expected to decrease with increasing distance from vent¹. However, because of the relatively small size of Ascension (~92km²), the majority of the airfall deposits sampled are interpreted to be relatively 'proximal' and hence here field evidence such as welding is the most useful guide to proximity to the volcanic vent for the airfall deposits.

The felsic airfall deposits sampled for T_e information display T_e s in the range of 175°C to 210°C. These deposits are interpreted as trachytic or rhyolitic in composition (Section 4.5; Nielson and Sibbett, 1996; Kar et al, 1998) and are therefore expected to have been erupted at temperatures of ~900°C to 1100°C (Table 4.4). This suggests that a substantial degree of cooling took place between the eruption and emplacement of these units, to produce such

¹ However, *higher* T_e s may be predicted at *further distances* (from vent), if there is an increase in either the overall grain size of ejecta, the height of the eruption column or magmatic temperature.

low T_e s. After a pyroclastic eruption, fragments of juvenile material cool rapidly, during transport in the air or volcanic plume. Calculations on the cooling rate of tephra by Thomas and Sparks (1992) suggest that the major controls on emplacement temperature are grain size and column height. At a given distance from vent, T_e decreases with decreasing grain size and increasing fall height (thus increasing column height). The models of Thomas and Sparks predict that even for coarse juvenile clasts in proximal regions, T_e will be less than 80% of the magmatic temperature (i.e. $\sim 720^{\circ}\text{C}$ to 880°C for Ascension airfall deposits). Furthermore, pumice clasts of $\sim 6\text{cm}$ or less (the typical size of clasts sampled from Ascension airfall deposits) will lose a significant proportion of their heat during transport and thus airfall pumice clasts of this size should be relatively cold on deposition (Thomas and Sparks, 1992).

The mafic airfall deposits sampled on Ascension for T_e analysis display significantly higher T_e s than their felsic equivalents (273°C to $>580^{\circ}\text{C}$). This is expected, as airfall deposits of mafic compositions are produced from higher temperature magmas than felsic airfall deposits; i.e. basalt to basaltic-andesite for scoria, trachyte to rhyolite for pumice (Table 4.4).

composition	eruption temperature
rhyolite	700-900°C
dacite	800-1100°C
trachyte	900°C-1100°C (approx.)
andesite	950°C-1200°C
basalt	1000°C-1200°C

Table 4.4: Estimates of typical eruption temperatures for magmas of different compositions (data from Cas and Wright, 1988).

The emplacement temperature of an airfall deposit is not dependent only on magmatic temperature, but is also a function of distance from vent, grain size and column height (Thomas and Sparks, 1992). As previously mentioned, the T_e of an airfall deposit should (in general terms) decrease with increasing distance from vent, as grain size decreases. Furthermore, at a *given distance from vent*, T_e will decrease with decreasing overall grain size of ejecta, or *increasing* column height (thus increasing fall height). However, the mafic airfall deposits sampled on Ascension typically have a smaller grain size than felsic airfall deposits, but have *higher* T_e s. This suggests that relatively little cooling of clasts occurred in mafic airfalls (during the fall from the eruption column) in relation to felsic airfalls. These findings concur with work by McClelland et al. (1997), who show that that mafic (andesitic) scoria airfall deposits from Santorini (Greece) display higher emplacement temperatures than felsic (rhyodacitic) pumice airfall deposits of the same thickness (e.g.

100°C- >580°C for the andesitic Upper Scoriae 1 compared with 130°C-250°C for the Minoan rhyodacitic pumice).

The relatively high temperature of the mafic airfall deposits on Ascension suggests that the eruption columns that produced them are likely to have been significantly smaller (lower in height) than those that produced the felsic airfall deposits. This is in keeping with the literature (see for example Cas and Wright, 1988), which suggests that such deposits are produced by less vigorous eruptions than felsic airfall deposits.

4.6.3 Magnetic mineralogy

A stable remanence is exhibited by 82% of clasts from Ascension airfall deposits. A range of T_b spectra are displayed by clasts (Table 4.2), implying that they have varied magnetic mineralogies. In the majority of clasts, remanence is inferred to be carried by more than one mineral phase, as just over half of clasts (52%) display a multi-phase T_b spectra (Table 4.2). Most of these clasts contain a high-titanium titanomagnetite phase (with a composition between TM14 and TM70, as calculated from T_b spectra) plus a magnetite, maghaemite, or additional (titanium-poor) titanomagnetite phase. The remaining clasts are inferred to have single-phase mineralogies, as they display single-phase T_b spectra. In these clasts, magnetite is interpreted to be the most common remanence carrier, represented by type A demagnetisation behaviour (Table 3.3; displayed by 25% of clasts overall). Titanomagnetite is the next most common single-phase mineralogy (type C behaviour; Table 3.3; 13% of clasts) with compositions ranging from TM03 to TM58 (as calculated from T_b spectra). A single-phase maghaemite mineralogy is relatively rare, displayed by only 8% of clasts from Ascension airfall deposits.

The majority of clasts (79%) display distributed T_b spectra, which suggests that they contain magnetic minerals with a range of grain sizes. However, 21% of clasts display discrete T_b spectra, i.e. the majority of demagnetisation occurs over a narrow temperature range, typically at low temperatures (between 0°C and 200°C). This can make isolation of any high-T component impossible and implies that the clasts contain magnetic minerals with a narrower range of grain sizes. Demagnetisation over a narrow, low temperature range (type E behaviour; Table 3.3) is inferred to represent the removal of a CRM overprint in the majority of these clasts.

4.6.4 Geochemistry, secular variation and correlation

Geochemical data for the pumice airfall units sampled on Ascension substantiate the stratigraphic interpretation proposed in Enclosures 1 and 2 (constructed from field and palaeomagnetic data). This suggests that the pumice airfall units sampled for XRF analysis represent five individual major airfall deposits: the Lower Pumice, Middle Pumice and the Upper Pumice 1, 2 and 3 (see Enclosures 1 and 2). Moreover, the

geochemical data suggest that the majority of the units sampled belong to the Middle Pumice or Upper Pumice 1. Field evidence suggests that both of these major deposits comprise a number of individual fall units, which vary in lithic content and grain size, and this is supported by small variations in some of the trace element values for samples from these deposits. However the overall similarity of geochemical signatures for samples from the Middle Pumice and Upper Pumice 1 suggests that little change in magma composition occurred between their eruptions. This is in contrast to suggestions by Harris (1982) and Nielson and Sibbett (1996) that the pyroclastic deposits on Ascension were erupted from a compositionally zoned magma chamber, as if this were the case, a distinct variation in magma geochemistry (due to fractionation processes) would be expected to be seen in the products of such widely spaced eruptions. Furthermore, the data suggest that the felsic magma system that produced these airfall deposits underwent a significant repose period between the eruptions of the Middle and Upper 1 pumices. The duration of this repose period can be calculated from stratigraphic evidence and radiometric dating, which imply that: a) the Middle Pumice conformably overlies reversed polarity units (which are interpreted to be older than 0.78Ma; see Enclosure 1), and b) that the Upper Pumice 1 has been dated at 0.61 ± 0.02 Ma (Kar et al., 1998), suggesting a maximum repose time of ~ 0.17 Ma.

The Lower Pumice airfall displays reversed polarity and is inferred to be the oldest of the pumice airfall units exposed on Ascension (see Enclosure 1) and its composition is transitional; i.e. it lies between that of the scoria airfalls and those of the Middle and Upper Pumice 1 airfall deposits (Figure 4.12). This is in keeping with conclusions that the felsic magmas on Ascension were a product of the fractional crystallisation of the mafic (alkali-basalt) magmas (Harris, 1983; Weaver et al., 1996), and suggests that the magma that produced the Lower Pumice was a less-differentiated version of the magma that produced the Middle and Upper Pumice 1. However, this further contradicts suggestions by Harris (1982) and Nielson and Sibbett (1996) of the presence of a compositionally zoned magma chamber beneath the island (in which case, the pyroclastic deposits would be expected to become increasingly more mafic with time).

GMP1/2, UVA1/2 and the upper Turtle's Back airfall unit (loc. 71, Figure 4.14; Enclosure 2) are distinct from the units of the Middle Pumice and Upper Pumice 1 (Figure 4.13) and are inferred to represent the Upper Pumice 2. Moreover, units from the Upper Pumice 2 display a similar signature to the Green Mountain ignimbrite (GMI, Figure 4.14; Enclosure 2), suggesting that they may have been produced by the same eruption. This also supports field evidence that suggests that GMI1 overlies GMP1/2 and concurs with the literature, which indicates that ignimbrites commonly overlie substantial pumice airfall deposits in the field (see for example Fisher and Schmincke, 1984; Cas and Wright, 1988). UVA3 is further distinct from the other pumice units sampled (in terms of secular variation and geochemistry) and is inferred to represent the Upper Pumice 3.

Chapter 5

WELDED DEPOSITS AND LAVAS

Fully welded pyroclastic deposits and lavas comprise 7% of the deposits sampled on Ascension for palaeomagnetic analysis. Samples were taken from two fully welded deposits (GMI1 and SB2) and seven lavas (Figure 5.1). This chapter describes the palaeomagnetic characteristics (remanence, emplacement temperature, magnetic mineralogy and secular variation) displayed by these deposits.

The lavas discussed in this chapter were sampled in order to determine their polarity and hence to provide an age framework for the pyroclastic deposits on Ascension. Some of the lavas exposed on Ascension contain individual clasts (e.g. where mafic inclusions are incorporated into a felsic lava), however

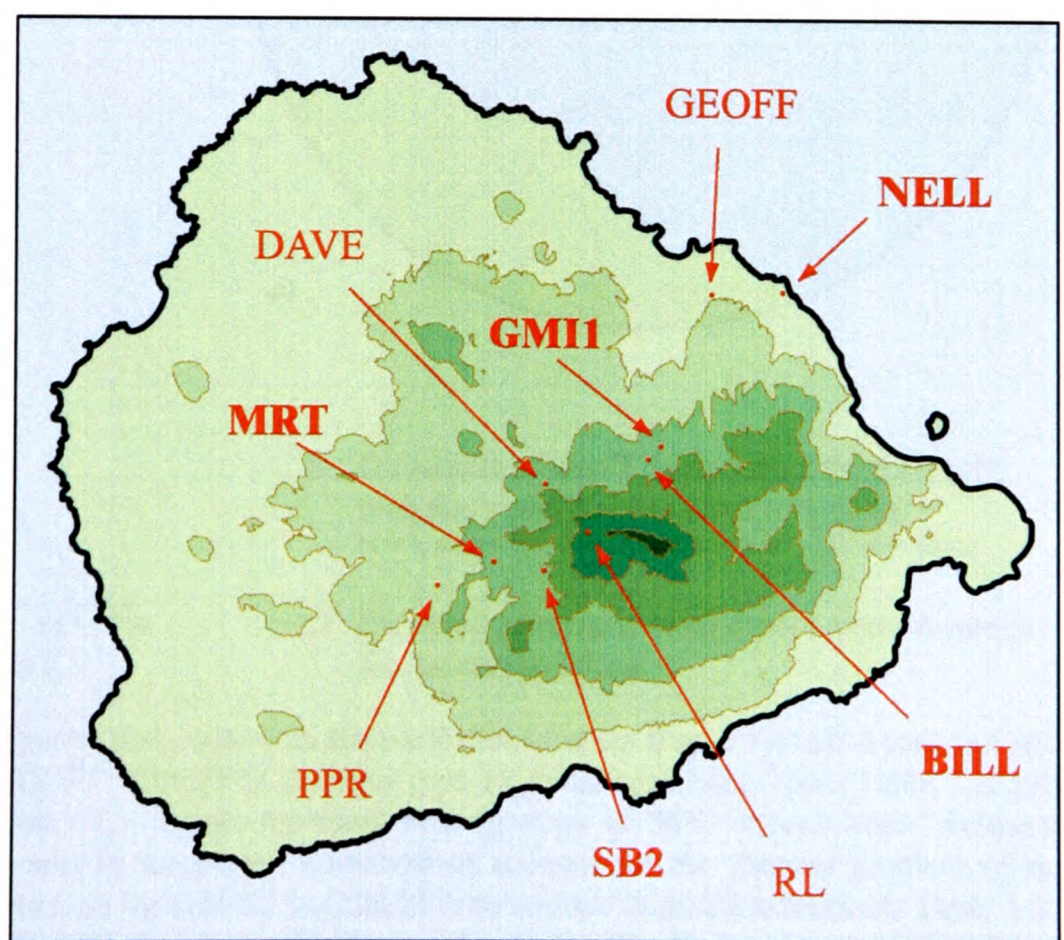


Figure 5.1: Topographic map of Ascension Island showing individual palaeomagnetic sampling locations of welded pyroclastic deposits and lavas. Sites shown in bold are discussed individually in the text. Shading represents contours of 500ft.

these clasts are strictly xenoliths and are not considered in this chapter. The welded units discussed in this chapter typically resemble lava, and individual clasts (i.e. juvenile and lithic clasts) cannot be distinguished from the surrounding ‘matrix’. Both welded deposits and lavas were therefore *block* sampled in the field. Semi-welded pyroclastic deposits (in which individual clasts *can* be differentiated from the surrounding matrix) are discussed in Chapter 6.

5.1 REMANENCE CHARACTERISTICS

5.1.1 Lavas

The majority of the lavas sampled on Ascension (71%) display a single-component remanence, in a direction sub-parallel to the expected normal or reversed geocentric axial

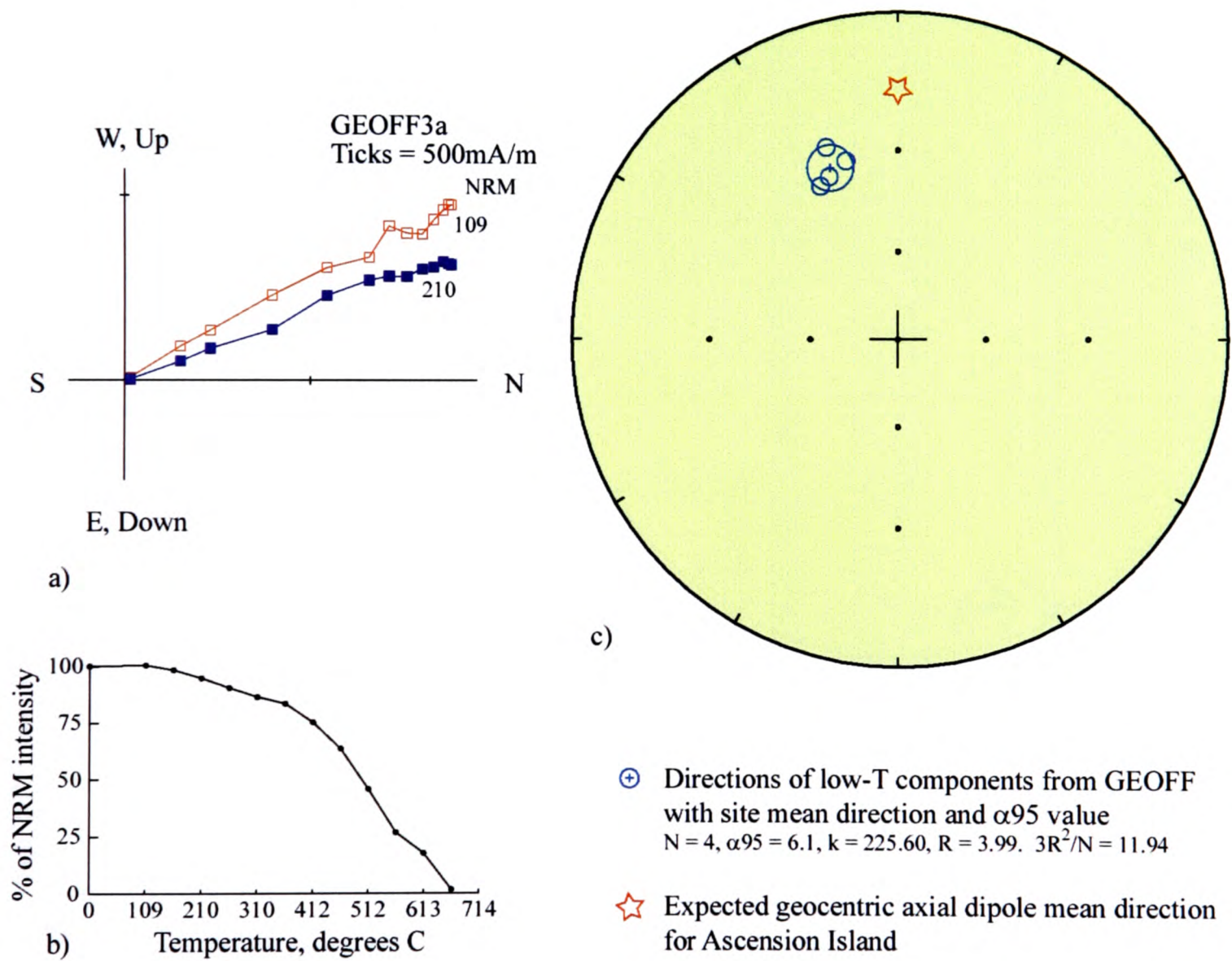


Figure 5.2: Zijderveld plot, T_b spectra and equal area stereoplot for samples from a typical Ascension lava that displays normal polarity (GEOFF). GEOFF3a displays type 1a remanence behaviour (Table 3.2; plot a), suggesting that it was emplaced $>T_c$. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for GEOFF3a (plot b) is two-phase (type E2 behaviour; Table 3.3), suggesting that remanence is carried by two mineral phases. Drops in intensity are seen at ~580°C and ~663°C, implying that remanence is carried by magnetite and maghaemite or haematite. Plot c) shows the distribution of individual low-T components for samples from GEOFF, with site mean direction (small cross) and α_{95} value (large circle). Low-T directions are tightly grouped, but the site mean direction deviates from the expected GAD for Ascension by ~21°. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

dipole mean direction (GAD) for Ascension (360/-15), i.e. type 1a remanence behaviour (Table 3.2; e.g. Figures 5.2a, 5.3a). This is interpreted as a primary thermoremanent magnetism (TRM) acquired as the lava cooled from magmatic temperatures through the Curie temperatures (T_c) of its magnetic minerals. Directions of type 1a (TRM) components are interpreted as tightly grouped following the criterion outlined in Watson, 1956 (Appendix A; e.g. Figures 5.2c, 5.3c). Site mean directions for TRM components typically approximate the expected (normal or reversed) GAD for Ascension, but some sites deviate from the GAD because of secular variation (e.g. Figures 5.2c, 5.3c).

Several samples show an additional VRM component, which is typically removed by $\sim 150^\circ\text{C}$ (e.g. Figure 5.3a).

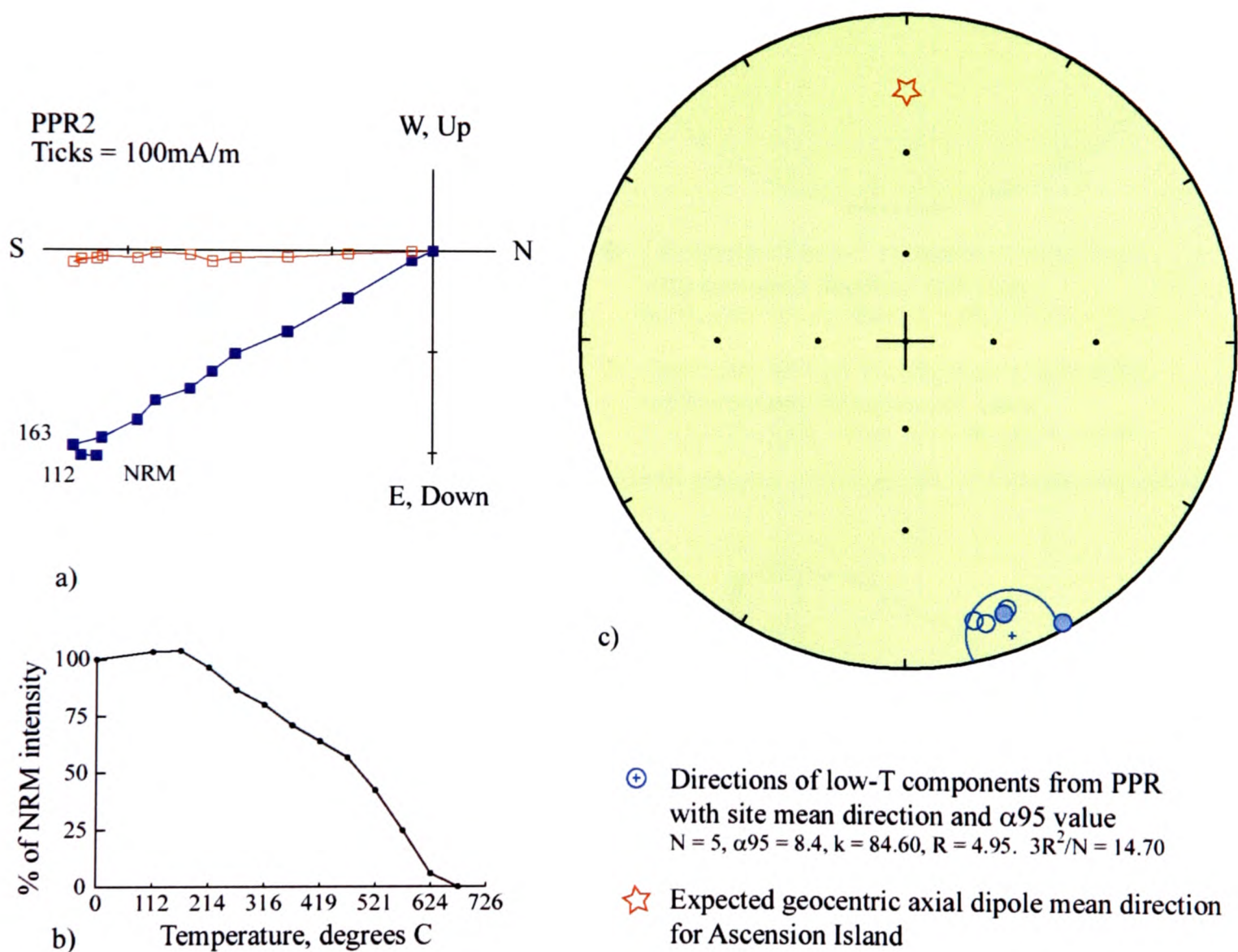


Figure 5.3: Zijderveld plot (z-plot), T_b spectra and equal area stereoplot for samples from a typical lava from Ascension Island that displays reversed polarity (PPR). PPR2 displays type 1a remanence behaviour (Table 3.2; plot a), but displays an additional VRM component that persists to 163°C . Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for PPR2 (plot b) is two-phase (type E2 behaviour; Table 3.3), suggesting that remanence is carried by two mineral phases. Drops in intensity are seen at $\sim 265^\circ\text{C}$ and $\sim 675^\circ\text{C}$, implying that remanence is carried by titanomagnetite and maghaemite/haematite. Plot c) shows the distribution of individual low-T (TRM) components for samples from PPR, with site mean direction (small cross) and α_{95} value (large circle). Low-T directions are tightly grouped, but the site mean direction deviates from the expected reversed GAD for Ascension by $\sim 20^\circ$. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

Units BILL and NELL (Figure 5.1) differ from the majority of the lavas discussed in this chapter, as samples from these units typically display a two-component remanence. Both

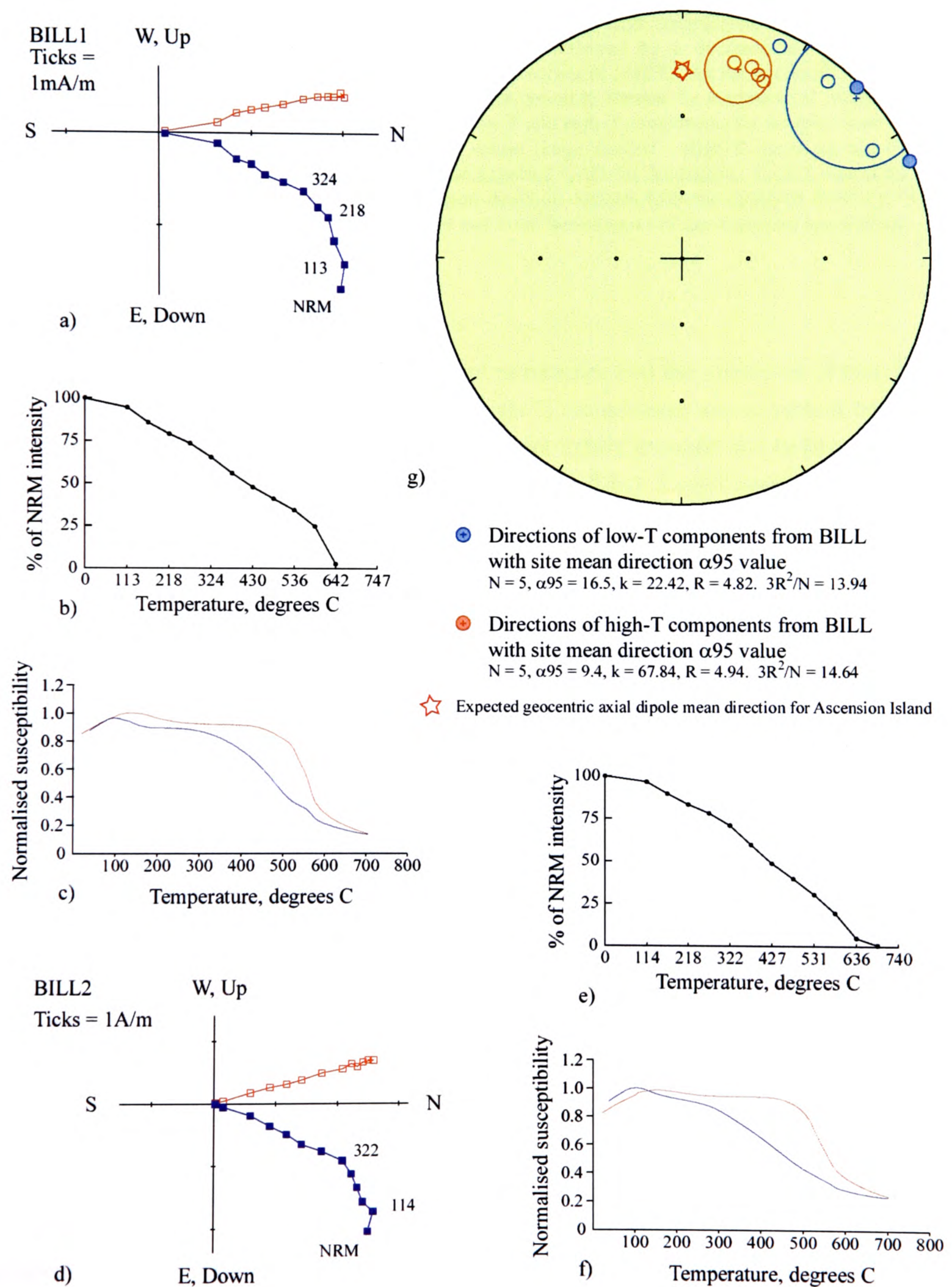


Figure 5.4: Zijderveld plots, T_b spectra, temperature-dependent susceptibility (high-T χ) plots and equal area stereoplot for samples from BILL. See over page for full caption.

Figure 5.4 continued: Samples from BILL display a two-component remanence. High-T components lie sub-parallel to the expected GAD for Ascension whilst directions of low-T components deviate from the expected GAD by up to 70° (plots a, c). Points represent heating steps of 50°C except where indicated otherwise and temperatures on z-plots and T_b spectra have been corrected to account for the thermal gradient of the demagnetising furnace. T_b spectra for BILL1 and BILL2 (plots b, d) are three-phase (type G behaviour; Table 3.3). Drops in intensity seen at ~165°C, ~320°C and ~640°C, suggesting that remanence is carried by two compositions of titanomagnetite, plus maghaemite. This corresponds with high-T χ data, which show a rise in susceptibility from 0°C to ~150°C followed by a decrease to ~300°C (two titanomagnetite phases). A major decrease in susceptibility occurs at ~580°C, but the minimum value is not reached until >600°C (suggesting maghaemite is present, possibly formed by alteration of magnetite on heating). Plot c) shows the distribution of individual low-T and high-T components for samples from BILL, with site mean directions (small crosses) and α_{95} values (large circles). High-T directions are tightly grouped with a mean direction that approximates the expected GAD for Ascension. Low-T directions are grouped, though grouping is less tight and their mean direction deviates from the expected GAD by ~45°. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

units are mafic in composition.

In BILL, all samples display a two-component remanence and the directions of both low-temperature (low-T) and high-temperature (high-T) components are consistent between samples (e.g. Figure 5.4a,d). High-T components are tightly grouped and lie in a direction sub-parallel to the expected GAD for Ascension (Figure 5.4,c). Low-T components (which persist to temperatures of ~320°C) are also grouped, but lie in a direction distinct from the expected GAD for Ascension (e.g. Figures 5.4a,d,g). Possible reasons for the anomalous direction of low-T components are discussed in Section 5.4.

The presence of more than one component of magnetism in samples from BILL implies that remagnetisation of the unit occurred some time after eruption. High-T components are inferred to represent original TRMs, as directions lie close to the expected GAD for Ascension and are similar between samples. Directions of low-T components are also consistent between samples, suggesting that they were acquired in situ and are therefore secondary overprints. In general, a secondary overprint can be attributed to the acquisition of one or more of the following: a) a new TRM, formed by significant reheating (and subsequent cooling) of the unit, b) a CRM (chemical remanent magnetism), formed by chemical alteration or weathering of the unit, or c) a VRM (viscous remanent magnetism), acquired by simple exposure of the unit to the ambient field over time. Lightning strikes may also be a source of a secondary IRM (induced remanent magnetism) overprint.

The oldest surface rocks dated on Ascension have an age of ~1Ma (from lavas; Harris, 1982; Nielson and Sibbett, 1996; Kar et al., 1998). However, any VRM component displayed by samples sampled on Ascension must have been acquired in the last ~0.78Myrs (the date of the last magnetic reversal). A VRM acquired over this timescale at ambient temperature would be expected to be removed by heating to 163°C over a laboratory timescale (see Section 3.3.3). Low-T components from BILL persist to ~320°C and are therefore unlikely to be VRMs. Low-T components are also unlikely to be thermal

in origin, as thermal overprinting to 320°C would require the presence of a substantial hot deposit overlying BILL, which is not evident from field relationships. An IRM origin is also unlikely as storms are not common on Ascension and lightning strikes are typically restricted to topographically high areas. In addition, the intensities of IRM components are typically much greater than those of components acquired by other mechanisms and this is not the case with BILL. Low-T components are therefore most likely to be CRMs acquired by the alteration or new growth of magnetic minerals within the lava. This interpretation is supported by comparison of remanence characteristics with T_b spectra and temperature-dependent susceptibility (high-T χ) data for samples from BILL (Figures 5.4a-f). High-T χ plots for BILL1 and BILL2 (Figures 5.4c,f) show an initial increase in susceptibility (which is typical of titanomagnetite), then a decrease to ~300°C (the approximate temperature to which low-T components persist). A sharp decrease follows at ~580°C, which is behaviour typical of magnetite, but susceptibility continues to decrease (slowly) above 600°C, suggesting that maghaemite is present or is being formed by alteration of magnetite at high temperatures. These data suggest that low-T components from BILL are CRMs carried by titanomagnetite and high-T components are original TRMs carried by magnetite or maghaemite. This behaviour is seen in clasts from a number of other units sampled on Ascension, as well in clasts from reworked pyroclastic deposits sampled at Ruapehu volcano, New Zealand (see Section 3.7).

Unit NELL shows more complex remanence behaviour than BILL. Directions of high-T components in all samples from NELL are similar and sub-parallel to the expected GAD for Ascension (Figures 5.5a,d,h,k and g). However, directions of low-T components range from northwest to southwest in declination and from shallowly to steeply upward in inclination (e.g. Figures 5.5a,d,h,k), although they are loosely grouped (Figure 5.5g). This behaviour suggests that low-T components are overprints, formed in situ, and high-T components are original TRMs (as is seen in BILL). T_b spectra and high-T χ plots indicate that samples from NELL exhibit a two-component mineralogy, comprising a titanomagnetite (T_c ~400°C) phase plus a magnetite (or maghaemite) phase (Figures 5.5c,f,j,m), but there is no clear association between mineralogy and remanence characteristics for these samples, and it is therefore not possible to determine conclusively which component (low-T or high-T) is carried by which mineral phase. However, it is proposed that the low-T CRM component is carried by titanomagnetite and the high-T original TRM component is carried by magnetite/maghaemite, as is seen in samples from BILL. This is supported by the fact that the T_c of the magnetite (/maghaemite) phase remains the same on cooling as it is on heating (e.g. Figures 5.5c,j)¹. Clasts sampled from the Pourahu Formation (see Chapter 3, Section 3.7.4.4) show similar behaviour (i.e. the

¹ A slight change in T_c for the magnetite/maghaemite phase is seen in NELL2b and NELL4a (5.5f,m), however these samples were heated in air rather than argon and this change is hence interpreted as the result of oxidation on heating.

low-T inferred CRM component is carried by titanomagnetite). It is proposed that in these clasts, and in samples from NELL, the (CRM-carrying) titanomagnetite phase is an

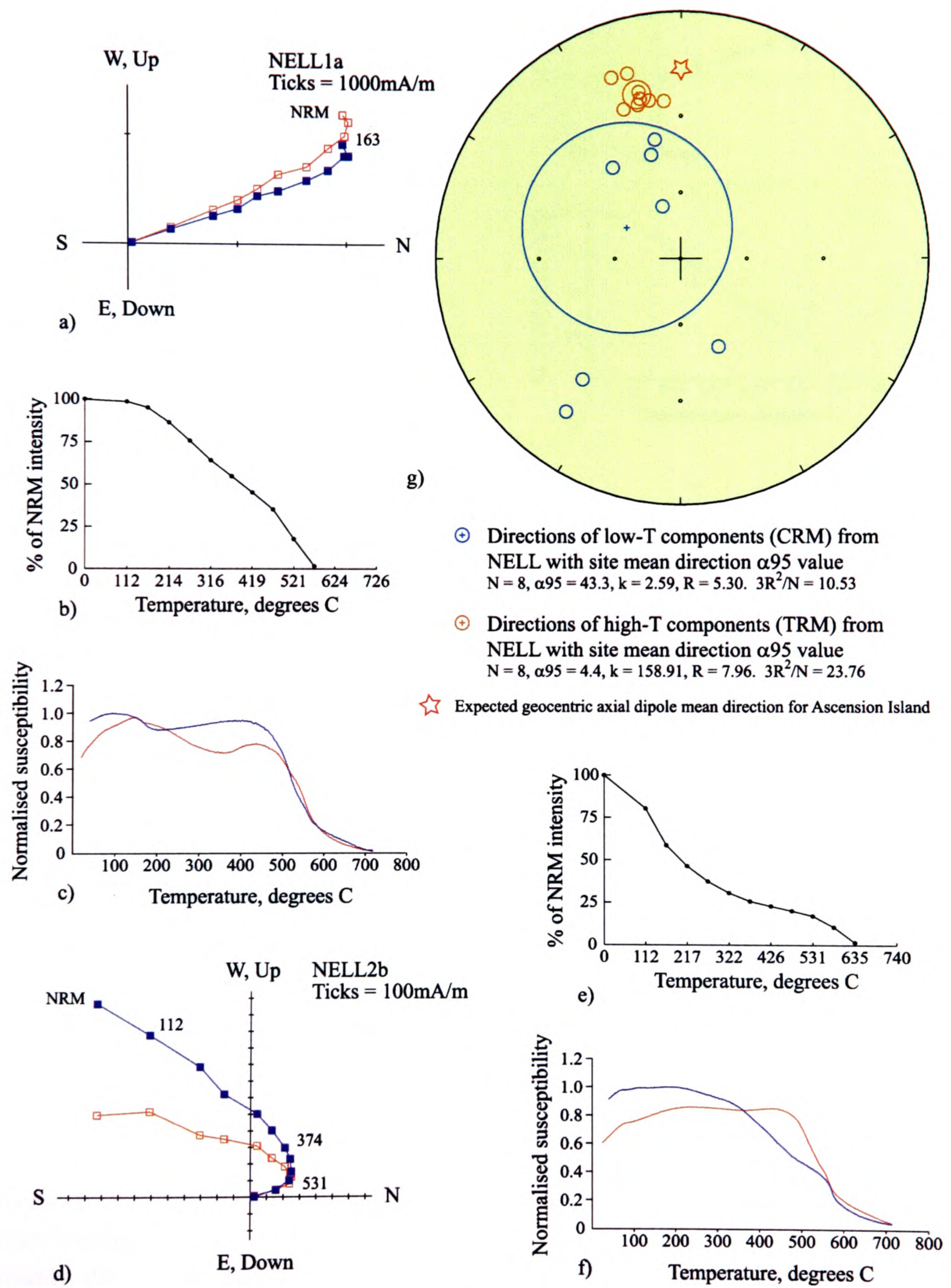


Figure 5.5: Zijderveld plots (z-plots), T_b spectra, temperature-dependent susceptibility plots and equal area stereoplot for samples from NELL. See over page for further plots and full caption.

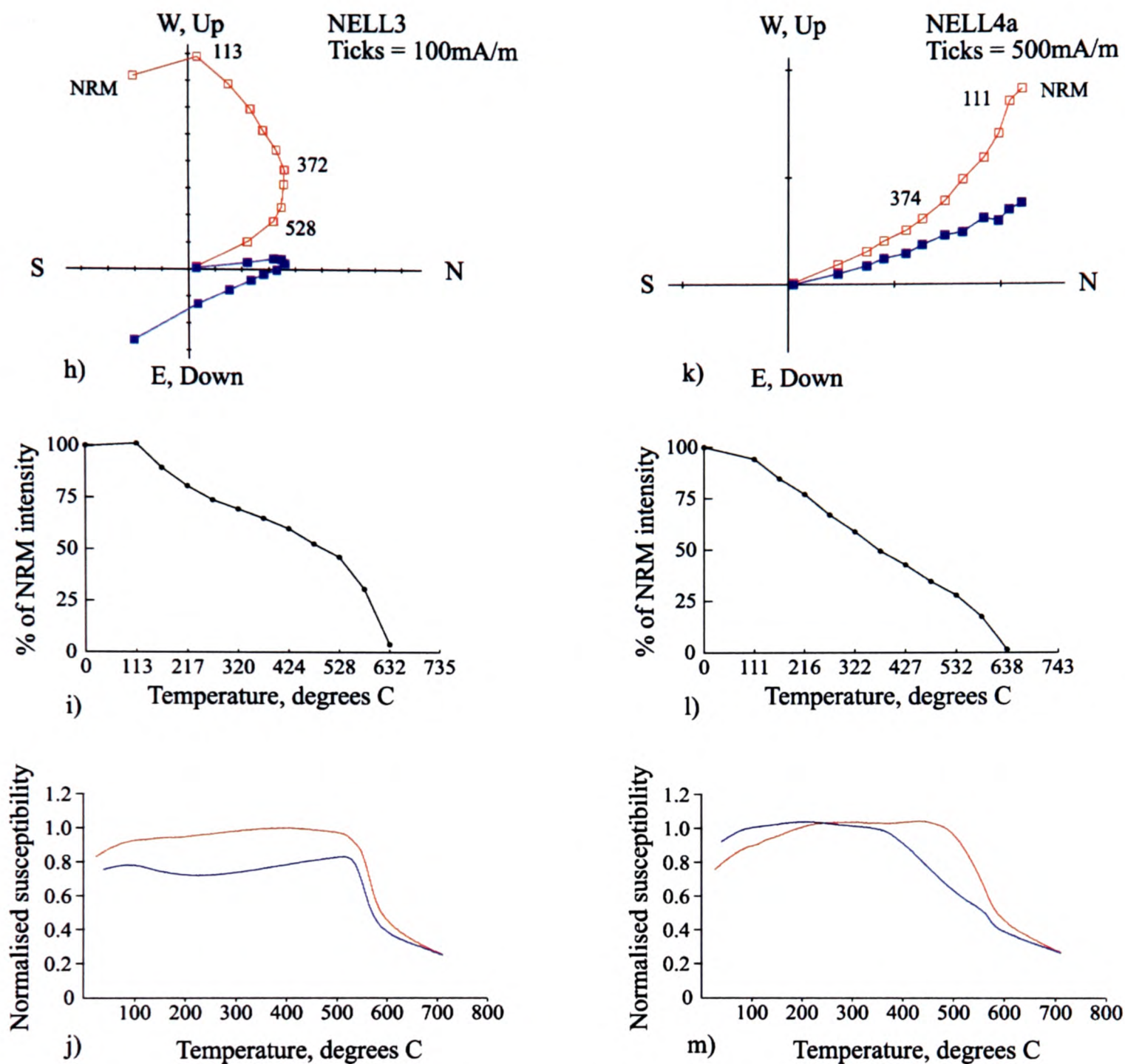


Figure 5.5 continued: Directions of high-T components from all samples are similar (sub-parallel to the expected GAD for Ascension), and are tightly grouped (plots a,d,h,k and g). Conversely, directions of low-T components vary between samples (plots a,d,h,k), although directions are loosely grouped (plot g). Samples exhibit a two-component mineralogy (plots b,c,e,f,i,j,l,m) comprising a titanomagnetite phase and a magnetite or maghaemite phase, but mineralogy cannot be linked to remanence characteristics (i.e. presence/direction of low-T components). However, low-T components are inferred to be CRMs, carried by the titanomagnetite phase and high-T components are inferred to represent the original TRMs, carried by the magnetite/maghaemite phase. Points on z-plots represent heating steps of 50°C except where indicated otherwise and temperatures on z-plots and T_b spectra have been corrected to account for the thermal gradient of the demagnetising furnace. Open shapes on the stereoplot represent points on the upper hemisphere.

alteration product, formed through the homogenisation of original titanium-rich and titanium-poor phases.

A CRM origin for low-T components is also substantiated by bulk susceptibility measurements for clasts from NELL, which show an increase, followed by a decrease upon heating. This behaviour suggests that samples have an unstable mineralogy and readily alter (on heating). In addition, low-T and high-T components in samples from NELL display curved trajectories (e.g. Figure 5.5d), which is a common feature of samples

that are affected by CRM (McClelland & Druitt 1989) and is caused by an overlap in the blocking temperature (T_b) spectra of low-T and high-T components (Section 3.6.1.4).

As (low-T) CRMs in NELL are interpreted as secondary components, they are expected to have been acquired *after* high-T (TRM) components. However, polarity information for samples from NELL appears to challenge this assumption. Low-T components display reversed polarity, which suggests that they were acquired before the last magnetic reversal ($\sim 0.78\text{Ma}$), within the Matuyama reversed epoch (see Section 3.6.4, Figure 3.18). Conversely, high-T components display normal polarity, suggesting that TRMs were acquired (and hence NELL was erupted) *before* the Matuyama reversed epoch (during the previous Gauss normal epoch). This would give NELL a *minimum* age of 2.58Ma (Cande and Kent, 1995), which is unlikely as the oldest rocks dated on Ascension have an age of $\sim 1\text{Ma}$ (Harris, 1982; Nielson and Sibbett, 1996; Kar et al., 1998). Two explanations can be invoked to explain the remanence behaviour of clasts from NELL. Firstly, NELL may have been formed during the Brunhes normal epoch and subsequently remagnetised during one of the reversed 'events' within this period (see Figure 3.18). Secondly, low-T components in NELL may be a product of partial *self-reversal* of the magnetic minerals formed during chemical alteration of the lava. This can occur where a deposit is so strongly magnetised that it generates its own local magnetic field, effectively acting in a similar manner to a bar magnet (Figure 5.6). If a CRM is acquired by the lava some time after deposition, it will record the direction of the internally generated field rather than

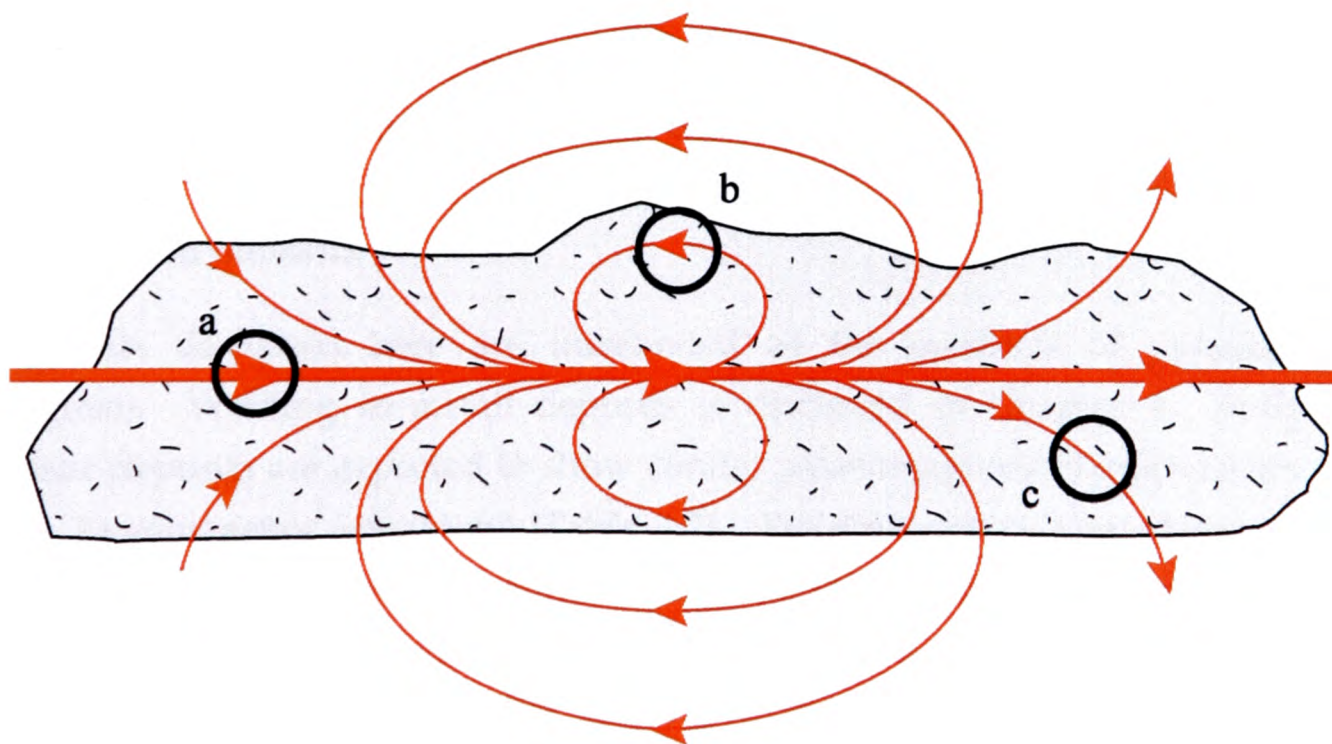


Figure 5.6: Schematic showing how a 'self-reversals' can occur in strongly magnetised lavas. The thick red line represents the direction of the original TRM, acquired by the lava upon eruption and cooling. If the intensity of the TRM is great enough, it can generate its own local field (represented by thin red lines), effectively causing the lava to act like a bar magnet. If a CRM is subsequently acquired by the lava (e.g. as a result of alteration), it will record a different magnetic direction in different parts of the rock, in accordance with the internal field lines. If the lava is sampled at 'a', the CRM will lie in a direction parallel to the original TRM. At 'b', the CRM direction will be reversed with respect to the TRM direction and at 'c', the CRM direction will be oblique to the TRM direction.

the geomagnetic field (Figure 5.6). The direction of the measured CRM component may therefore be distinct from the original TRM direction, depending on where the sample was taken from within the lava (Figure 5.6). If the lava is sampled at position a (Figure 5.6), the CRM direction will be parallel to the original TRM direction. At position b (Figure 5.6), the CRM direction will be reversed with respect to the TRM direction and at position c, the CRM direction will be oblique to the TRM direction. Intermediate CRM directions have been recorded previously in mafic rocks by a number of authors, including Hunt et al. (1986), Walderhaug et al. (1991), Walderhaug (1992) and Rolph (1997).

An alternative hypothesis to explain the behaviour of clasts from NELL is that low-T components are *primary* components, which represent the original titanomagnetite mineralogy, whilst high-T components are *secondary* CRMs, resulting from the transformation of titanomagnetite to magnetite (due to alteration). If this is the case, it suggests that more of the original mineralogy remains intact in clasts that display a significant low-T component (e.g. NELL 2b; Figure 5.5d) than it does in clasts in which low-T components are minimal (e.g. NELL1a; Figure 5.5a). If high-T components are overprints, this would suggest that in clasts such as NELL1a, the original magnetism has been almost fully overprinted by the secondary magnetite component.

The magnetostratigraphic correlation of the pyroclastic sequence that overlies NELL (Section N, Enclosure 2) suggests that NELL is younger than 0.78Ma (the reversal date). However the time gap that separates units EFB1 and NELL is unknown and hence the relative dating of NELL from Enclosure 2 is not conclusive. There is therefore not sufficient evidence to discriminate between the two hypotheses set out above.

5.1.2 Welded deposits

The deposits discussed here are interpreted as the products of pyroclastic flows (ignimbrites). Welding in airfall deposits is discussed in Chapter 4. Fully welded pyroclastic deposits are expected to show similar palaeomagnetic characteristics to lavas; i.e. type 1a remanence behaviour (Table 3.2). Welding occurs after deposition, when loading and compaction cause juvenile fragments and glass shards to sinter together (Cas and Wright, 1988). Experimental studies indicate that in rhyolitic ignimbrites, welding begins at temperatures between 600°C and 750°C, depending on load pressure and water content of the glass (Friedman et al. 1963; Cas & Wright, 1988). Felsic deposits may weld at slightly lower temperatures (due to their more alkaline composition), however it is likely that fully welded deposits will reach temperatures in excess of T_c of their magnetic minerals (see Chapter 3, Table 3.1 for values of T_c for common magnetic minerals) and a new TRM will be acquired upon cooling, which will completely overprint any original components of magnetisation. Where deposits are incompletely welded, they typically

display a multi-component remanence, as part of the original magnetisation will remain. These deposits are discussed in the Chapter 6.

Of the two welded units sampled on Ascension, only unit GMI1 (Figure 5.1) displays the expected type 1a remanence behaviour (Table 3.2), although the majority of samples from GMI1 display an additional VRM component (e.g. Figure 5.7a). Directions of type 1a components for samples from GMI1 are tightly grouped and their mean direction approximates the expected GAD for Ascension (Figure 5.7c).

Samples from unit SB2 (Figure 5.1) typically display a two-component remanence and most show an additional VRM (e.g. Figure 5.8a). Directions of high-T components for samples from SB2 are tightly grouped although their mean direction has a shallow

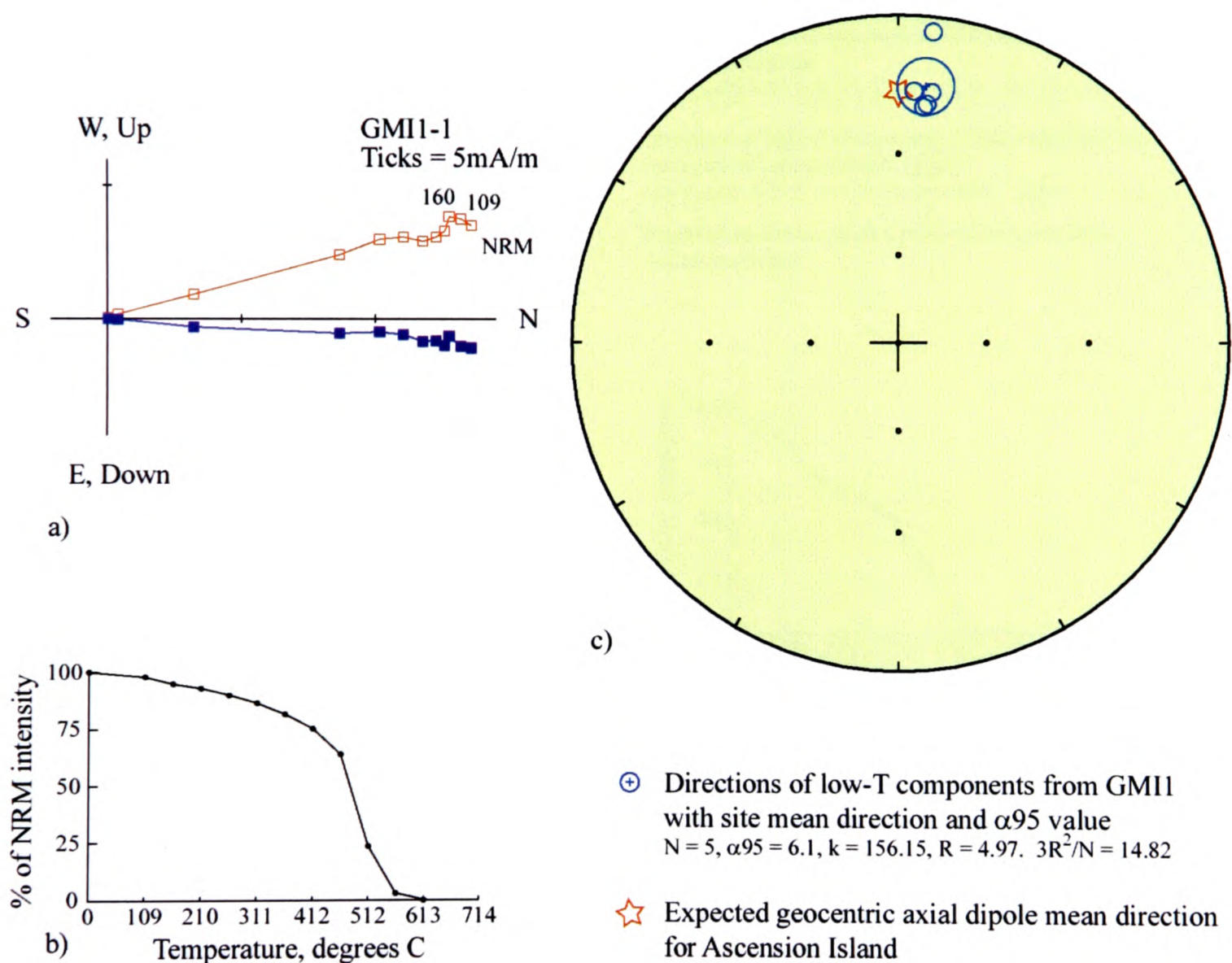


Figure 5.7: Zijderveld plot (z-plot), T_b spectra and equal area stereoplot for a welded deposit from Ascension Island (GMI1). GMI1-1 displays type 1a remanence behaviour (Table 3.2; plot a), but displays an additional VRM component that persists to $\sim 160^\circ\text{C}$. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectrum for GMI1-1 (plot b) is single-phase (type A1 behaviour; Table 3.3), with the major decrease in intensity seen at $\sim 580^\circ\text{C}$, suggesting that remanence is carried by magnetite. Plot c) shows the distribution of individual low-T components for samples from GMI1, with site mean direction (small cross) and α_{95} value (large circle). Low-T directions are tightly grouped and their mean direction approximates the expected GAD for Ascension. Open shapes represent points on the upper hemisphere of the stereoplot.

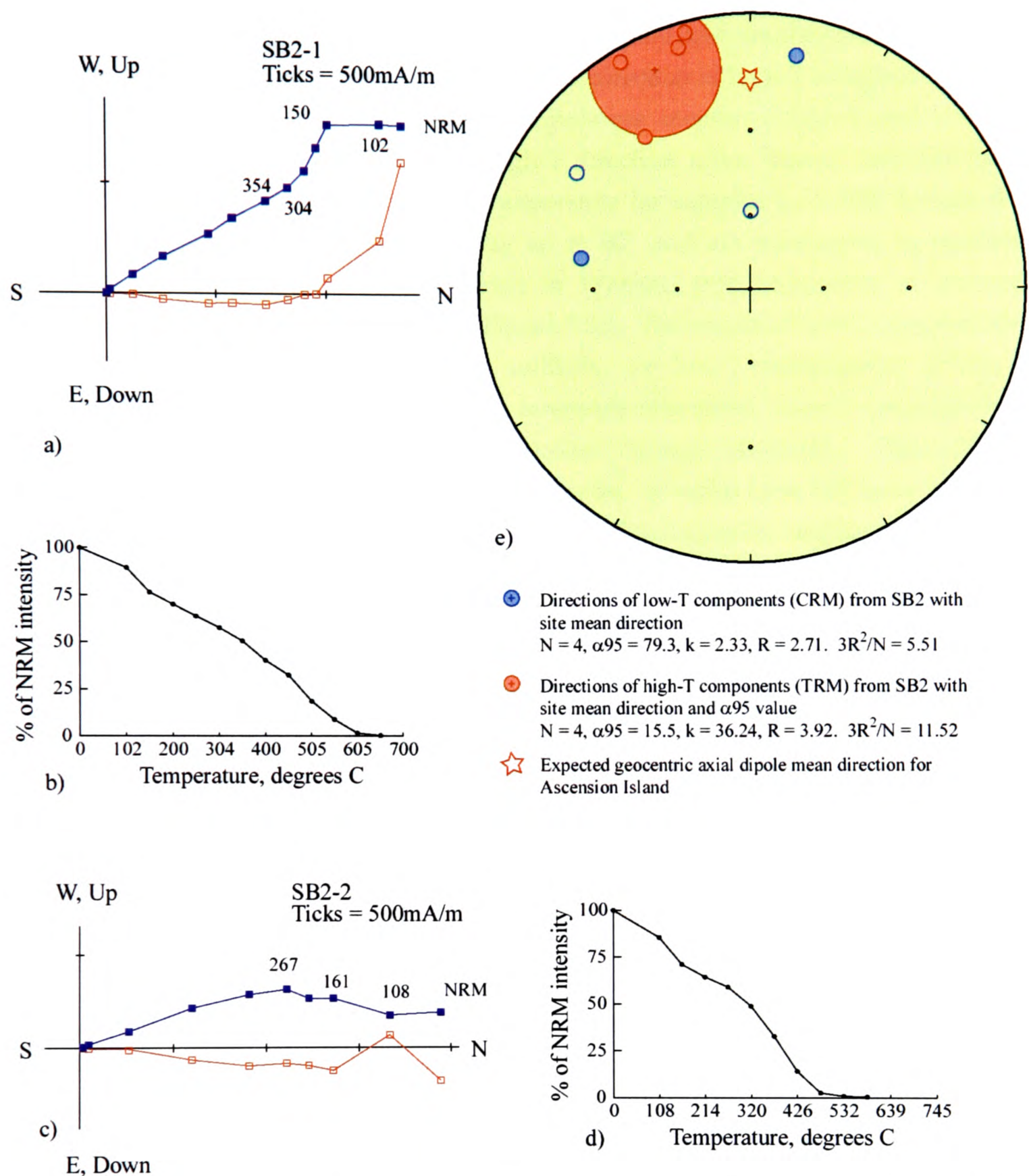


Figure 5.8: Zijderveld plots, T_b spectra and equal area stereoplot for samples from SB2. SB2-1 (plot a) and SB2-2 (plot d) display a two-component remanence, with similarly directed high-T components and low-T components that are randomly orientated between samples. Points represent heating steps of 50°C except where indicated otherwise and temperatures on z-plots and T_b spectra have been corrected to account for the thermal gradient of the demagnetising furnace. The T_b spectra for SB2-1 (plot b) and SB2-2 are two-phase (types E2 and E4 behaviour respectively; Table 3.3). Intensity decreases from 0°C to ~150°C initially, though this is inferred to represent the removal of a VRM component and does not reflect mineralogy. Intensity decreases from 150°C to ~270°C in both clasts and then to ~1% of the NRM value at ~605°C and ~480°C respectively. Remanence carriers are interpreted to be titanomagnetite and maghaemite in SB2-1 and two titanomagnetites in SB2-2. Plot c) shows the distribution of individual low-T (CRM) and high-T (TRM) components for samples from SB2, with site mean directions (small crosses) and α_{95} values (large circles). Low-T directions are random but high-T directions are grouped, although their mean direction deviates from the expected GAD for Ascension by ~24° and has an upward inclination. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

downward direction. This direction is close to horizontal and can therefore be attributed to secular variation. Alternatively, the downward direction of high-T components may be a product of the overlap of the blocking temperature spectra of high-T and low-T (or VRM) components. This can cause the high-T direction to be 'biased' towards that of other components. Directions of low-T components for samples from SB2 deviate from the expected GAD mean for Ascension by up to 40°, and are interpreted as randomly orientated following the criterion outlined in Watson, 1956 (Appendix A; hereafter referred to as 'randomly orientated'; e.g. Figure 5.8c). The origin of low-T components is unclear, however a thermal origin is unlikely, as low-T components persist to temperatures up to 354°C and directions are randomly orientated. Low-T components are most likely to be chemical remanences, formed through alteration. This origin is substantiated by comparison of z-plots and T_b spectra. Samples from SB2 have two-phase mineralogies, comprising a titanomagnetite phase and a magnetite, maghaemite or second (low-titanium) titanomagnetite phase (e.g. SB2-1, SB2-2; Figure 5.8). In each clast, the T_c of the (high-titanium) titanomagnetite phase is equivalent to the temperature to which the low-T component persists (e.g. ~270°C-300°C in SB2-1 and SB2-2). This suggests that low-T components are carried by (high-titanium) titanomagnetite and high-T components by magnetite, maghaemite or low-titanium titanomagnetite. The anomalous directions of low-T (inferred CRM) components may be a product of the self-reversal of magnetic minerals within the deposit, as described for NELL. Alternatively, they may have been produced by the overlap of the T_b spectra of VRM, low-T and high-T components.

5.2 EMPLACEMENT TEMPERATURES

In the case of both lavas and welded deposits, emplacement temperatures are expected to exceed T_c . Hence for individual samples, the Curie temperature of the (highest T_b) remanence carrier (e.g. 580°C for clasts in which remanence is carried by magnetite) provides a minimum estimate for T_e , but a more precise estimate cannot be made. Samples from BILL, NELL and SB2 display a multi-component remanence, however low-T components are not inferred to be thermal in origin and cannot therefore be used to provide an estimate of T_e .

5.3 MAGNETIC MINERALOGY

Magnetic mineralogy for clasts from Ascension welded deposits and lavas was estimated mainly through analysis of blocking temperature T_b spectra, with high-T χ measurements carried out on selected clasts to corroborate conclusions drawn from T_b spectra. Less variation is seen in the T_b spectra of samples from Ascension welded deposits and lavas than in clasts from other types of deposit sampled on Ascension and they are hence inferred to display less variation in magnetic mineralogy. A summary of the different

types of T_b spectra displayed by samples from lavas and welded deposits is shown in Table 5.1. Examples of the various different types of T_b spectra are shown in Chapter 3 (Figure 3.16).

LAVAS		WELDED DEPOSITS		INTERPRETATION
T_b spectra type	% of clasts	T_b spectra type	% of clasts	(mineralogy)
A	6	A	56	single-phase magnetite
B	17	B	0	single-phase maghaemite
C	11	C	0	single-phase haematite
D	0	D	0	single-phase titanomagnetite
E	58	E	44	two-phase
F	0	F	0	two/three phase (low T_c)
G	8	G	0	three+ phase

Table 5.1: Summary of T_b spectra types displayed by samples from lavas and welded deposits sampled on Ascension (with basic interpretation).

5.3.1 Lavas

Thirty-six samples (from seven individual lavas) were thermally demagnetised in the laboratory. Eighty-one percent of samples display distributed T_b spectra, whilst 11% display discrete T_b spectra (where the majority of demagnetisation occurs over a narrow temperature range, at elevated temperatures). NRM intensities range from 32mA/m to 3.8A/m and maximum unblocking temperatures range from 580°C to 698°C.

Sixty-seven percent of samples display a multi-phase T_b spectrum (Table 5.1) and remanence is inferred to be carried by titanomagnetite plus magnetite, maghaemite or haematite in these samples. Compositions of titanomagnetite phases can be estimated using a graph of T_c v titanium content (see Chapter 3; Figure 3.9). Compositions calculated from T_b spectra data range from TM10 to TM62 and are in-keeping with estimates from high-T χ data which range from TM14 to TM60 (also calculated from Figure 3.9). In the remaining single-phase samples, remanence is inferred to be carried by magnetite, maghaemite or haematite.

5.3.2 Welded deposits

Nine samples from welded deposits were thermally demagnetised in the laboratory. Fifty-six percent display distributed T_b spectra, whilst 44% display discrete T_b spectra. NRM intensities range from 1.2mA/m to 14A/m. Maximum unblocking temperatures range from 479°C to 647°C, but in most samples, full demagnetisation occurs at ~580°C.

Fifty-six percent of samples display single-phase T_b spectra, with the major decrease in intensity seen at $\sim 580^\circ\text{C}$ (type A demagnetisation behaviour; Table 4.2, Table 5.1; e.g. Figure 5.7b). Remanence is inferred to be carried by magnetite in these samples. The remaining 44% of samples display a two-phase T_b spectra (type E demagnetisation behaviour; Table 4.2, Table 5.1; e.g. Figures 5.8b,d). Remanence is inferred to be carried by titanomagnetite plus magnetite, maghaemite or a second (low-titanium) titanomagnetite in these samples. Titanomagnetite compositions range from TM19 to TM65 (estimated from T_b spectra and high-T χ data, using Figure 3.9).

In samples from welded deposits, mineralogy appears to reflect remanence characteristics. Samples from GMI1 display a single-phase remanence (typical of welded deposits) and a single-phase mineralogy (type A demagnetisation behaviour; Table 3.3). However, samples from SB2 display a two-component remanence and typically display a two-phase mineralogy (type E demagnetisation behaviour; Table 3.3). Low-T components in samples from SB2 are interpreted as CRM overprints, carried by titanomagnetite, and high-T components are inferred to be TRMs, carried by magnetite or maghaemite.

5.3.3 Magnetic mineralogy and VRM

The majority of samples from lavas and welded deposits show an additional VRM component e.g. Figure 5.3a). However, in many samples the direction of the VRM component deviates from the expected GAD for Ascension (e.g. Figures 5.7a, 5.8a). This may be due to the overlap of blocking temperature spectra of the VRM and low-T components, which can cause the direction of the VRM component to be 'biased' toward that of the low-T component.

5.4 SECULAR VARIATION

Site mean directions for type 1 components (Table 3.2) from lavas and welded deposits are shown in Figures 5.9a and 5.9b respectively. Where samples display more than one component of magnetism, the site mean direction (and hence polarity) is taken from the direction of the high-T (TRM) component (as low-T components are interpreted as CRMs).

Of the seven lavas sampled, five display normal polarity and two display reversed polarity (Figure 5.9a). Site mean directions for normal units deviate from the expected geocentric axial dipole mean direction (GAD) for Ascension by up to 22° (Figure 5.9a). Site mean directions for GEOFF and NELL are distinct from one another and from BILL and DAVE at the 95% confidence level, suggesting that they were *not* deposited contemporaneously. This substantiates field evidence (GEOFF is seen to be younger than NELL from field relationships) and the correlation set out in Enclosure 2, which also suggest that these units are distinct from one another. RL cannot be distinguished from

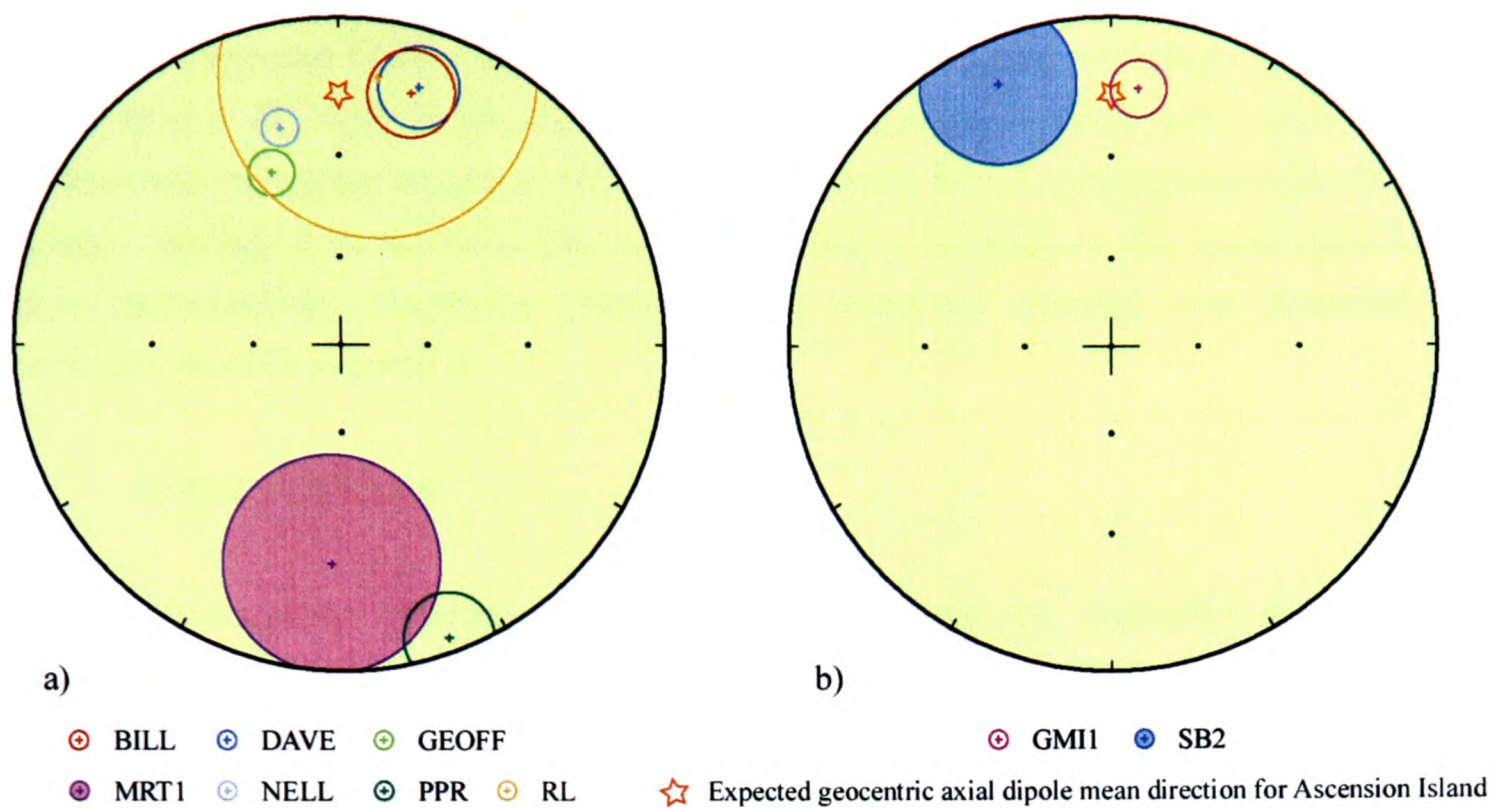


Figure 5.9: Equal area stereoplots showing site mean directions for lavas (a) and welded deposits (b). Five of the lavas sampled display normal polarity. Site mean directions for these units deviate from the expected GAD for Ascension by up to 22°. Units GEOFF and NELL are distinct from one another and from BILL and DAVE at the 95% confidence level, however BILL and DAVE cannot be distinguished from one another. RL cannot be distinguished from the other normal lavas at the 95% confidence level, due to large errors. Errors are also large for MRT1 meaning that site mean directions for reversed units cannot be distinguished from one another. Both welded units display normal polarity and are distinct from one another at the 95% confidence level. The site mean direction for GMI1 approximates the expected GAD for Ascension, however that of SB2 deviates from the GAD by ~24° and has an upward inclination.

the other normally magnetised lavas (due to large errors). Reversed units are interpreted to be older than 0.78Ma (the date of the most recent magnetic reversal). Site mean directions deviate from the expected reversed GAD for Ascension by up to 24°. Large errors for MRT1 mean that no distinction can be made between MRT1 and PPR at the 95% confidence level.

Both welded deposits sampled show normal polarity (Figure 5.9b) and the site mean direction for GMI1 approximates the expected GAD for Ascension. The site mean declination for SB2 deviates from that of the expected GAD by ~24° and displays downward as opposed to upward inclination. However, it is close to horizontal and may therefore be attributed to secular variation. An alternative origin for the downward site mean inclination is that the directions of high-T components are biased toward that of low-T or VRM components, due to the overlap of T_b spectra.

In addition to variation in site mean directions, variation is seen in the mean directions of low-T and high-T components within individual units (e.g. BILL, NELL). In BILL, high-T components are tightly grouped, with a mean direction of 016/-13, close to the expected GAD for Ascension (Figure 5.4c). Low-T components (which are interpreted as having been formed in situ) are also grouped, but have a mean direction of 047/-03, which is 47°

east of the expected GAD. This may be the result of secular variation, in which case it implies that a 47° shift in the direction of the geomagnetic field occurred between the eruption and remagnetisation of BILL. Alternatively, low-T components may have been acquired during a transitional period (i.e. during a reversal of the geomagnetic field), when intermediate directions (between the expected normal and reversed GAD directions) may be recorded.

5.5 CONCLUSIONS

The palaeomagnetic characteristics of samples from the deposits described here substantiate field interpretations as welded pyroclastic flow deposits and lavas (from evidence such as lithified texture and *fiamme*). Where samples display more than one component of magnetism, the low-T component is interpreted as a CRM. Of the lavas sampled, only the mafic lavas (BILL and NELL) display a two-component remanence, whereas the felsic lavas sampled display type 1a remanence behaviour (Table 3.2), which is typical of lavas. These results suggest that mafic lavas may be more susceptible to alteration (and hence CRM acquisition) than felsic lavas, and are therefore less desirable for use in palaeomagnetic studies (especially where accurate assessment of the original TRM direction is required).

Welded deposits and lavas display less variation in magnetic mineralogy than other deposits sampled on Ascension. T_b spectra suggest that the majority of clasts display a simple magnetite or maghaemite mineralogy, or a mixed mineralogy with remanence carried by titanomagnetite plus magnetite, maghaemite or an additional titanomagnetite phase. Titanomagnetite phases are inferred to have compositions ranging from TM10 to TM65. In most cases, clasts that display a multi-phase T_b spectrum are inferred to have acquired a CRM.

Site mean directions for individual lavas vary by as much as 40° , suggesting that they represent eruptions with a range of ages. Three of the lavas display reversed polarity and are interpreted to be older than 0.78Ma.

The anomalous directions of low-T CRM components displayed by NELL and SB2 (i.e. the fact that they deviate from the expected GAD for Ascension) may be the result of partial self-reversal of the magnetic minerals within these units. Alternatively, such directions may be the result of the overlap of low-T and high-T or VRM components. These results suggest that care should be taken when analysing the directions of low-T components inferred to be acquired in-situ (i.e. TRM, CRM, VRM), as these may not always reflect the local geomagnetic field direction at the time of formation.

Chapter 6

BRECCIA DEPOSITS

Breccia deposits comprise 54% of the pyroclastic units sampled for palaeomagnetic analysis on Ascension (Figure 6.1). I have classified them into five basic groups according to common field characteristics: 1) pumiceous breccias, 2) scoriaceous breccias, 3) lithic breccias, 4) lava breccias and 5) stratified breccias.

This chapter describes the palaeomagnetic characteristics displayed by the Ascension breccia deposits, incorporating information on remanence characteristics, emplacement temperature, magnetic mineralogy and secular variation. A small study of thermal stratification within one of the breccia deposits is also included.

For each group of deposits, palaeomagnetic data is combined with field data, to allow further interpretations of mode of formation.

6.1 PUMICEOUS BRECCIAS

Pumiceous breccias comprise 29% of the breccia deposits on Ascension Island sampled for palaeomagnetic analysis. Fifteen individual units were sampled (Figure 2.15) and these are subdivided into clast-dominated and matrix-dominated deposits.

6.1.1 Remanence characteristics

A classification of remanence types is given in Table 3.2. Type 1 clasts display a low-temperature (low-T) component in a direction sub-parallel to the expected geocentric axial dipole mean direction (GAD) for Ascension (360/-15). Type 2 clasts display a low-T

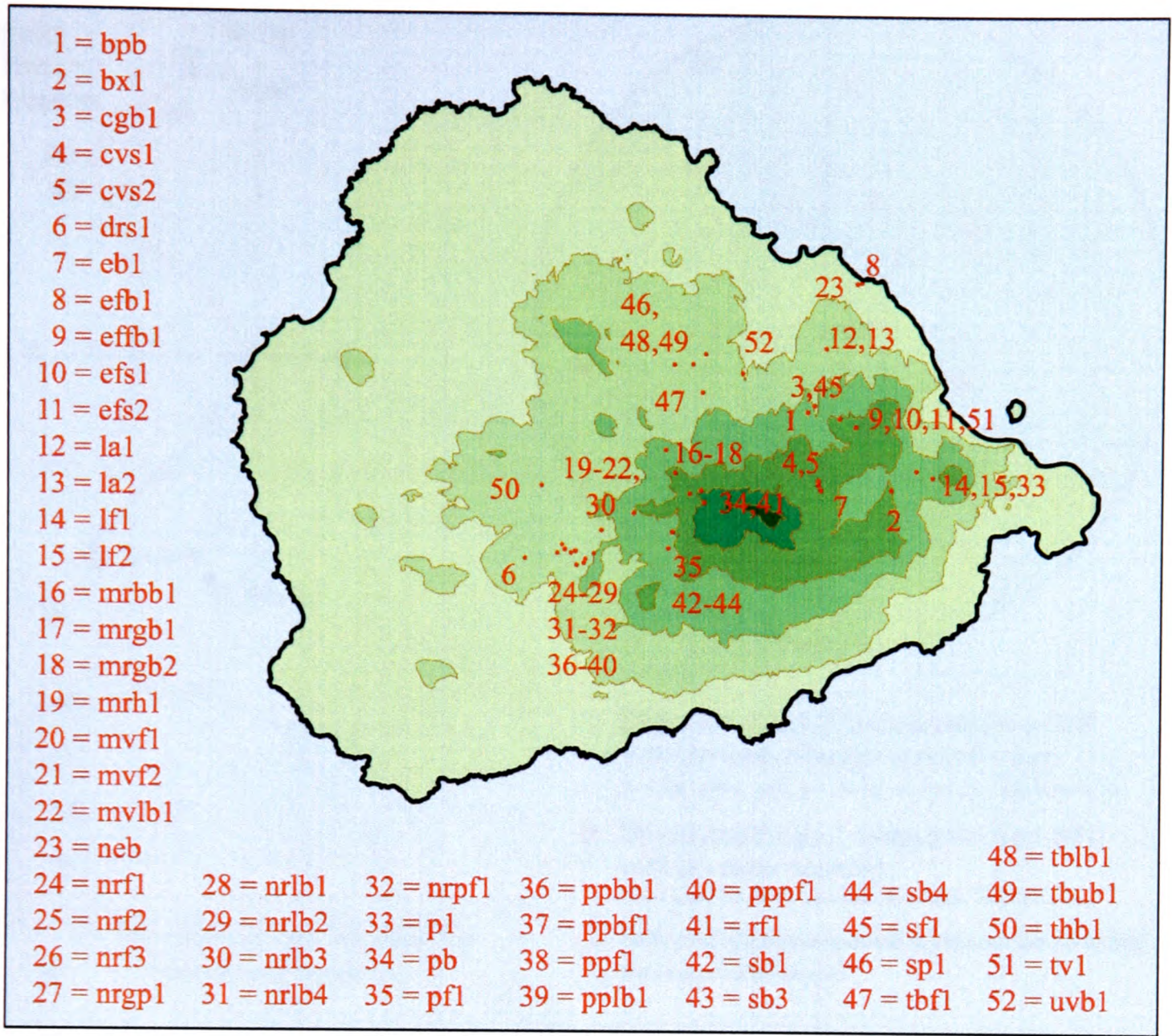


Figure 6.1: Topographic map of Ascension Island showing individual palaeomagnetic sampling locations of breccia deposits. Shading represents contours of 500ft.

component in a direction distinct from the expected GAD for Ascension. Remanence subtypes a, b and c refer to clasts with a single, two or three-component remanence respectively.

6.1.1.1 Clast-dominated pumiceous breccias

A stable remanence is carried by all but two clasts from clast-dominated pumiceous breccias. Lithic clasts typically display a low-T component that lies in a direction subparallel to the expected GAD for Ascension, i.e. type 1 remanence behaviour (Table 3.2). More than 50% of clasts show a two-component remanence, i.e. type 1b remanence behaviour (e.g. Figure 6.2a), 27% show a single-component remanence, i.e. type 1a behaviour and 4% show a three-component remanence, i.e. type 1c behaviour (Table 3.2). An additional VRM component is exhibited by 18% of samples. Pumice clasts from clast-dominated pumiceous breccias typically display type 1a or 1b behaviour.

Four percent of clasts from clast-dominated pumiceous breccias (excluding NRGP1) display low-T components that lie in a direction *distinct* from the expected GAD (i.e. type 2 remanence behaviour; Table 3.2; e.g. Figure 6.3). However, in these clasts,

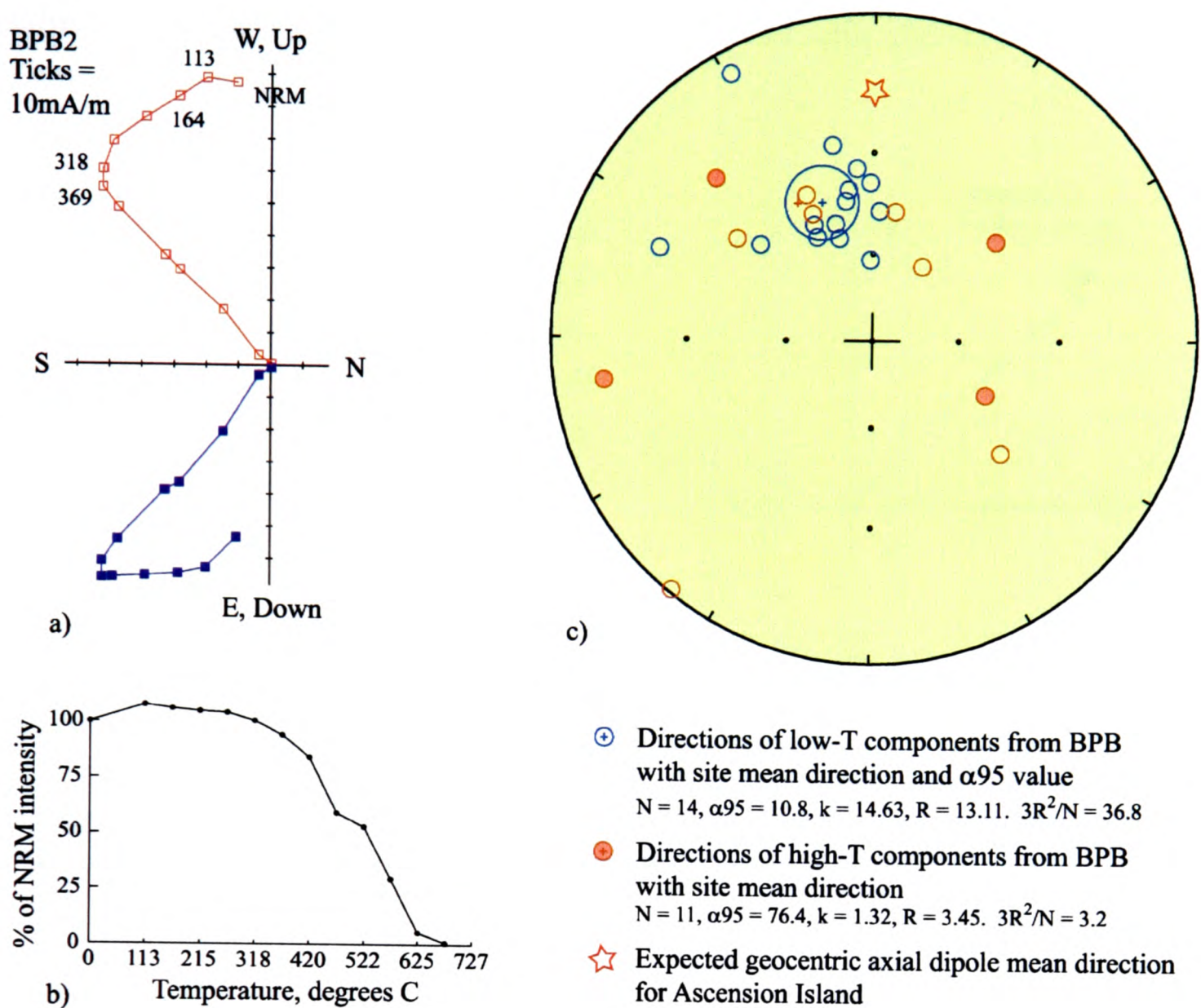


Figure 6.2: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot for clasts from a typical clast dominated pumiceous breccia (BPB). BPB2 displays type 1b remanence behaviour (Table 3.2) and has a T_e of between 260°C and 369°C (plot a). T_e cannot be calculated more precisely because of curvature between low-T and high-T components on the z-plot. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for BPB2 (plot b) is two-phase (type E2 behaviour; Table 3.3), suggesting that remanence is carried by two mineral phases. Drops in intensity are seen at ~470°C and ~625°Cs, implying that titanomagnetite and maghaemite are the remanence carriers. Plot c) shows the distribution of individual low-T and high-T components for all samples from BPB, with site mean directions (small crosses) and α_{95} value (large circle). Low-T directions are tightly grouped and high-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

demagnetisation occurs over a narrow temperature range at elevated temperatures, preventing the isolation of any low-T component.

Low-T components in samples from all clast-dominated pumiceous breccias except NRG1 are interpreted as tightly grouped following the criterion outlined in Watson, 1956 (Appendix A; hereafter referred to as 'tightly grouped'; e.g. Figure 6.2c). Directions of high-T or medium-T (med-T) components are interpreted as random following the criterion outlined in Watson, 1956 (Appendix A; hereafter referred to as 'random'; e.g. Figure 6.2c). Site mean directions for low-T components approximate the expected GAD for Ascension, or a direction antipodal to the expected GAD mean (Figure 6.12a). Normal

polarity (in the low-T component) is displayed by 67% of units and reversed polarity (in the low-T component) by 23% of units.

Units SB1 and SB3 (Figure 6.1) differ from other clast-dominated pumiceous breccias because clasts from these units display low-T and high-T components that are sub-parallel Figure 6.4a). Directions of both low-T *and* high-T components are tightly grouped and mean directions approximate the expected GAD for Ascension (Figure 6.4c).

In unit NRGP1 (Figure 6.1), the majority of lithic clasts show type 2 remanence behaviour (Table 3.2; e.g. Figure 6.5a) and directions of both low-T and high-T components are random (Figure 6.5c). Sixty-six percent of clasts display a multi-component remanence (e.g. NRGP1-5; Figure 6.5a), 20% display a single-component remanence and for the remaining 14% of clasts, no reliable component of magnetisation can be resolved. Fourteen percent of clasts show an additional VRM component. Pumice clasts from NRGP1 display type 1a or 1b remanence behaviour.

6.1.1.2 Matrix-dominated pumiceous breccias

In the majority of matrix-dominated pumiceous breccias (63%), most clasts exhibit type 1 remanence behaviour (Table 3.2; e.g. Figures 6.6a, 6.7a,d). Furthermore, type 1b remanence behaviour (Table 3.2) is the most common and is displayed by 44% of clasts (e.g. Figure 6.6a). Type 1a, 1c (e.g. Figure 6.7a) and 1d behaviour are displayed by 12%, 13% and 2% of clasts respectively.

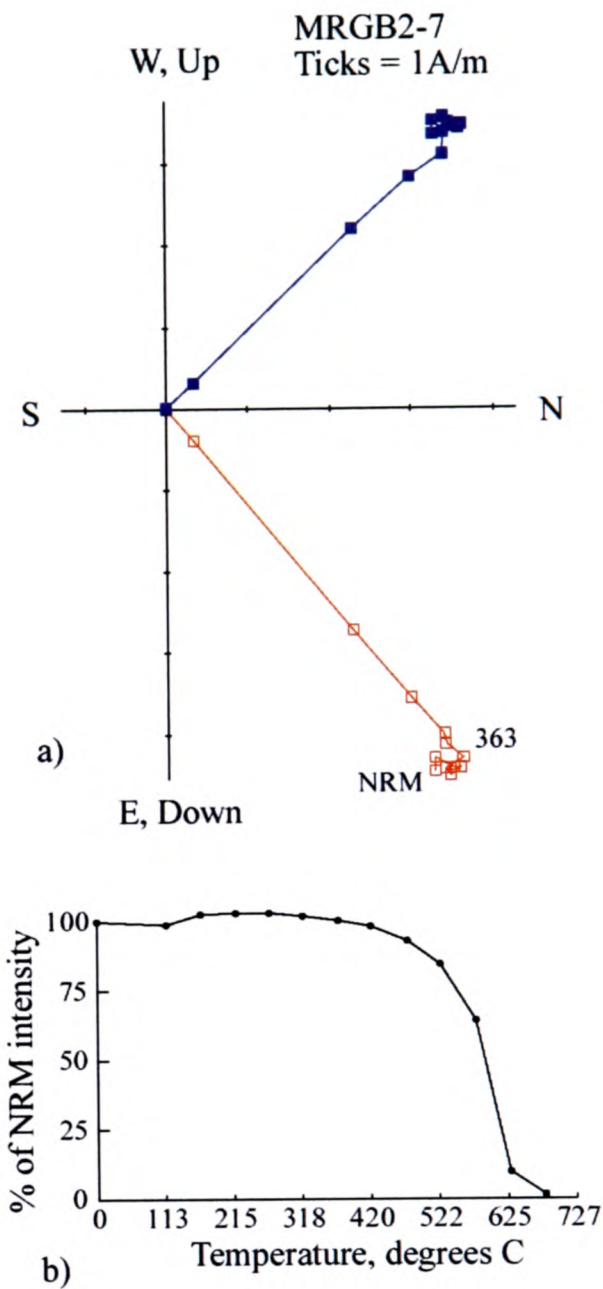


Figure 6.3: a) Zijderveld plot and b) T_b spectrum for a type 2 clast from a clast-dominated pumiceous breccia (MRGB2). MRGB2-7 displays a single-component remanence that lies in a direction distinct from the expected GAD for Ascension (type 2 remanence behaviour; Table 3.2). However, no demagnetisation occurs before $\sim 363^\circ\text{C}$, preventing the isolation of any low-T component. The T_b spectrum for MRGB2-7 is discrete, reflecting the lack of demagnetisation at lower temperatures. The majority of demagnetisation occurs over a narrow temperature range, between $\sim 522^\circ\text{C}$ and 625°C (type B1 demagnetisation behaviour; Table 3.3) and NRM intensity is only reduced to $\sim 1\%$ above 625°C , implying that remanence is carried by maghaemite. Points on the z-plot represent heating steps of 50°C except where indicated otherwise and temperatures have been corrected to account for the thermal gradient of the furnace.

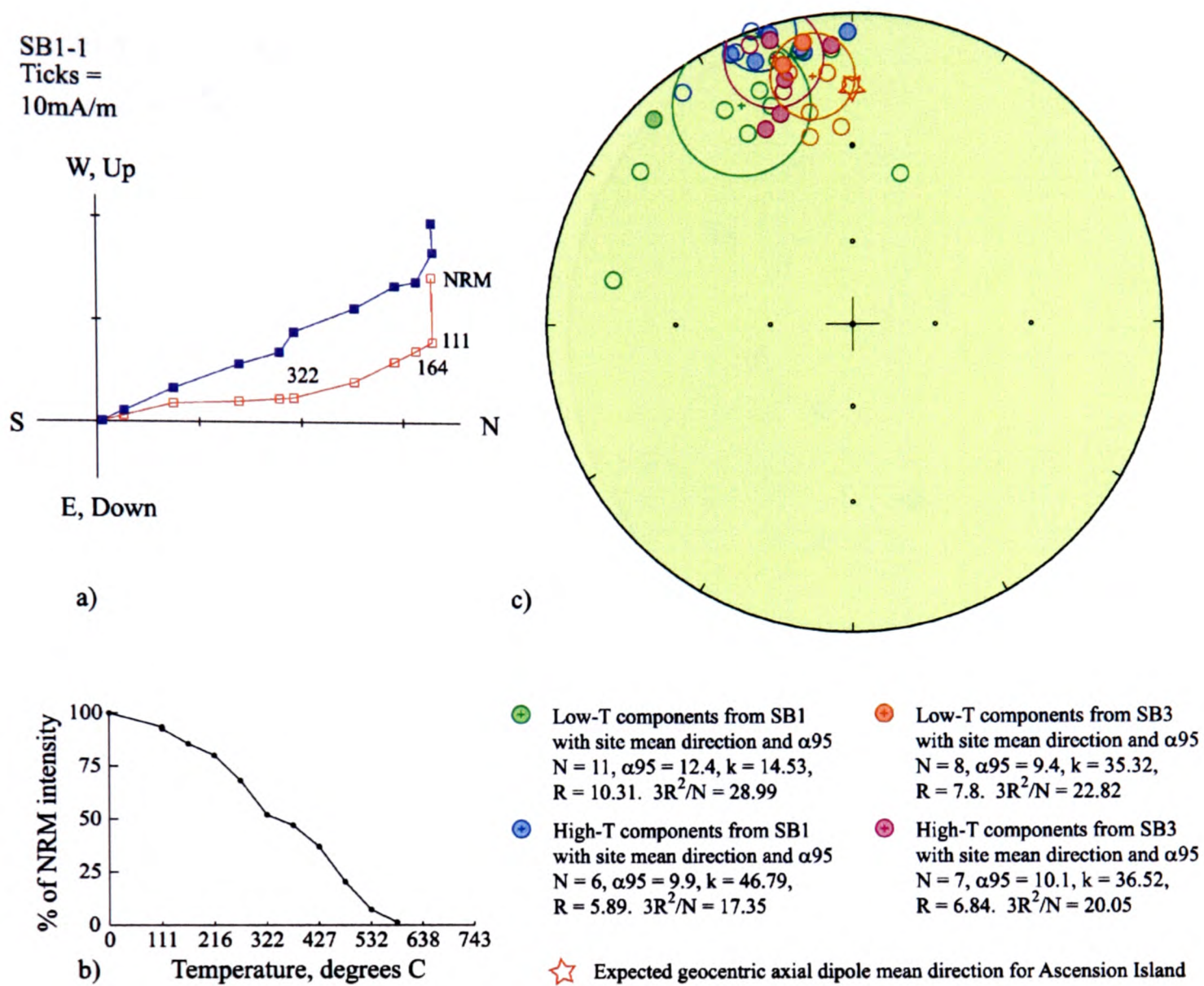


Figure 6.4: Zijderveld plot (z-plot), T_b spectra and equal area stereoplot showing directions of low-T and high-T components for units SB1 and SB3. SB1-1 displays type 1b remanence behaviour (Table 3.2) but low-T and high-T components are sub-parallel (plot a). T_e for SB1-1 is $\sim 322^\circ\text{C}$. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for SB1-1 (plot b) is two-phase (type E1 behaviour, Table 3.3) with a drop in intensity at $\sim 322^\circ\text{C}$ (probably corresponding to the removal of the low-T component) and a reduction to $\sim 1\%$ of NRM intensity at 580°C . Remanence is inferred to be carried by titanomagnetite and magnetite. Plot c) shows the distribution of individual low-T and high-T components for samples from SB1 and SB3, with site mean directions (small crosses) and α_{95} values (large circles). Low-T and high-T directions for both sites are tightly grouped. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplot respectively.

In 4% of clasts, no magnetic components can be resolved. All of these units display normal polarity in the low-T component (Figure 6.12b).

Four percent of clasts display type 2 remanence behaviour (Table 3.2), however demagnetisation in these clasts occurs over a narrow but elevated temperature range, preventing the isolation of any low-T component.

Directions of low-T components in the majority of matrix-dominated pumiceous breccias are tightly grouped (e.g. Figure 6.6c). Med-T or high-T components are typically random (e.g. Figure 6.6c).

Unit PPF1 (Figure 6.1) displays similar remanence characteristics to units SB1 and SB3,

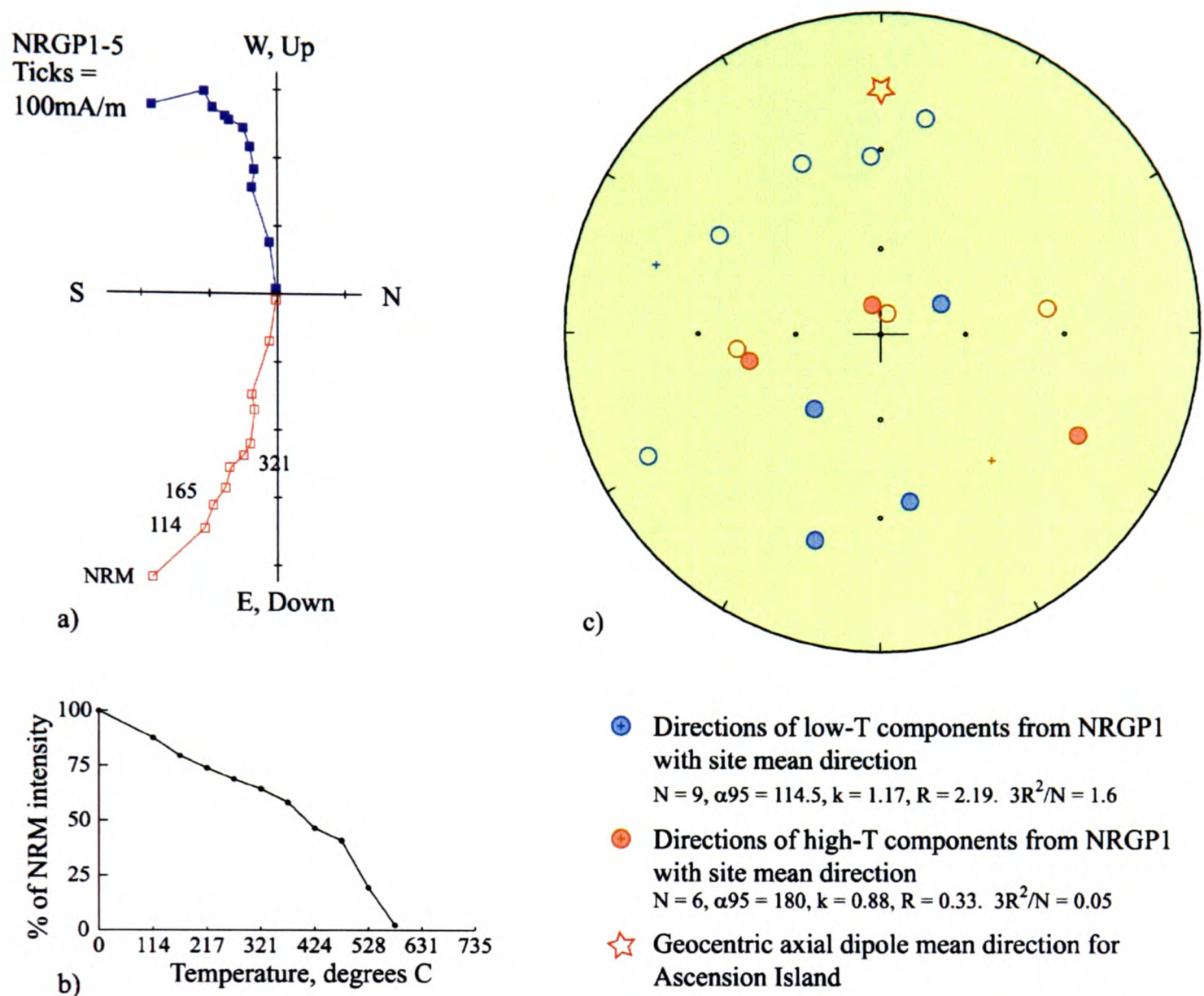


Figure 6.5: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot showing directions of low-T and high-T components for NRGP1. NRGP1-5 displays type 2b remanence behaviour (Table 3.2) with a randomly orientated low-T component (plot a), which is typical of samples from NRGP1. The relict T_e for NRGP1-5 is $\sim 321^\circ\text{C}$. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for NRGP1-5 (plot b) is two-phase (type E1) with decreases in intensity seen at $\sim 424^\circ\text{C}$ and $\sim 580^\circ\text{C}$, suggesting that remanence is carried by titanomagnetite and magnetite. Plot c) shows the distribution of directions of individual low-T and high-T components for all samples from NRGP1, with site mean directions (small crosses). Both Low-T and high-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

with clasts that display sub-parallel low-T and high-T components (e.g. Figure 6.7d). Directions of both low-T and high-T components are tightly grouped (Figure 6.7c).

Components in some clasts from RF1 (Figure 6.1) display curved trajectories (e.g. Figure 6.7a), which is common where the T_b spectra of high-T and low-T components overlap. Low-T components are not *tightly* grouped, but are interpreted as grouped, following the criterion outlined in Watson, 1956 (Appendix A; hereafter referred to as 'grouped'), e.g. Figure 6.7c). The low-T mean direction approximates the expected GAD for Ascension. High-T components are random (Figure 6.7c).

Clasts from PPBF1 and TBF1 (Figure 6.1) display type 2 remanence behaviour (Table 3.2, e.g. Figure 6.8d), except where no magnetic component can be resolved.

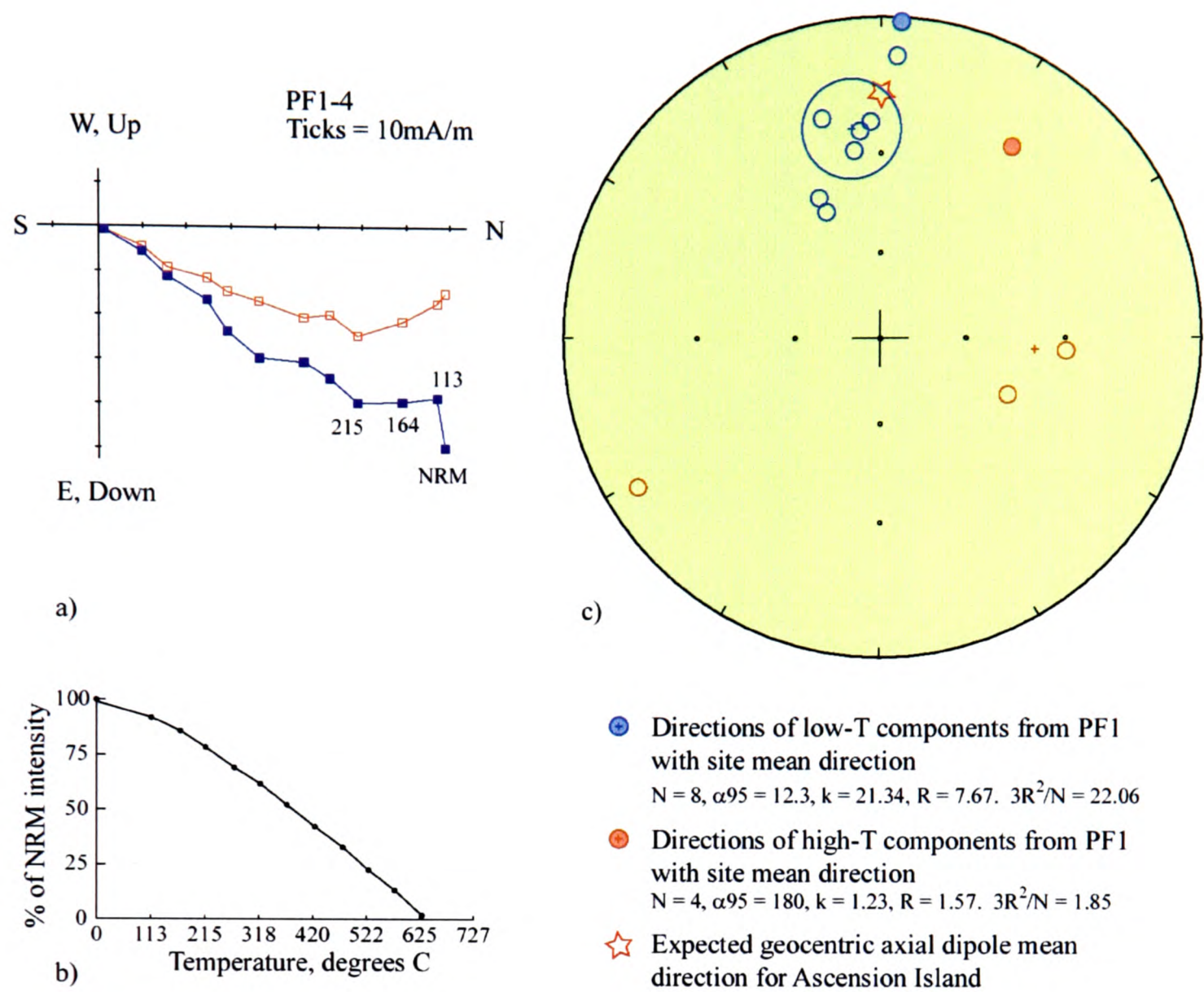


Figure 6.6: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot showing directions of low-T and high-T components for a typical matrix-dominated pumiceous breccia (PF1). Sample PF1-4 displays type 1b remanence behaviour (Table 3.2) and has a T_e of $\sim 215^\circ\text{C}$ (plot a). Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for PF1-4 (plot b) is single-phase and full demagnetisation does not occur until $\sim 625^\circ\text{C}$ (type B2 behaviour; Table 3.3), suggesting that remanence is carried by maghaemite. Plot c) shows the distribution of individual low-T and high-T components for all samples from PF1, with site mean directions (small crosses) and α_{95} value (large circle). Low-T directions are tightly grouped and high-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

Eighty-three percent of clasts from PPBF1 display a single-component remanence (type 2a behaviour, Table 3.2). However, an additional VRM component is shown by 67% of type 2a clasts, which is removed after demagnetisation to between 100°C and $\sim 160^\circ\text{C}$ (e.g. Figure 6.8a).

Directions of low-T components in clasts from PPBF1 are grouped, but grouping is poor and the low-T mean direction lies in a direction distinctly different to the expected GAD for Ascension (Figure 6.8c). VRM components are also grouped and at the 95% confidence level (Appendix A), the VRM mean direction cannot be distinguished from the expected GAD for Ascension (Figure 6.8c). Directions of high-T components are random (Figure 6.8c).

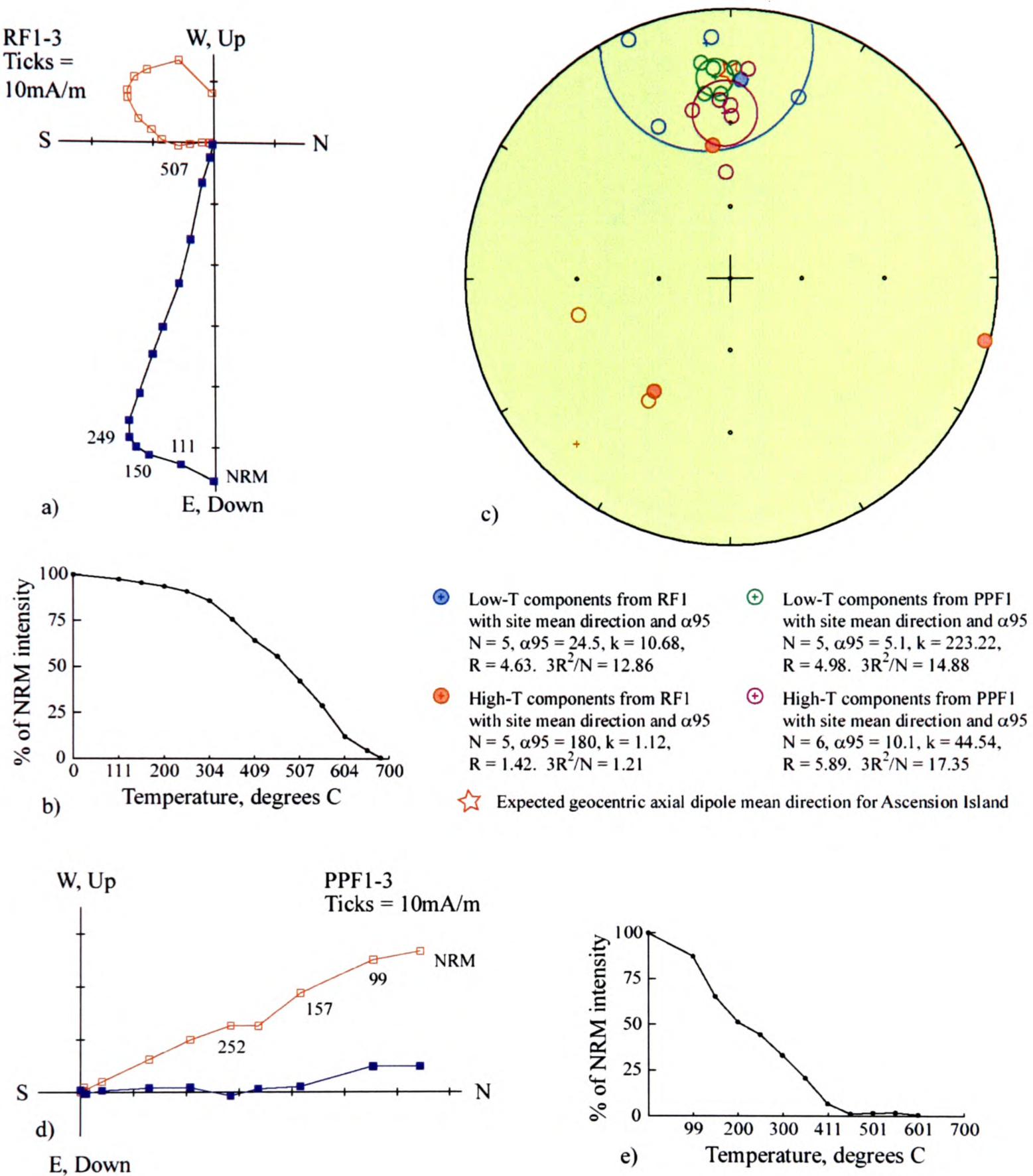


Figure 6.7: Zijderveld plots, T_b spectra and equal area stereoplots for PPF1 and RF1. RF1-3 displays type 1c remanence behaviour (Table 3.2) and exhibits curvature between components (plot a). T_e s for RF1-3 are 249°C-304°C and ~507°C. The T_b spectrum for RF1-3 (plot b) is single-phase (type C2, Table 3.3) and NRM intensity is only reduced to ~1% above 675°C, implying that remanence is carried by haematite. Plot c) shows the distribution of individual low-T and high-T components for all samples from RF1, with site mean directions (small crosses) and α_{95} value (large circle). Low-T directions are grouped and high-T directions are random. PPF1-3 displays type 1b remanence behaviour (Table 3.2), but low-T and high-T components are sub-parallel (plot d). T_e for PPF1-3 is ~252°C. The T_b spectrum for PPF1-3 (plot e) is two-phase (type E4, Table 3.3) with drops in intensity at ~200°C and ~450°C, suggesting that remanence is carried by titanomagnetites of two different compositions. Plot c) shows the distribution of individual low-T and high-T components for all samples from PPF1, with site mean directions (small crosses) and α_{95} values (large circles). Both low-T and high-T directions are tightly grouped. Points on z-plots represent heating steps of 50°C except where indicated otherwise and temperatures on z-plots and T_b spectra have been corrected to account for the thermal gradient of the furnace. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

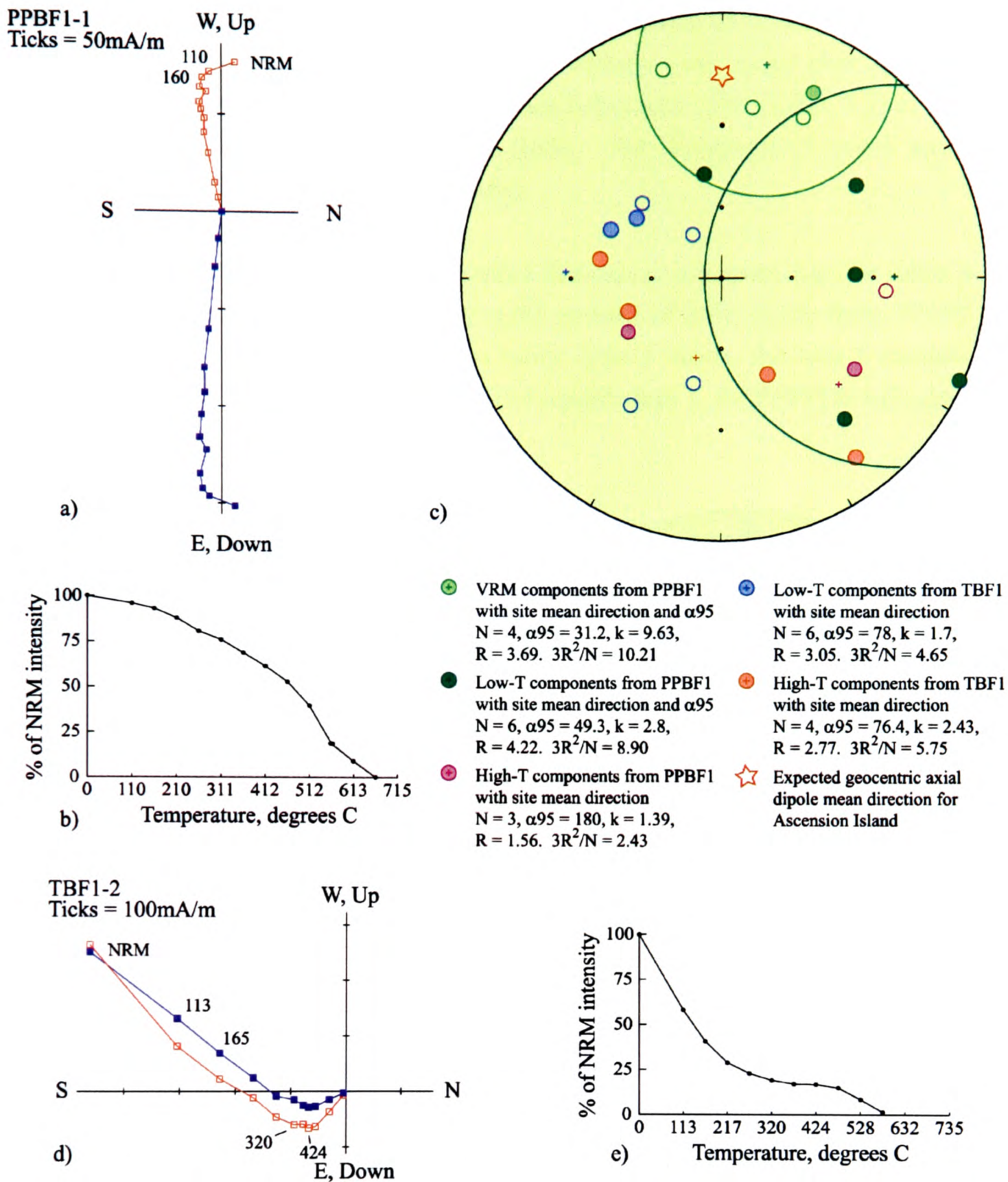


Figure 6.8: Zijderveld plots, T_b spectra and equal area stereoplots for clasts from matrix-dominated pumiceous breccias that show type 2 remanence behaviour (Table 3.2). PPBF1-1 displays type 2a remanence behaviour (Table 3.2), but has an additional VRM component, present to $\sim 160^\circ\text{C}$ (plot a). The T_b spectrum for PPBF1-1 (plot b) is two-phase (type E2, Table 3.3), with decreases in intensity seen at $\sim 580^\circ\text{C}$ and $\sim 650^\circ\text{C}$, implying that remanence is carried by magnetite and maghaemite (or haematite). Plot c shows the distribution of individual VRM, low-T and high-T components for samples from PPBF1, with site mean directions (small crosses) and α_{95} values (large circles). VRM directions are grouped and the VRM mean direction approximates the expected GAD for Ascension. Low-T directions are also grouped, however the site mean direction lies in a direction distinctly different to the GAD for Ascension. Directions of high-T components are random. TBF1-2 displays type 2b remanence behaviour (plot d) and has a relict T_e of $\sim 424^\circ\text{C}$. The T_b spectrum for TBF1-2 (plot e) is two-phase (type F1, Table 3.3) with drops in intensity at $\sim 217^\circ\text{C}$ and $\sim 580^\circ\text{C}$, suggesting that remanence is carried by titanomagnetite and magnetite. Plot c shows the distribution of individual low-T and high-T components for samples from TBF1, with site mean directions (small crosses) and α_{95} values (large circles). Both low-T and high-T directions are random. Points on z-plots represent heating steps of 50°C except where indicated otherwise and temperatures on z-plots and T_b spectra have been corrected to account for the thermal gradient of the furnace. Open and filled shapes on stereoplots represent points on the upper and lower hemispheres respectively.

Fifty percent of clasts from TBF1 display type 2b remanence behaviour (e.g. Figure 6.8d). The remaining 50% of clasts can be divided equally into those that show type 2a remanence behaviour (17%), type 2c remanence behaviour (17%; Table 3.2) or for which no magnetic components can be resolved (16%). The directions of low-T and high-T components in TBF1 are random (Figure 6.8c).

Remanence characteristics for PPPF1 are more difficult to interpret than for other matrix-dominated pumiceous breccias. Seventy-eight percent of lithic clasts from PPPF1 show type 1 remanence behaviour, however in many type 1 clasts, the low-T component is removed by ~150-200°C (e.g. Figure 6.9a). The equilibrium T_e for PPPF1 is estimated to be

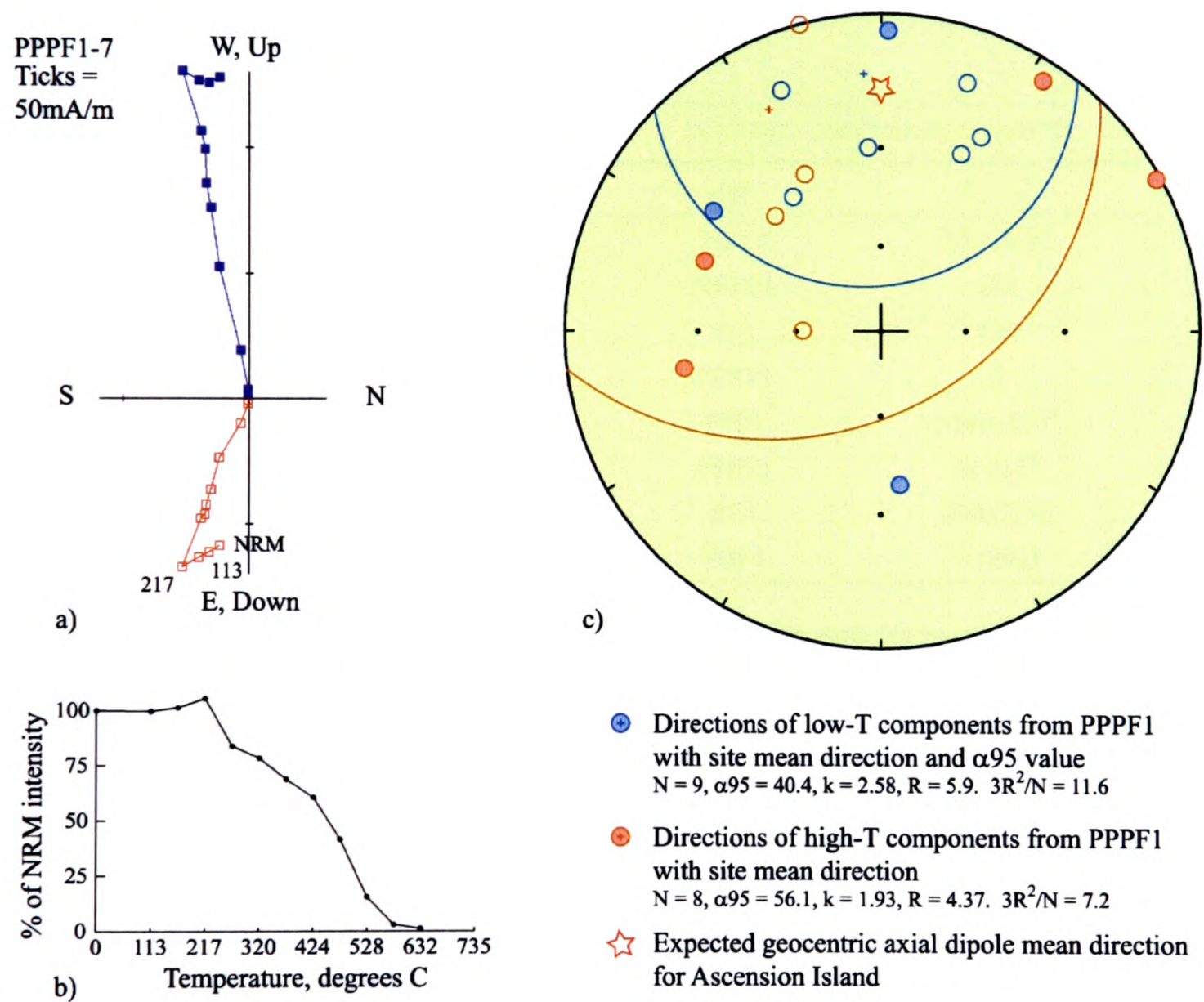


Figure 6.9: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot for clasts from PPPF1. PPPF1-7 displays type 1b remanence behaviour (Table 3.2), however the low-T component is removed by ~217°C and consequently may be a VRM (plot a). Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for PPPF1-7 (plot b) is of type A2 (Table 3.3) and shows an apparent increase in intensity from 0°C -217°C as the low-T component tracks away from the origin. Intensity decreases to <1% of the NRM value by ~580°C, suggesting that remanence is carried by magnetite. Plot c) shows the distribution of individual low-T and high-T components for all samples from PPPF1, with site mean directions (small crosses) and α_{95} values (large circles). Low-T and high-T directions are grouped, though grouping is poor (α_{95} values are high). Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

211°C (Table 6.1; Figure 6.10). In rocks of ~1Ma (the oldest age of exposed rocks on Ascension), VRM components are expected to be removed by 163°C (Section 3.3.3), however VRMs may persist to higher temperatures if they are carried by multi-domain grains. It is therefore not possible to determine whether low-T components in PPPF1 are VRMs or low temperature TRMs. Directions of low-T components are grouped, though grouping is poor (Figure 6.9c). The remaining 22% of clasts from PPPF1 show type 2 remanence behaviour (Table 3.2).

6.1.2 Emplacement temperatures

Table 6.1 shows best estimates of equilibrium emplacement temperature for the pumiceous breccia units sampled on Ascension.

CLAST-DOMINATED UNITS		MATRIX-DOMINATED UNITS	
unit	T _e , °C	unit	T _e , °C
BPB1 (average)	204	NRF3	243 (404)
BPB1 (separate)	204 ^U , 356 ^L	NRPF1	186
MRGB1	265	PF1	199
MRGB2	350	PPBF1	0
NEB1	438	PPF1	>580, 227 ²
NRGP1	0 (295)	PPPF1	0/ 211 [†]
SB1	450, 216 ²	RF1	200 (300)
SB3	>580, 229 ²	TBF1	0 (292)

Table 6.1: Best estimates of equilibrium emplacement temperature for pumiceous breccia units sampled on Ascension. Units that are inferred to have been emplaced at ambient temperature are given a T_e of 0° (although *sensu stricto* T_e should = ambient temperature). Values in brackets represent relict T_es for deposits (i.e. the average T_e of the source deposit(s)). ²secondary (pTRM) overprint temperature. ^U and ^L represent upper and lower units (respectively) sampled at BPB1. [†]this unit has two possible values for T_e.

Eleven of the pumiceous breccias (73%) are interpreted as having been emplaced above ambient temperature. Emplacement temperatures for these units range from 186°C to >580°C (Table 6.1). Samples were taken from two units at BPB1. T_es for the upper and lower units are given in Table 6.1, along with an overall estimate of T_e for the unit. Units SB1, SB3 and PPF1 each display two T_es, the second of which is interpreted as the result of thermal overprinting by overlying units.

Units NRGP1, PPBF1 and TBF1 are interpreted as having been emplaced at ambient temperature (cold) and have therefore been given a T_e of 0°C (although T_e should strictly be ambient temperature). NRGP1 and TBF1 have also been given a secondary T_e, shown in brackets (Table 6.1), which represents the *relict* T_e for the unit (i.e. T_e for the unit from

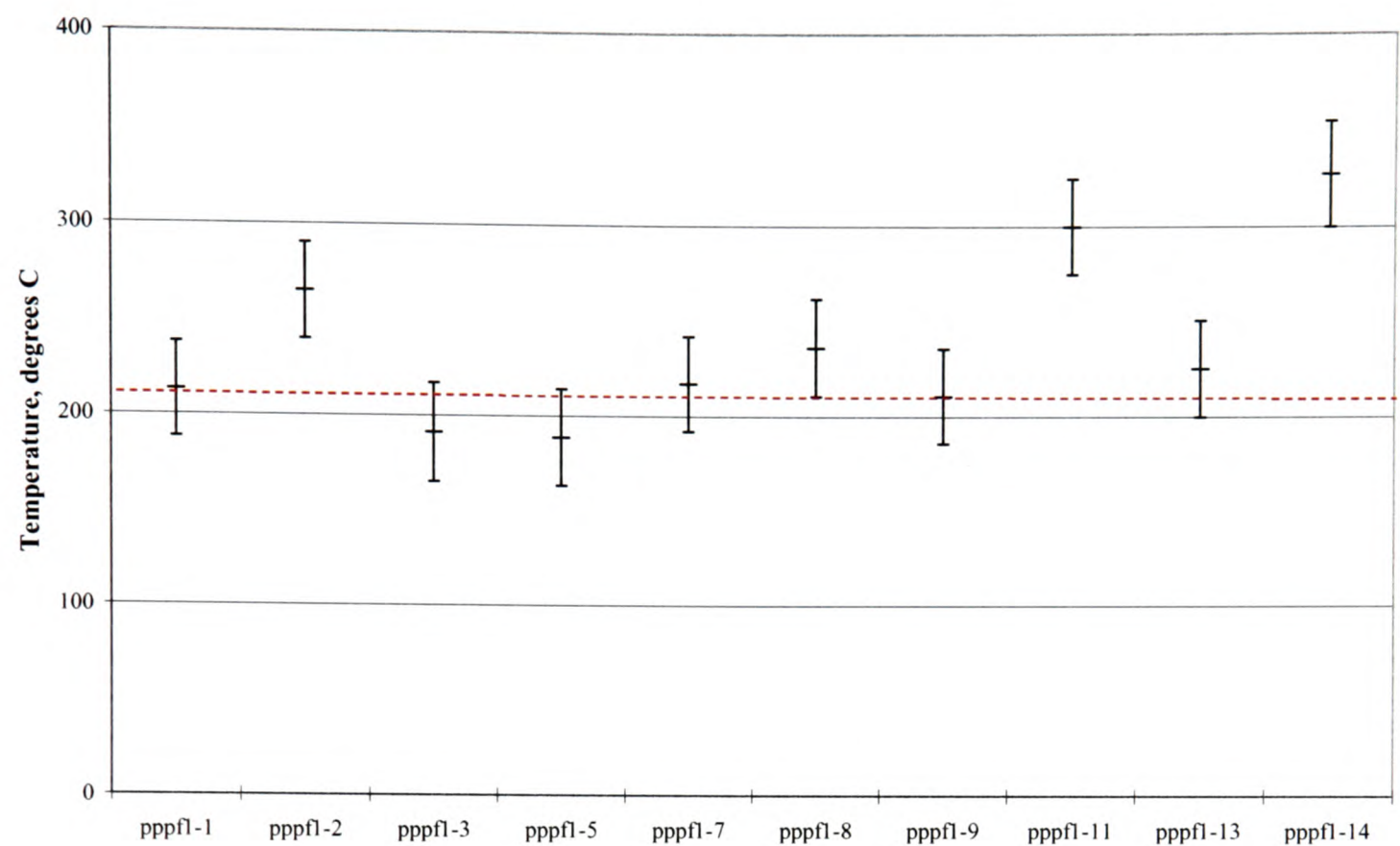


Figure 6.10: Plot showing individual emplacement temperatures for clasts from PPPF1. The red line represents the equilibrium emplacement temperature for the deposit, which is 211°C.

which clasts were sourced). Relict T_e s were calculated from the break-points between low-T and high-T components in multi-component type 2 clasts.

Two possible T_e s are given for PPPF1 (Table 6.1): 1) a T_e of 0°C, which assumes that low-T components are VRMs and hence that the unit was emplaced at ambient temperature, and 2) a T_e of 211°C, which assumes that low-T components are TRMs and hence that the unit was emplaced hot (Figure 6.10).

6.1.3 Magnetic mineralogy

One hundred and forty-four clasts from pumiceous breccias were thermally demagnetised in the laboratory. Magnetic mineralogy for these clasts was estimated mainly through analysis of blocking temperature T_b spectra, with high-T χ measurements carried out on selected clasts to corroborate conclusions drawn from T_b spectra. Eighty-five percent of clasts display distributed T_b spectra, whilst 15% display discrete T_b spectra. NRM intensities range from 1.4mA/m to 6.5A/m for lithic clasts and from 0.2mA/m to 238mA/m for pumice clasts. Maximum unblocking temperatures range from 422°C to 680°C, however the most common maximum unblocking temperature is 580°C, suggesting that magnetite is the most ubiquitous magnetic mineral in clasts from felsic airfall deposits.

A summary of the different types of T_b spectra displayed by clasts from pumiceous breccias is shown in Table 6.2. Thirty-nine percent of clasts display single-phase T_b spectra (demagnetisation types A, B, C and D, Table 6.2), suggesting that they have single-phase mineralogies. In 58% of clasts, T_b spectra are multi-phase (demagnetisation types E, F and G, Table 6.2), suggesting that remanence is carried by more than one mineral phase. In the remaining 3% of clasts, demagnetisation spectra cannot be classified due to noisy data.

T_b spectra type	% of clasts	INTERPRETATION
A	17	single-phase magnetite
B	17	single-phase maghaemite
C	4	single-phase haematite
D	1	single-phase titanomagnetite
E	35	two-phase
F	15	two/three phase (low T_c)
G	8	three+ phase

Table 6.2: Summary of T_b spectra types for clasts from pumiceous breccias sampled on Ascension (with basic interpretation).

The most common demagnetisation behaviour displayed by clasts from pumiceous breccias is type E (Table 3.3; e.g. Figure 6.4b; 35% of clasts). The two-phase nature of T_b spectra for these clasts suggests that remanence is carried by two mineral phases: a titanomagnetite phase plus magnetite (type E1; 21 clasts), maghaemite (type E2; 14 clasts), a second titanomagnetite (type E4; 7 clasts) or haematite (type E3; 9 clasts). The composition of the titanomagnetite phase can be approximated from its T_c using a graph of T_c v titanomagnetite composition (see Section 3.5.1, Figure 3.9). T_b spectra data suggest that high-titanium (low T_c) titanomagnetites have T_c s ranging from 114°C to 400°C, suggesting compositions of TM31 to TM69. Low-titanium (high T_c) titanomagnetites have T_c s ranging from 400°C to 569°C, suggesting compositions of TM02 to TM31.

Next most common are types A and B demagnetisation behaviour (Table3.3), which are each displayed by 17% of clasts (e.g. Figures 6.3b, 6.9b). These clasts display a single-phase T_b spectrum with intensity reduced to ~1% of the NRM value at ~580°C (A), suggesting that remanence is carried by magnetite, or between ~590°C and 675°C (B), suggesting that remanence is carried by maghaemite.

Type F demagnetisation behaviour (Table 3.3) is displayed by 15% of clasts from pumiceous breccias. These clasts display a multi-phase T_b spectrum, with a sharp decrease in intensity in the first few steps of demagnetisation (between 0°C and ~200°C).

This type of behaviour can be attributed to the removal of a high-Ti titanomagnetite component and is displayed by the majority of samples from units NRPF1 and PPPF1. However, alteration products such as goethite may also demagnetise over this temperature range. In some cases, the drop in intensity may simply represent the removal of a lab-induced viscous component, so that the T_b spectra curve does not reflect the magnetic mineralogy of the sample. For example, BPB1-1 has a T_b spectrum that displays a drop in intensity from 0°C to 114°C (Figure 6.11b). However, a corresponding drop in susceptibility is not seen in the high-T χ data (Figure 6.11c). The remaining part of the T_b spectrum for BPB1-1 is two-phase and is interpreted to reflect the presence of titanomagnetite with a T_c of ~424°C and magnetite with a T_c of ~580°C. This is consistent with the high-T χ data, which show an initial increase, then a decrease in susceptibility between 400°C and 450°C, corresponding to the titanomagnetite phase. A further increase (interpreted as a Hopkinson Peak) and then sharp drop in susceptibility between ~550°C and 580°C follows, which is typical of single domain magnetite.

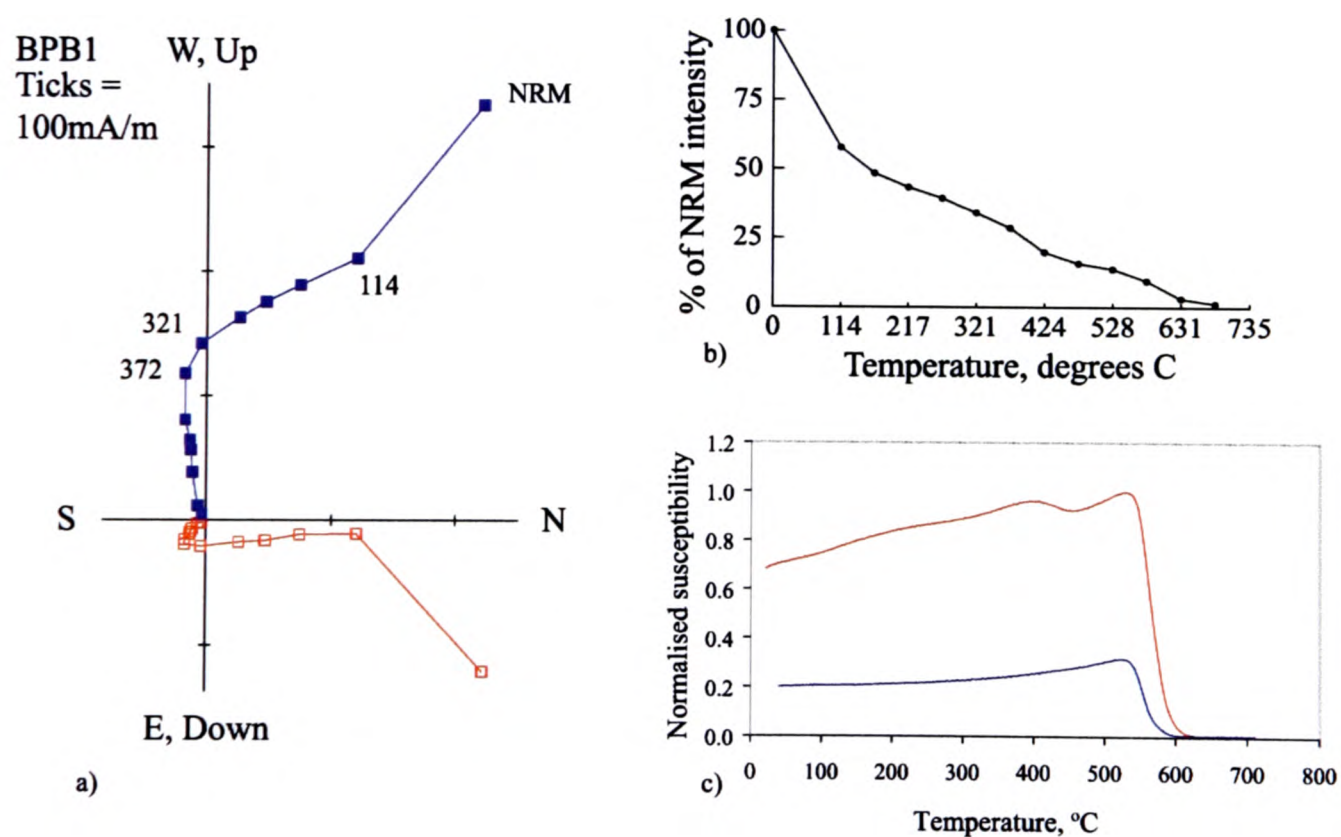


Figure 6.11: a) Zijderveld plot, b) T_b spectrum and c) high-T susceptibility (high-T χ) data for BPB1. The T_b spectrum for BPB1 shows a drop in intensity from 0°C to 114°C. This is inferred to reflect the removal of a lab-induced VRM component, rather than the demagnetisation of a (low T_c) titanomagnetite phase. This is substantiated by the z-plot (which shows that the NRM direction does not lie on the same trajectory as the rest of the low-T component), and the high-T data, which gives no indication of the presence of a mineral phase with a T_c of ~100°C. The remainder of the T_b spectrum correlates with the high-T data, showing a decrease in intensity at ~424°C and at ~585°C, which is reflected in the high-T data. In plot c), the red and blue curves represent heating and cooling respectively. The sample was measured in air and alteration has consequently occurred on heating. A large drop in susceptibility is seen in the cooling curve and the inferred low-Ti titanomagnetite phase (T_c ~450°C) disappears. This suggests that the sample has oxidised on heating, causing the alteration of titanomagnetite to magnetite. Points on the z-plot represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace.

Eight percent of clasts display a three-phase, or more complex T_b spectra (type G demagnetisation behaviour; Table 3.3). This is inferred to reflect a three-phase or more complex mineralogy.

Types C and D demagnetisation behaviour (Table 3.3) are displayed by just 4% and 1% of clasts from pumiceous breccias, respectively. These clasts display single-phase T_b spectra with intensity reduced to ~1% of the NRM value at or above 675°C (C; e.g. Figure 6.7b), or below 580°C (D). Remanence in these clasts is inferred to be carried by haematite (C) or titanomagnetite (D).

In general, a multi-phase T_b spectrum is inferred to reflect a multi-phase mineralogy, and comparison of T_b spectra with high-temperature susceptibility (high-T χ) data for pumiceous breccias suggests that in most cases, the T_b spectrum provides a reliable estimate of magnetic mineralogy (Section 3.6.3).

6.1.4 Secular variation

Figure 6.12 shows mean directions for low-T components from hot pumiceous breccia deposits.

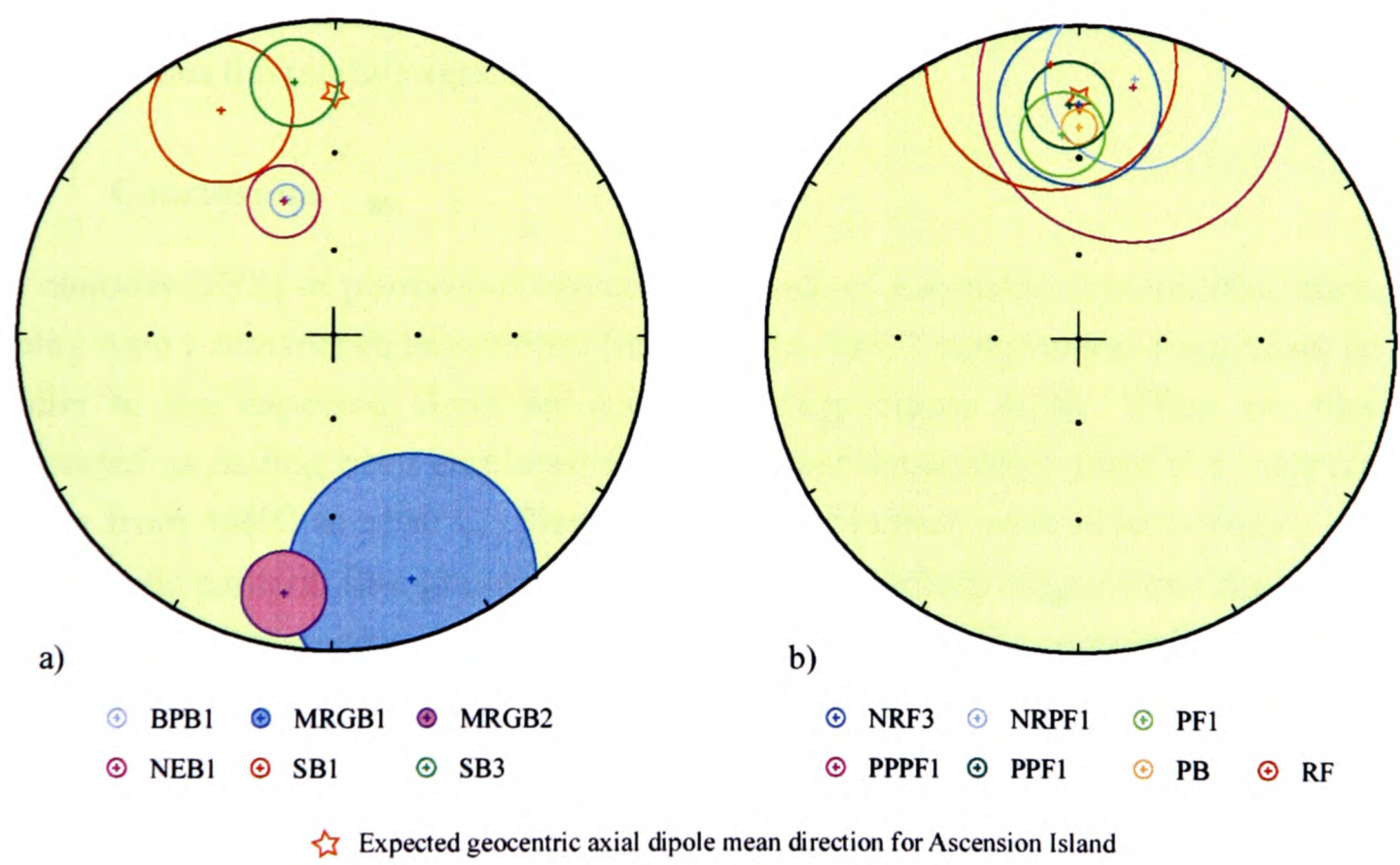


Figure 6.12: Equal area stereoplots showing site mean directions (small crosses) and a95 values (circles) for a) clast-dominated and b) matrix-dominated pumiceous breccia units from Ascension. Three of the clast-dominated units show normal polarity and mean directions for these units deviate from the expected GAD mean direction for Ascension both in declination and inclination. Two units show reversed polarity. Mean directions for BPB and NEB1 are almost identical, suggesting that they may be part of the same deposit. Mean directions for SB1 and SB3 vary, but cannot be distinguished from one another at the 95% confidence level. This is also the case for MRGB1/2. All matrix-dominated pumiceous breccia units display normal polarity and approximate the expected GAD for Ascension. Mean directions cannot be distinguished from one another at the 95% confidence level. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplots respectively.

6.1.4.1 Clast-dominated pumiceous breccias

Units BPB, NEB1, SB1 and SB3 show normal polarity, but mean directions deviate from the expected GAD for Ascension by up to 20° in declination and 26° in inclination (Figure 6.12a). Clast-dominated pumiceous breccias can be placed into three groups, which share similar site mean directions: BPB/NEB1, SB1/SB3 and MRGB1/MRGB2 (Figure 6.12a). The mean direction for each group of units is distinct from the other two, suggesting that the three groups were *not* deposited contemporaneously. At the 95% confidence level (Appendix A), mean directions for units from individual groups (e.g. BPB and NEB) cannot be distinguished from one another and relative ages cannot therefore be inferred. Units MRGB1 and MRGB2 display reversed polarity, which suggests that they were deposited before the last magnetic reversal (i.e. within the Matuyama reversed epoch), or during a reversed event within the Brunhes normal epoch (Section 3.6.4). Magnetostratigraphic data (Chapter 7) suggests that these units are more likely to have been deposited during the Matuyama epoch and hence that they have ages of >0.78Ma.

6.1.4.2 Matrix-dominated pumiceous breccias

All matrix-dominated breccias display normal polarity and mean directions approximate the expected GAD for Ascension (Figure 6.12b). Mean directions cannot be distinguished from one another at the 95% confidence level (Appendix A) and hence no inferences can be made about the relative ages of these units.

6.1.5 Conclusions

The majority (73%) of pumiceous breccias sampled on Ascension contain lithic clasts that display type 1 remanence behaviour (Table 3.2), i.e. low-T components from clasts lie sub-parallel to the expected GAD for Ascension (e.g. Figure 6.2a). They are therefore interpreted as having been emplaced above ambient temperature ('hot'), at temperatures ranging from 186°C to >580°C. These data in combination with field evidence (such as high juvenile content, fine-grained basal layers, poor sorting) suggest that these units are the products of pumiceous pyroclastic flows, which typically contain hot juvenile and lithic clasts (Section 3.6). Juvenile (pumice) clasts from clast-dominated pumiceous breccias also typically display type 1 remanence behaviour (Table 3.2), moreover most display a single-component remanence (i.e. type 1a behaviour; Table 3.2), which is expected from juvenile clasts from hot pyroclastic deposits (Section 3.6.1). However, some clasts display a two-component remanence (i.e. type 1b remanence behaviour; Table 3.2). This is inferred to reflect clast rotation during cooling or VRM overprinting. Alternatively, it may be the result of incomplete CRM overprinting of an original TRM component in a reworked deposit, as is the case in juvenile (pumice) samples from the Pourahu deposits of Ruapehu (Section 3.7).

Three pumiceous breccias (20% of units) contain lithic clasts in which low-T components lie in a direction distinct to the expected GAD for Ascension (i.e. type 2 remanence behaviour; Table 3.2, e.g. Figure 6.5a). Many of these lithic clasts display a multi-component remanence (i.e. types 2b, 2c). These units are interpreted as having been emplaced at ambient temperature (cold) and multi-component clasts are inferred to have been reworked from pre-existing (previously hot) pyroclastic material. Cold units are interpreted to be the product either of mudflows, debris flows, or of the reworking of pyroclastic material by water, all of which processes commonly incorporate multi-component, cold clasts.

Two possible interpretations are presented for PPPF1, each of which assumes a different origin for low-T components in clasts from the unit. However, PPPF1 is preferentially interpreted as a cold reworked deposit, sourced from pre-existing pyroclastic material, because of the presence of cross-stratified grit layers within the deposit and the narrow range of T_c s displayed by individual clasts from the deposit (hot pyroclastic deposits commonly display a range of clasts T_c s; Section 3.6.2). This interpretation assumes that low-T components are VRMs.

Most clasts from pumiceous breccias demagnetise over a wide temperature range (i.e. display a distributed T_b spectrum), suggesting that magnetic minerals in these clasts have a wide range of grain sizes. Those clasts in which T_b spectra are discrete are interpreted to contain magnetic grains with a more narrow range of sizes. In the majority of cases, T_b spectra provide a reliable estimate of magnetic mineralogy. The major remanence carrier in pumiceous breccia samples is inferred to be magnetite, although maghaemite and titanomagnetite also carry remanence. Compositions of titanomagnetite phases (estimated from Figure 3.9) range from TM02 to TM69.

6.1.5.1 Clast-dominated pumiceous breccias

Palaeomagnetic interpretations for all clast-dominated pumiceous breccias except NRGP1 confirm field interpretations that clast-dominated pumiceous breccias are the products of pyroclastic flows. These deposits display features such as poor sorting, fine-grained basal layers and are juvenile (pumice) rich.

Palaeomagnetic results conflict with field interpretations for NRGP1. NRGP1 lies within a sequence of steeply dipping pumice airfall units on the NASA road (Chapter 2). Field evidence (such as its position within a sequence of airfalls, angular pumice and lithic-rich nature, plus the presence of some cross-stratification) suggested that NRGP1 was a hot pyroclastic deposit, formed by minor collapse of the eruption column that produced the associated airfall deposits. However, palaeomagnetic data suggests that NRGP1 was emplaced at ambient temperature (clasts show type 2 remanence behaviour; Table 3.2; e.g. Figure 6.5a). Moreover, 50% of the clasts from NRGP1 display a multi-component

remanence, which suggests that the unit has been reworked from the associated airfall deposits some time after deposition and cooling. Reworking is inferred to be the result of slumping of the airfall deposits, either because they were deposited on such steep slopes (Figure 2.5), or because they were tilted by the intrusion of the rhyolite dome that is situated beneath this pyroclastic sequence.

Mean low-T directions for BPB and NEB1 are almost identical (Figure 6.12a) and they also show similar field characteristics. BPB and NEB1 may therefore be parts of the same pyroclastic deposit. However, emplacement temperatures for BPB and NEB1 differ by more than 200°C and NEB1, which is likely to be the more distal unit¹, has a higher T_c than that of BPB (Table 6.1). This is unusual, because proximal pyroclastic deposits are typically hotter than their distal equivalents (Cas and Wright, 1988; Fisher and Schmincke, 1984). An explanation for this behaviour may be provided if water was involved in the early stages of the eruption of NEB1 and BPB. This would have caused initial eruptive material (which is likely to be deposited proximally) to be cooled. If the source of water was later removed or blocked, subsequent eruptive material (which is likely to be deposited more distally) would be erupted and hence emplaced at higher temperatures.

Clasts from SB1 and SB3 display sub-parallel low-T and high-T components. Directions of both low-T *and* high-T components are tightly grouped (Figure 6.4c). This implies that both low-T and high-T components were formed *in situ* and thus that low-T components are overprints. Clasts from SB1 and SB3 are interpreted, therefore, to have originally held a single-component remanence, suggesting that they were emplaced at temperatures above the Curie temperatures of their constituent magnetic minerals.

Low-T components from SB1 and SB3 are unlikely to be VRMs, as they persist to temperatures up to ~450°C. A CRM origin for low-T components is possible, as in many clasts (e.g. SB1-1) low-T and high-T components are inferred to be carried by different mineral phases. SB1-1 has a two-phase T_b spectrum (suggesting a two-phase mineralogy). The initial drop in intensity displayed by the T_b spectrum corresponds to the removal of the low-T component and the subsequent decrease in intensity to the removal of the high-T component (Figures 6.4a,b). A change in bulk susceptibility on heating is also seen in SB1-1, which suggests an unstable mineralogy. An alternative origin for low-T components is as thermal overprints (pTRMs) acquired when overlying hot material was subsequently deposited. Thermal overprinting is plausible for SB1 and SB3 as field evidence suggests that they are each overlain by a hot flow deposit. Low-T and high-T mean directions for SB1 and SB3 are statistically similar (Figure 6.12a) and it is possible, therefore that they have similar ages. This is substantiated by field relationships, which

¹ NEB1 is located on the northeast coast of the island whilst BPB1 is closer to the eastern-central part of the island (Figure 6.1), which is the likely source of the majority of the pyroclastic material on the island (see Chapter 7).

suggest that SB1 and SB3 are part of the same thick sequence of pumice deposits (the Streaky Bacon Formation; see Chapter 2, Section 2.2.2.1).

6.1.5.2 Matrix-dominated pumiceous breccias

Palaeomagnetic data for matrix-dominated pumiceous breccias allows further interpretation of these deposits to be made. Field evidence, such as poor sorting and high matrix content, suggests that the majority of the matrix-dominated pumiceous breccias originated as flows, but allows no distinction between hot and cold flow types.

Sixty-three percent of units (NRF3, NRPF1, PF1, PPF1 and RF1) contain lithic clasts in which low-T components are orientated sub-parallel to the expected GAD for Ascension (i.e. type 1 remanence behaviour; Table 3.2), suggesting that they were emplaced hot. These units typically have a high juvenile (pumice) and fines content and are poorly-sorted and are therefore interpreted as the products of hot pumiceous pyroclastic flows (which are expected to incorporate hot lithic and juvenile clasts).

PPBF1 and TBF1 contain lithic clasts in which low-T directions are distinct from the expected GAD (i.e. type 2 remanence behaviour; Table 3.2), suggesting that they were emplaced cold. These data in combination with field evidence such as rounded pumice clasts and cross-stratification, suggests that PPBF1 and TBF1 are either fluvially reworked deposits or mudflow deposits. Low-T components are grouped in PPBF1, though the low-T mean direction lies in direction that is distinct from the GAD for Ascension (Figure 6.8c). Grouping of low-T components is therefore not interpreted to reflect heating of clasts, but may result from imbrication, which can occur during fluvial reworking. This favours a reworked origin for PPBF1.

Palaeomagnetic data suggest that PPPF1 is either a hot deposit (assuming that low-T components are TRMs) or a cold deposit (assuming that low-T components are VRMs). However the combination of palaeomagnetic and field evidence for PPPF1 (such as internal stratification and the location of PPPF1 at the base of a dry riverbed), suggest that it has a reworked origin.

PPF1 displays similar palaeomagnetic characteristics to SB1 and SB3 (e.g. sub-parallel low-T and high-T components, tightly grouped low-T and high-T directions). This suggests that low-T components are secondary overprints, which in turn suggests that clasts from PPF1 originally held a single-component remanence and were hence emplaced at temperatures $>T_c$. As with SB1 and SB3, low-T components in PPF1 are interpreted to be either CRM or pTRM overprints. A CRM origin for low-T components is substantiated by the two-phase nature of T_b spectra for clasts from PPF1, however, thermal overprinting is also plausible as PPF1 is overlain by a hot lava breccia deposit.

6.2 SCORIACEOUS BRECCIAS

Only one scoriaceous breccia deposit (SF1) was sampled on Ascension for palaeomagnetic analysis (Figure 6.1). All samples from this unit are lithic clasts of vesicular mafic lava. Some clasts have a ropy texture and others contain discrete areas of less dense, scoriaceous-like material. 'True' vesicular juvenile (scoria) clasts were difficult to distinguish from lithic clasts in SF1.

6.2.1 Remanence characteristics

All clasts from SF1 show a stable type 1 remanence (Table 3.2), i.e. low-T components lie in a direction sub-parallel to the expected GAD for Ascension. Furthermore, the majority of clasts show a two-component remanence, i.e. type 1b remanence behaviour. However, in these clasts low-T and high-T components are sub-parallel (e.g. Figure 6.13a,d; as is seen in clasts from SB1/3 and PPF1). Both sets of components are well-grouped and approximate the expected GAD mean direction for Ascension (Figure 6.13g). This implies that low-T and high-T components were both acquired in situ and hence that low-T components are overprints.

In clasts SF1-9 (Figure 6.13d), SF1-5 and SF1-7, the low-T component persists to $\sim 250^\circ\text{C}$ and carries the majority of the NRM remanence (Figure 6.13e). The high-T component is inferred to have been almost entirely overprinted by the low-T component, as it is carried by only a small percentage of the remanence (Figure 6.13e). In clasts SF1-6 (Figure 6.13a) and SF1-8, low-T components are present to 300°C - 355°C . High-T components are more prominent in these clasts (carried by a greater part of the remanence), suggesting that overprinting has occurred to a lesser degree.

Low-T components are inferred to be CRM overprints. A chemical origin for low-T components is likely as low-T and high-T components are carried by different mineral phases. In addition, bulk susceptibility for clasts from SF1 shows a significant increase on heating above 300°C , suggesting that the mineralogy of samples is unstable and alters at high temperatures. As low-T components are present to temperatures well above 200°C , they are unlikely to be VRMs. A pTRM origin is also unlikely as it assumes the presence of a significant hot unit stratigraphically above unit SF1, which is not seen in the field.

6.2.2 Emplacement temperatures

Temperature information cannot be used to provide an estimate for T_c in clasts from SF1, as low-T components are inferred to be of chemical rather than thermal origin. However, assuming low-T components are overprints, clasts are likely to have held a single-component TRM prior to overprinting, suggesting that SF1 was emplaced at a temperature above T_c (580°C).

6.2.3 Magnetic mineralogy

Magnetic mineralogy in clasts from SF1 was estimated using blocking temperature T_b spectra and high-temperature susceptibility (high-T χ) data. T_b spectra in clasts from SF1 are distributed, although all show a significant drop in intensity in the first few steps of

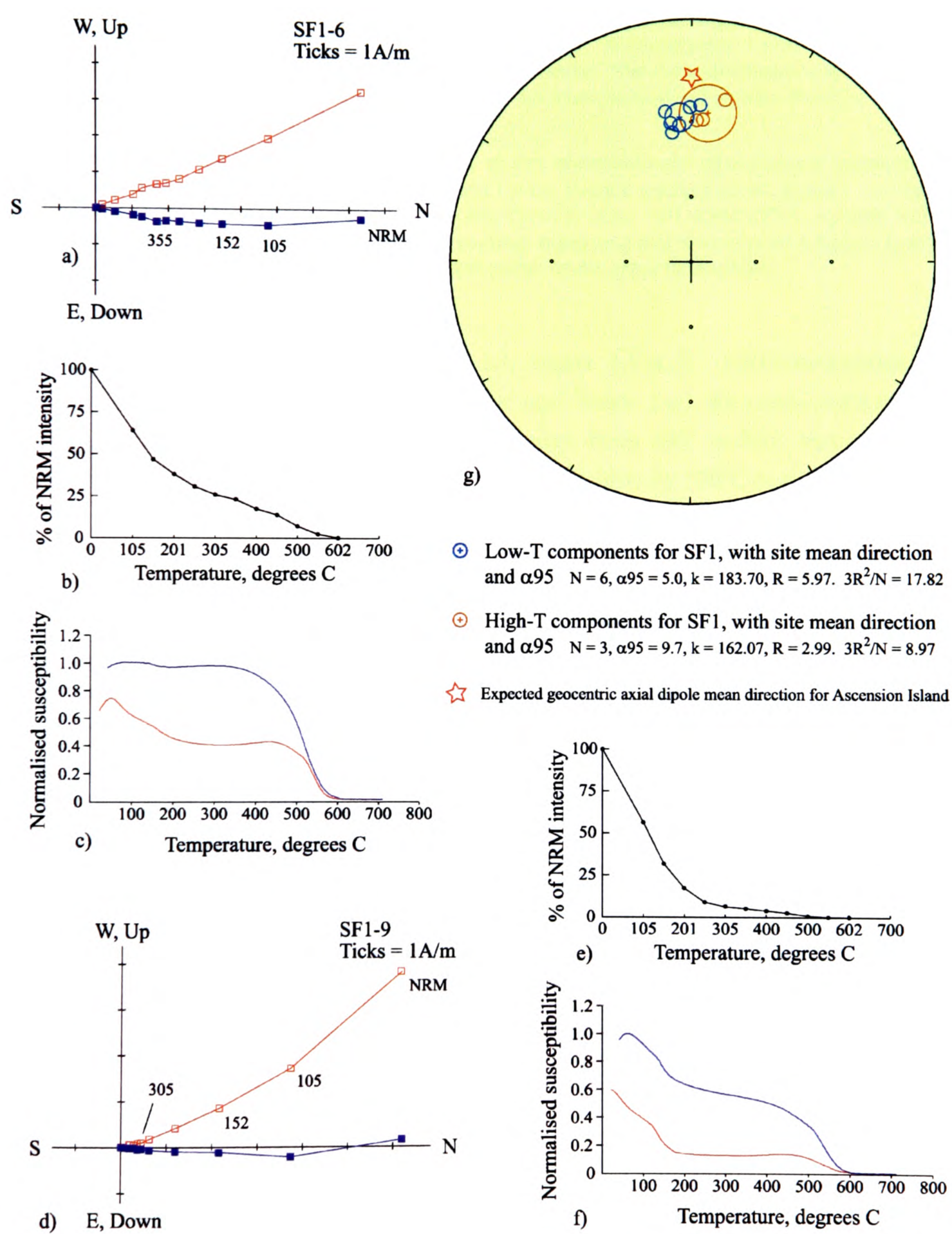


Figure 6.13: Zijderveld plots, T_b spectra and high-temperature susceptibility plots for SF1-6 and SF1-9, plus equal area stereonet showing individual low-T and high-T directions for all samples from SF1. See over page for full caption.

Figure 6.13 (continued): SF1-6 and SF1-9 show type 1b remanence behaviour, with sub-parallel low-T and high-T components. In SF1-9 the low-T component persists to 250°C-305°C (plot d) and has almost fully overprinted the high-T component (1st point is inferred to a lab-induced VRM and is excluded from analysis). T_b spectra for SF1-9 (plot e) shows type F4 demagnetisation behaviour (Table 3.3) and implies that the low-T component comprises >90% of the NRM remanence. High-T χ data for SF1-9 (plot f) indicate a two-phase mineralogy, with a predominant low T_c titanomagnetite phase and a less significant magnetite or low-titanium titanomagnetite phase. In SF1-6 (plot a), the low-T component is present to 355°C, but the high-T component is more prominent, suggesting that overprinting has occurred to a lesser degree. T_b spectra for SF1-6 (plot b) shows type F1 behaviour (Table 3.3) with a decrease in intensity at 150°C-201°C and full demagnetisation at ~580°C. High-T χ data (plot d) suggests that the sample has a titanomagnetite – magnetite mineralogy with a more prominent titanomagnetite component. Low-T and high-T component directions (plot g) are well grouped and similar. Site mean declinations approximate that of the expected GAD mean direction for Ascension, but site mean inclinations deviate from the GAD mean by up to 13°.

Points on vector plots represent heating steps of 50°C except where indicated otherwise and temperatures on z-plots and T_b spectra have been corrected to account for the thermal gradient of the furnace. In high-T χ plots, the heating curve is shown in red and the cooling curve in blue. SF1-6 and SF1-9, samples were run in air, and an increase in susceptibility is seen on cooling, suggesting that alteration to a higher T_c mineral has occurred. Open shapes on the stereoplot represent points on the upper hemisphere.

demagnetisation (type F behaviour, Table 3.3, Figure 6.13a,d). NRM intensities range from 2.7-8.0 A/m, reflecting the mafic nature and hence high Fe oxide content of the deposit. Maximum unblocking temperatures range from 490° to 580°, but in all clasts except SF1-6, intensity is reduced to 1-2% of the NRM value by 550°C (e.g. Figure 6.13e).

T_b spectra and high-T χ data correlate well for clasts from SF1 and suggest that remanence is carried by two mineral phases – a low T_c titanomagnetite phase and a higher T_c Ti-poor titanomagnetite, or magnetite phase (Figures 6.13b,c,e,f). Titanium-rich titanomagnetite phases have T_c s ranging from ~150°C to ~250°C, suggesting compositions of TM52 to TM65 (estimated from Figure 3.9).

Clasts in which the high-T component has been mostly overprinted by the low-T component (e.g. SF1-9, Figure 6.13d) show a substantial (low T_c) titanomagnetite phase in their mineralogy and a less prominent magnetite phase (Figures 6.13e,f). In clasts in which the high-T component is more pervasive (e.g. SF1-6), the magnetite phase is more prominent (Figures 6.13a,b,c). This suggests that low-T components in these samples are carried by the lower T_c titanomagnetite phase, whilst high-T components are carried magnetite (or Ti-poor titanomagnetite). This behaviour is also exhibited by samples from the Pourahu deposit of Ruapehu, New Zealand (Section 3.7).

6.2.3.1 Magnetic mineralogy and VRM

VRM components are not displayed by any of the samples from unit SF1 and this is consistent with the fact that samples tend to possess a low T_c titanomagnetite phase in their mineralogy.

6.2.4 Secular variation

Mean declinations for low-T and high-T components from SF1 approximate that of the expected GAD mean direction for Ascension, however, mean inclinations deviate from the GAD mean inclination by up to 13° (Figure 6.13g). Mean directions for SF1 lie between the expected GAD mean direction (000/-15) and the present day field direction for Ascension (approximately -017/-35, from Merrill & McElhinny, 1983).

6.2.5 Conclusions

All clasts from SF1 display low-T components that lie sub-parallel to the expected GAD for Ascension (i.e. type 1 remanence behaviour; Table 3.2), suggesting that SF1 was emplaced hot. Furthermore, clasts are inferred to have originally held a single-component remanence, suggesting that SF1 was emplaced above 580°C. This type of remanence behaviour is typical of a mafic lava flow or hot scoria flow deposit, however, field evidence (erosive nature, lenses of fine scoria and lithics, fine-grained basal layer), suggest that SF1 is more likely to be a scoria flow deposit. Scoria flows are expected to be emplaced at higher temperatures than pumice flows, because mafic lavas have higher eruption temperatures (Section 4.2.2, Table 4.4).

Low-T components in clasts from SF1 are inferred to be CRM overprints, carried by titanomagnetite. Titanomagnetite phases are Ti-rich and have compositions ranging from TM52 to TM64 (estimated from Figure 3.9). High-T components are inferred to be primary TRMs, carried by magnetite. This observation is somewhat enigmatic as it suggests that titanomagnetite is produced through alteration of magnetite in clasts from SF1. However, this behaviour is also observed in clasts from the Pourahu deposit, described in Section 3.7.

6.3 LITHIC BRECCIAS

Lithic breccias comprise 23% of the breccias sampled for palaeomagnetic analysis on Ascension (Figure 2.18). Twelve individual units were sampled and these are subdivided into clast-dominated and matrix-dominated units.

6.3.1 Remanence characteristics

6.3.1.1 Clast-dominated lithic breccias

All clasts except one from clast-dominated pumiceous breccias carry a stable remanence. Units can be divided into those in which clasts display type 1 remanence behaviour, (Table 3.2; e.g. Figures 6.14, 6.15), those in which clasts display type 2 remanence behaviour (Table 3.2; e.g. Figure 6.16) and units for which remanence characteristics are less straightforward (e.g. Figure 6.17).

All clasts from units EFFB1, LF1 and PB (Figure 6.1) carry a stable type 1 remanence, i.e. low-T components are orientated sub-parallel to the expected GAD for Ascension. In EFFB1 and PB, 80% of clasts display type 1a behaviour (single-component remanence; e.g. Figure 6.14a) and the remaining 20% display type 1b behaviour (two-component remanence; e.g. Figure 6.15; Table 3.2). Fifty percent of clasts display an additional VRM component, which is removed in the first few steps of demagnetisation (e.g. Figure 6.15a). Directions of low-T components for EFFB1 and PB are tightly grouped and mean directions approximate the GAD for Ascension (e.g. Figure 6.15c). VRM components are also tightly grouped and approximate the GAD for Ascension. High-T components in EFFB1 are random. Statistics cannot be calculated for high-T components from PB due to small population size.

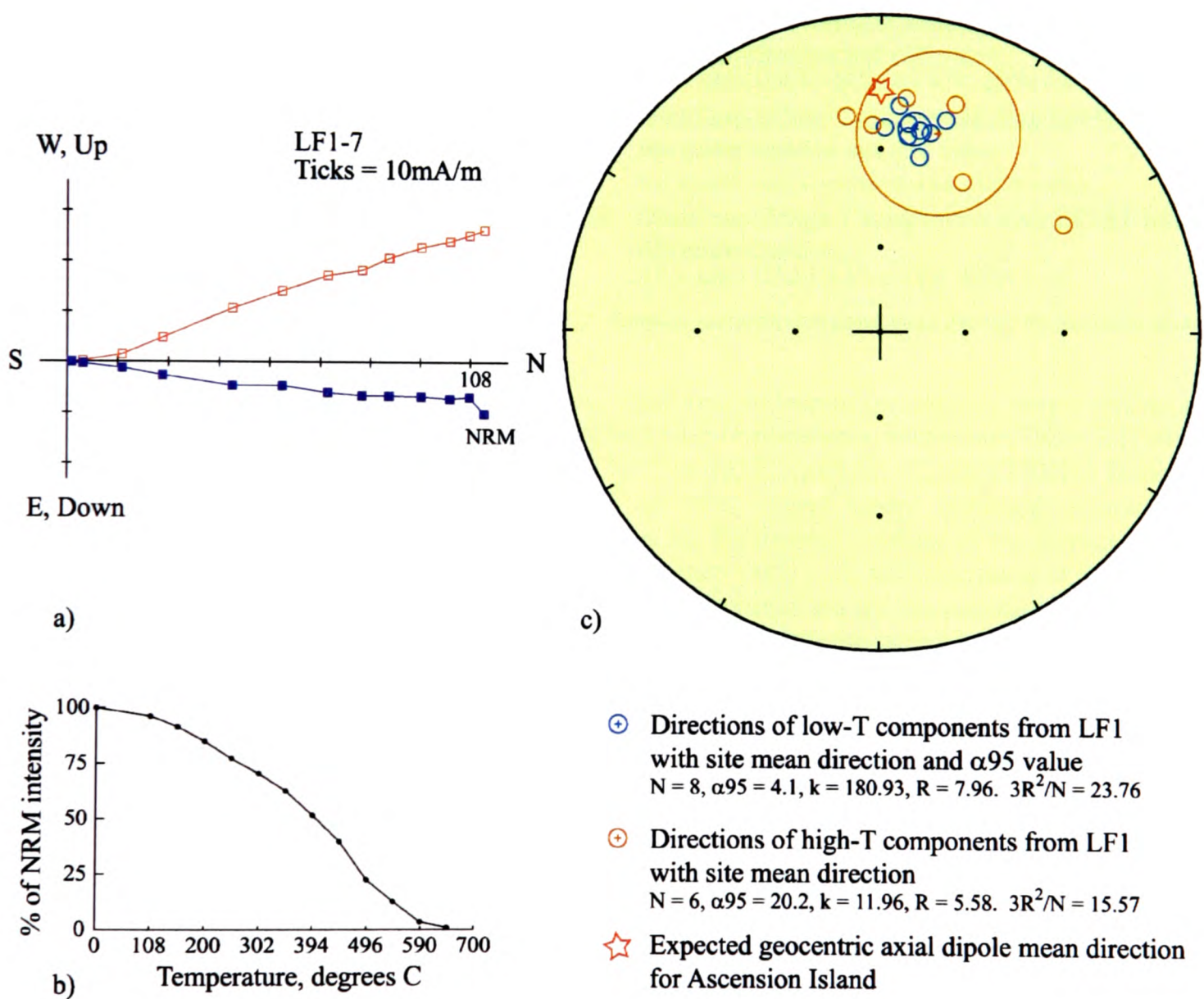


Figure 6.14: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot for clasts from a typical clast-dominated lithic breccia (LF1). LF1-7 displays type 1a remanence behaviour (Table 3.2), suggesting that it was emplaced at $>580^\circ\text{C}$. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for LF1-7 (plot b) is single-phase (type B2 behaviour; Table 3.3), with a decrease to 1% of the NRM intensity at $\sim 640^\circ\text{C}$, suggesting that remanence is carried by maghaemite. Plot c) shows the distribution of individual low-T and high-T components for samples from LF1, with site mean directions (small crosses) and α_{95} values (large circles). Directions of low-T components are tightly grouped. Directions of high-T components are also grouped, but grouping is less tight. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

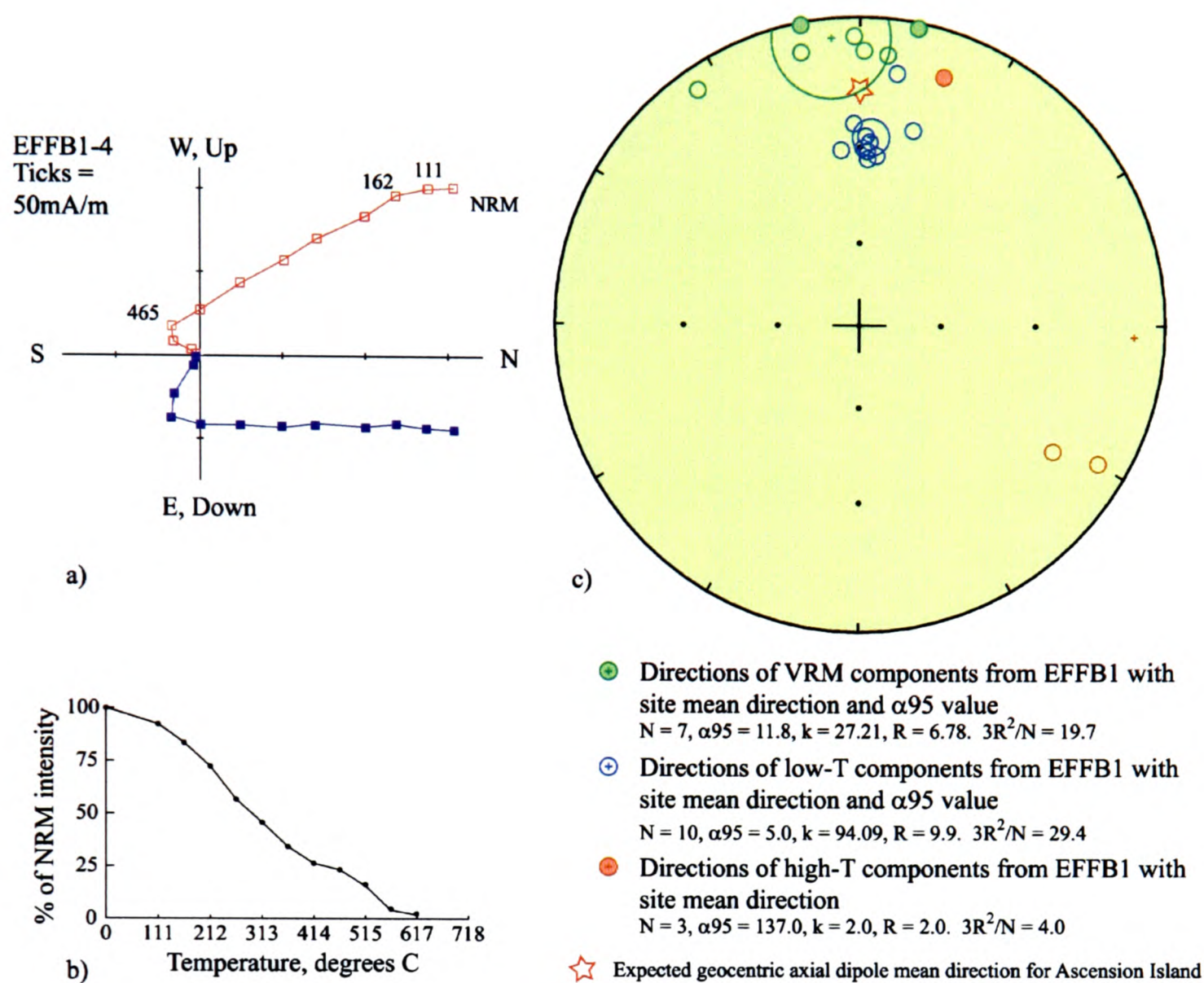


Figure 6.15: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot for samples from a typical clast dominated lithic breccia unit (EFFB1). EFFB1-4 displays type 1b remanence behaviour (Table 3.2) and has an additional VRM component that is removed by 111°C to 162°C (plot a). T_e for EFFB1-4 is between 465°C and 515°C. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for EFFB1-4 (plot b) is two-phase (type E1 behaviour; Table 3.3), with decreases in intensity seen at ~414°C and ~580°Cs, implying that titanomagnetite and magnetite are the remanence carriers. Plot c) shows the distribution of individual VRM, low-T and high-T components for samples from EFFB1, with site mean directions (small crosses) and α_{95} values (large circles). VRM and low-T directions are grouped, but grouping is tighter for low-T directions. High-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

Ninety percent of clasts from LF1 display 1b type remanence behaviour (e.g. Figure 6.14a). Directions of both low-T and high-T components are grouped, however the grouping of high-T components is substantially less tight than that of low-T components (Figure 6.14c).

Clasts from unit UVB1 (Figure 6.1) typically display type 2 remanence behaviour, i.e. low-T components lie in a direction distinct from the expected GAD for Ascension (Table 3.2). Seventy-three percent of clasts display a single-component remanence (e.g. Figure 6.16a) and 18% display a multi-component remanence. Multi-component clasts commonly show curved trajectories on vector component plots (Zijderveld plots). In the remaining 9% of

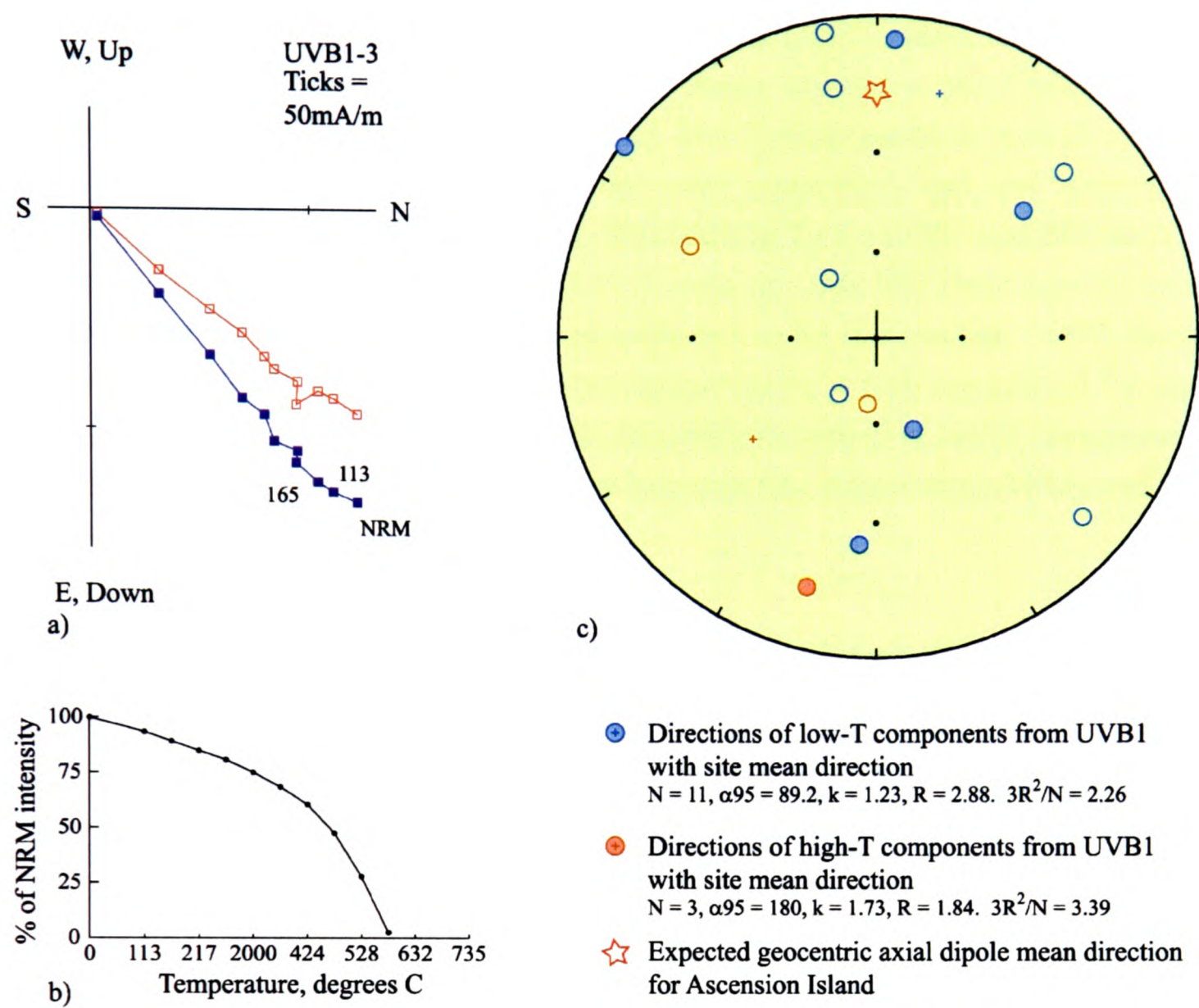


Figure 6.16: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot showing directions of low-T and high-T components for a clast-dominated lithic breccia (UVB1) that shows type 2 remanence behaviour (Table 3.2). UVB1-3 displays type 2a remanence behaviour (plot a; Table 3.2). Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for UVB1-3 (plot b) is single-phase (type A2, Table 3.3) and NRM intensity is reduced to ~1% by ~580°C, implying that remanence is carried by magnetite. Plot c shows the distribution of individual low-T and high-T components for samples from UVB1, with site mean directions (small crosses). Low-T directions and high-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

clasts, no magnetic components can be resolved. Directions of both low-T and high-T components are random (Figure 6.16c).

BX1, CGB1 and EB1 (Figure 6.1) contain clasts with varied remanence characteristics. In BX1, 50% of clasts display type 1 remanence behaviour and 50% display type 2 remanence behaviour (Table 3.2). Ninety percent of clasts are multi-component. Directions of low-T components are random, however, on removal of type 2 clasts from the data set, directions of the remaining low-T components are grouped and their mean direction approximates the GAD for Ascension. Directions of med-T and high-T components from all clasts are random.

In CGB1 and EB1, 56% of lithic clasts display type 1b remanence behaviour (Table 3.2; e.g.

Figure 6.17a). Directions of low-T components from type 1 clasts are grouped, but grouping is poor (e.g. Figure 6.17c). Low-T mean directions for CGB1 and EB1 approximate the GAD for Ascension. However, low-T components in type 1b clasts are typically carried by a small fraction of the total remanence and are removed by temperatures of 160°C-263°C (Figure 6.17a). Equilibrium T_e s for CGB1 and EB1 are 217°C and 185°C respectively (Figure 6.20; Table 6.3. In rocks of ~1Ma (the oldest age of exposed rocks on Ascension), VRM components are expected to be removed by 163°C (Section 3.3.3), however VRMs may persist to higher temperatures if they are carried by multi-domain grains. It is therefore not possible to determine the origin of low-T components in CGB1 and EB1 as no distinction can be made between low temperature TRMs and VRM components.

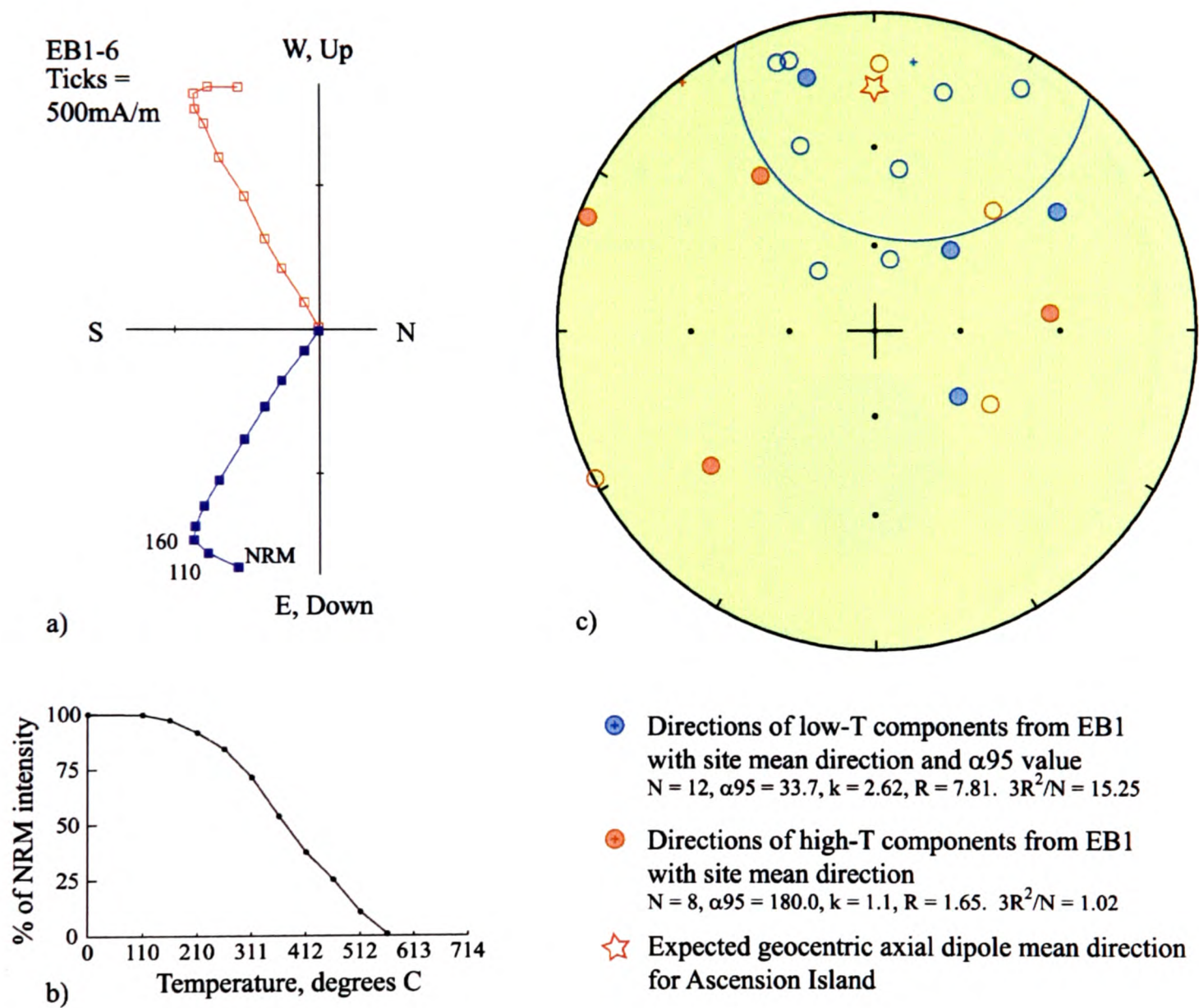


Figure 6.17: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot showing directions of low-T and high-T components for a clast-dominated lithic breccia (EB1) in which remanence behaviour is complex. EB1-6 displays type 1b remanence behaviour (plot a; Table 3.2), however the low-T component is removed by ~160°C. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for EB1-6 (plot b) is single-phase (type A2, Table 3.3) and NRM intensity is reduced to ~1% by ~580°C, implying that remanence is carried by magnetite. Plot c shows the distribution of individual low-T and high-T components for samples from EB1, with site mean directions (small crosses) and α_{95} value (large circle). Low-T directions are grouped but grouping is poor. High-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

Pumice clasts from CGB1 and EB1 display 1a or 1b type remanence behaviour (Table 3.2).

6.3.1.2 Matrix-dominated lithic breccias

The matrix-dominated lithic breccias can be divided into units in which the majority of clasts display type 1 remanence behaviour (60%) and units in which clasts typically display type 2 remanence behaviour (40%; Table 3.2).

Most clasts from MVF1, MVF2 and NRF1 (Figure 6.1) display type 1 remanence behaviour (e.g. Figure 6.18a). In all of these units, low-T components display *reversed* polarity, i.e. the low-T component lies sub-parallel to the expected reversed GAD for Ascension.

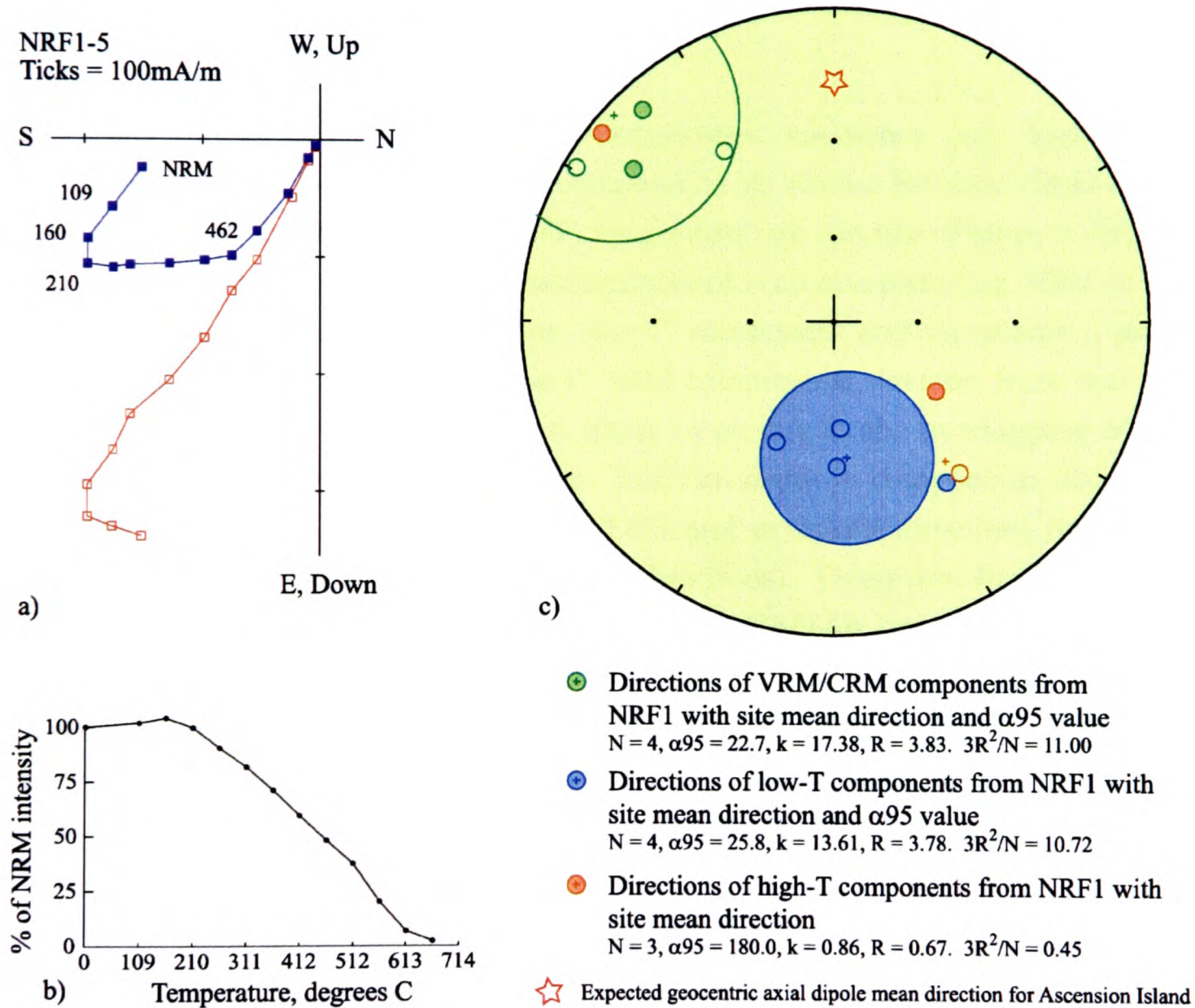


Figure 6.18: Zijderveld plot (z-plot), T_b spectra and equal area stereoplot showing directions of VRM/CRM, low-T and high-T components for NRF1. NRF1-5 displays type 1c remanence behaviour (plot a; Table 3.2), with a normal VRM/CRM overprint, a low-T reversed component and a high-T randomly orientated component. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for NRF1-5 (plot b) is single-phase (type B2, Table 3.3) and NRM intensity is only reduced to ~1% by >600°C, implying that the clasts contains maghaemite. Plot c shows the distribution of individual components for samples from NRF1, with site mean directions (small crosses) and α_{95} values (large circles). Both the VRM/CRM component and low-T component directions are grouped, but high-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

In MVF1, 60% of clasts display 1a remanence behaviour, but low-T directions are random. However, clasts that show ambiguous low-T directions are interpreted to have unstable mineralogies and this is verified by analysis of bulk susceptibility, which shows a rise on heating. On exclusion of altered clasts from the data set, low-T components become grouped.

Twenty percent of clasts from MVF1 show an additional VRM component, which is removed by 200°C.

In MVF2, most clasts also show a single-component remanence in a reversed direction, however inclination in these clasts is variable. Most clasts from MVF2 are scoriaceous and have been interpreted to have unstable mineralogies. Mineralogy in addition to a small clast population precludes an accurate assessment of remanence directions and thus T_e for MVF2.

Clasts from NRF1 each display a three-component remanence (e.g. Figure 6.18a). Directions of the two lower temperature components are similar between clasts (i.e. they are grouped), whilst directions of high-T components are random (Figure 6.18c). This suggests that lowest temperature (normal) component is an overprint (e.g. VRM or CRM) and the reversed component is the true 'low-T' component and represents a primary (p)TRM. The mean inclination for 'low-T' TRM components deviates from that of the expected reversed GAD by ~28°. This is likely to be due to the overlapping of the T_b spectra of TRM and overprint components. This can result in components displaying a 'composite' direction that lies between the TRM and overprint directions (in this case, TRM directions are 'biased' toward overprint directions). Overprint directions are also grouped, but their mean direction is distinct from the GAD for Ascension (Figure 6.18c). VRM components are expected to approximate the expected GAD for Ascension and overprints are therefore interpreted as CRMs. This is substantiated by the fact that overprints in some samples (e.g. NRF1-4) persist to >300°C (by which temperature VRMs are expected to be removed). Some clasts also exhibit curved trajectories on vector plots, which can be an indication of CRM overprinting.

Clasts from TBUB1 and THB1 (Figure 6.1) generally show type 2 remanence behaviour, i.e. low-T components lie in a direction distinct from the expected GAD for Ascension (Table 3.2; e.g. Figure 6.19a). Directions of low-T and high-T components for these units are random (e.g. Figure 6.19c).

In TBUB1, 56% of clasts display a two-component remanence and 44% display a single-component remanence. In most type 2a clasts, the majority of demagnetisation occurs over a narrow temperature range (between ~100°C and ~200°C), preventing the isolation of any high-T component (e.g. Figure 6.19a). No clasts from TBUB1 display a VRM

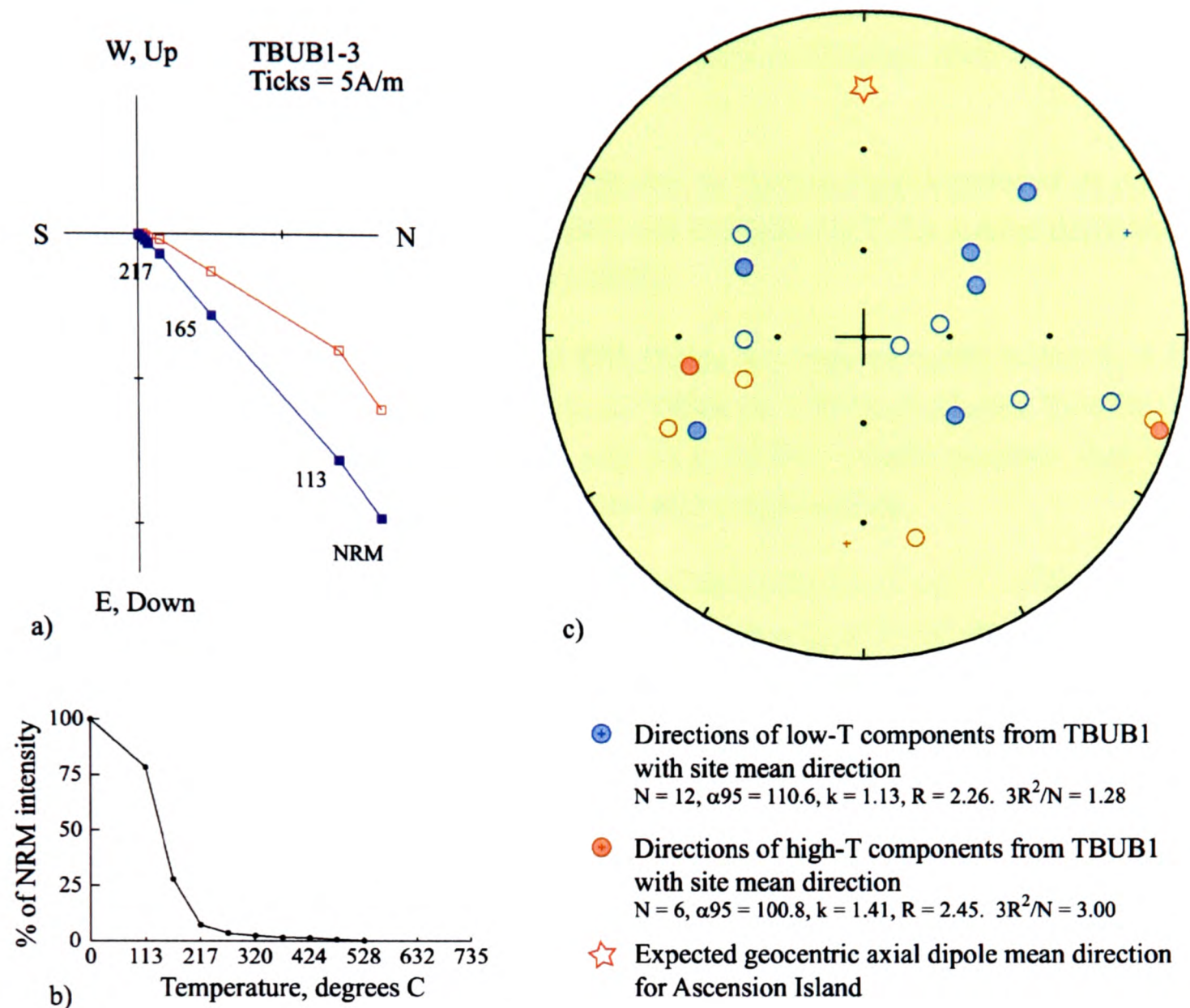


Figure 6.19: Zijderveld plot, T_b spectrum and equal area stereoplot showing directions of low-T and high-T components for a matrix-dominated lithic breccia that displays type 2 remanence behaviour (TBUB1). TBUB1-3 displays type 2b remanence behaviour (plot a; Table 3.2), though the high-T component has been almost entirely overprinted by the low-T component. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for TBUB1-3 (plot b) shows a sharp drop in intensity (corresponding to the removal of the low-T component) between 113°C and 217°C (type F4; Table 3.3), after which only ~5% of the NRM intensity remains. This suggests that the titanomagnetite is the main remanence carrier in TBUB1-3. Plot c shows the distribution of individual low-T and high-T components for samples from TBUB1, with site mean directions (small crosses). Both low-T and high-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

component. Pumice clasts from TBUB1 display type 1a or 1b remanence behaviour (Table 3.2).

Clasts from THB1 display type 2a or 2b remanence behaviour (Table 3.2). Twenty percent of clasts display curved trajectories on vector plots.

6.3.2 Emplacement temperatures

Table 6.3 shows best estimates of equilibrium emplacement temperature for the lithic breccias sampled on Ascension.

Six of the lithic breccias (50%) are interpreted as having been emplaced above ambient

temperature (hot). Emplacement temperatures for these units range from 313°C to >580°C (Table 6.3).

Three of the lithic breccias (25%) are interpreted as having been emplaced at ambient temperature (cold). Relict T_e s for these units (best estimates of T_e for source deposits) are shown in brackets and range from 239°C to 427°C.

Two possible T_e s are given for CGB1 and EB1 (Table 6.3; Figures 6.20b, 6.20c): 1) a T_e of 0°C, which assumes that low-T components are VRMs (or CRMs) and hence that the units were emplaced at ambient temperature, and 2) a $T_e > 0^\circ\text{C}$, which assumes that low-T components are TRMs and hence that the units were emplaced hot.

Two possible values for T_e are also given for BX1 (Table 6.3): 1) a T_e of 0°C, which assumes that BX1 was emplaced at ambient temperature, and 2) a T_e of 218°C (the average T_e for type 1 clasts from BX1) which assumes that BX1 contains a mixture of hot and cold clasts (Figure 6.20a).

A T_e estimate of >580°C is given for MVF2, as unaltered type 1 clasts display a single-component remanence, suggesting that they were emplaced at temperatures above T_c . However, this estimate is not reliable due to the unstable mineralogy of clasts and a small clast population.

CLAST-DOMINATED UNITS		MATRIX-DOMINATED UNITS	
unit	T_e , °C	unit	T_e , °C
BX1	0, 218 ¹ (427)	MVF1	>580
CGB1	0/217 [†]	MVF2	>580 ? ^{††}
EB1	0/185 [†]	NRF1	487
EFFB1	313	TBUB1	0 (239)
LF1	417	THB1	0 (269)
PB	>580		
UVB1	0		

Table 6.3: Best estimates of equilibrium emplacement temperature for lithic breccias sampled on Ascension. Units that are interpreted as having been emplaced at ambient temperature are given a T_e of 0° (although *sensu stricto* T_e should = ambient temperature). Values in brackets represent relict T_e s for deposits (i.e. the average T_e of the source deposit(s)). ¹best estimate of T_e for hot (type 1) clasts from BX1. [†]these units have two possible values for T_e . ^{††}an accurate T_e could not be calculated for this unit as most clasts were altered. However, clasts tend to have a one-component remanence and may therefore have been emplaced above T_c .

6.3.3 Magnetic mineralogy

One hundred and nine clasts from lithic breccias were thermally demagnetised in the

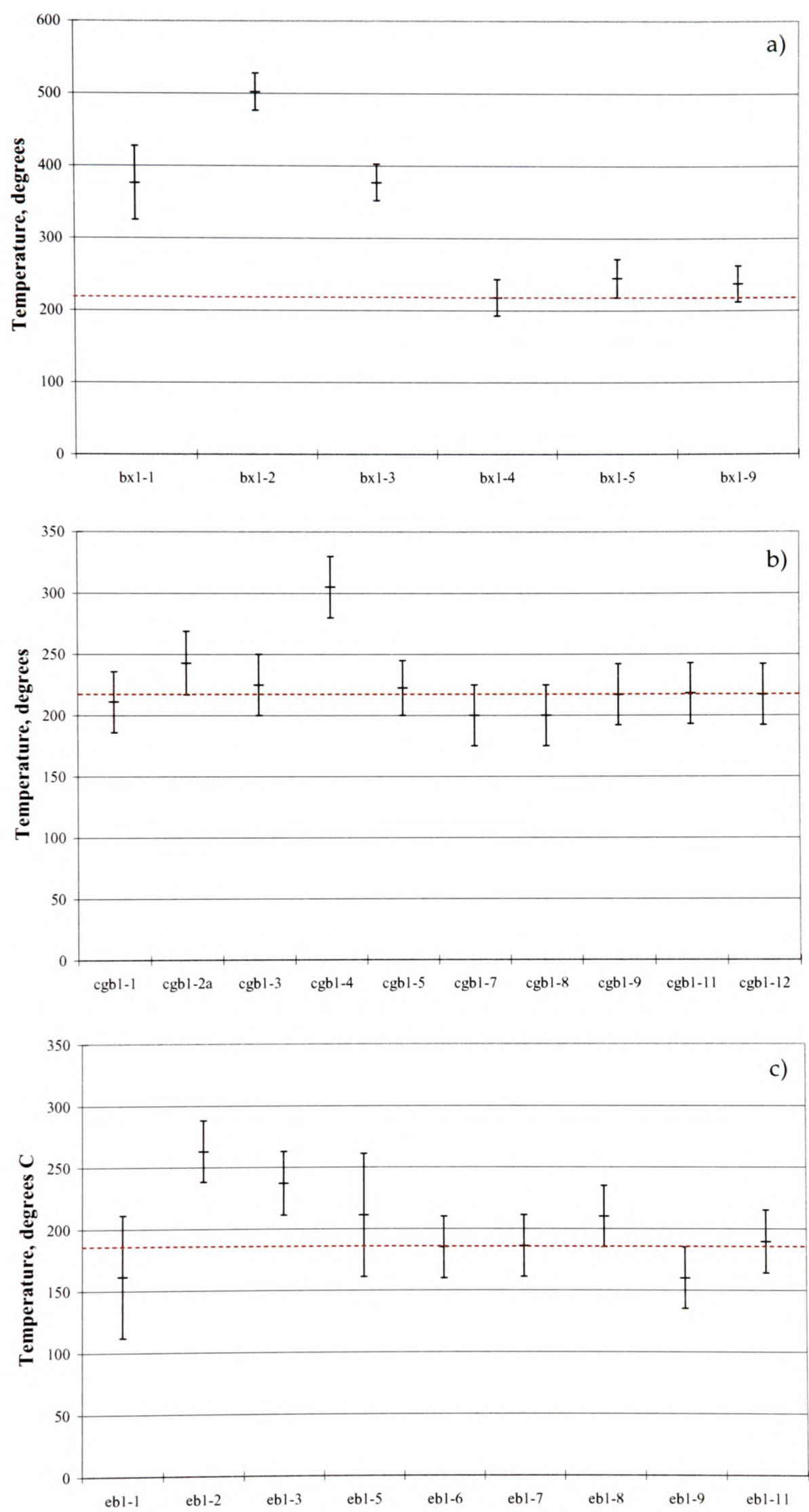


Figure 6.20: Emplacement temperatures for individual clasts from: a) BX1 (type 1 clasts only), b) CGB1 and c) EB1. Red lines represent equilibrium T_e s, which are 218°C, 217°C and 185°C for BX1, CGB1 and EB1 respectively.

laboratory. Magnetic mineralogy for these clasts was estimated mainly through analysis of blocking temperature T_b spectra, with high- T χ measurements carried out on selected clasts to corroborate conclusions drawn from T_b spectra. A summary of the different types of T_b spectra displayed by clasts from clast and matrix-dominated lithic breccias is shown in Table 6.4.

6.3.3.1 Clast-dominated lithic breccias

NRM intensities for clasts from clast-dominated lithic breccias range from 8 to 19.9A/m. T_b spectra are typically well distributed (e.g. Figure 6.14b). Maximum unblocking temperatures range from 550° to 680°, but clasts are most commonly reduced to 1-2% of the NRM intensity by ~580°C (e.g. Figure 6.16b), implying that magnetite is the most ubiquitous magnetic mineral in these clasts.

A summary of the different types of T_b spectra displayed by clasts from clast-dominated lithic breccias is shown in Table 6.4. Forty-five percent of clasts display single-phase T_b spectra (demagnetisation types A, B, C and D, Table 6.4), suggesting that they have single-phase mineralogies. In 52% of clasts, T_b spectra are multi-phase (demagnetisation types E, F and G, Table 6.4), suggesting that remanence is carried by more than one mineral phase. In the remaining 3% of clasts, demagnetisation spectra cannot be classified due to noisy data.

CLAST DOMINATED		MATRIX DOMINATED		INTERPRETATION
T_b spectra type	% of clasts	T_b spectra type	% of clasts	(mineralogy)
A	24	A	13	single-phase magnetite
B	10	B	8	single-phase maghaemite
C	4	C	5	single-phase haematite
D	7	D	8	single-phase titanomagnetite
E	31	E	31	two-phase
F	7	F	23	two/three phase (low T_c)
G	14	G	10	three+ phase

Table 6.4: Summary of T_b spectra types for clasts from clast and matrix-dominated lithic breccias sampled on Ascension (with basic interpretation).

The most common demagnetisation behaviour displayed by clasts from clast-dominated lithic breccias is type E (Table 3.3; e.g. Figure 6.15b; 31% of clasts). The two-phase nature of T_b spectra for these clasts suggests that remanence is carried by two mineral phases: a titanomagnetite phase plus magnetite (type E1; 13 clasts), maghaemite (type E2; 5 clasts), a second titanomagnetite (type E4; 1 clast) or haematite (type E3; 3 clasts). The composition of the titanomagnetite phase can be approximated from its T_c using a graph of T_c v

titanomagnetite composition (see Section 3.5.1, Figure 3.9). Titanomagnetite compositions (estimated from T_b spectra data) range from TM02 to TM63.

Next most common demagnetisation behaviours are: type A (Table 3.3), which is displayed by 24% of clasts (e.g. Figure 6.16b) and indicates that remanence is carried by magnetite, type G (Table 3.3), which is displayed by 14% of clasts and is inferred to reflect a three-phase or more complex mineralogy and type B (Table 3.3), which is displayed by 10% of clasts and indicates a maghaemite mineralogy. Type D (single-phase titanomagnetite) and type F (two/three phase, with high-titanium titanomagnetite phase) behaviour (Table 3.3) are each displayed by 7% of clasts (Table 6.4). Only 4% of clasts display type D behaviour (Table 3.3; Table 6.4) and suggesting that haematite is not a common remanence carrier in these clasts.

6.3.3.2 Matrix-dominated lithic breccias

NRM intensities for clasts from matrix-dominated lithic breccias range from 0.6 to 20.0 A/m. Fifty-one percent of clasts display well-distributed T_b spectra (e.g. Figure 6.18b), however in the remaining 49% of clasts, demagnetisation typically occurs over a narrow temperature range (discrete spectra; e.g. Figure 6.19b) meaning that isolation of all components may not be possible. Maximum unblocking temperatures range from 300°C to 650°C, however the majority of samples are fully demagnetised between ~550°C and 580°C.

A summary of the different types of T_b spectra displayed by clasts from clast-dominated lithic breccias is shown in Table 6.4. Thirty-four percent of clasts display single-phase T_b spectra (demagnetisation types A, B, C and D, Table 6.4), suggesting that they have single-phase mineralogies. In 64% of clasts, T_b spectra are multi-phase (demagnetisation types E, F and G, Table 6.4), suggesting that remanence is carried by more than one mineral phase. In the remaining 2% of clasts, demagnetisation spectra cannot be classified due to noisy data.

Type E demagnetisation behaviour (Table 3.3) – i.e. a mixed titanomagnetite–magnetite (or low-titanium titanomagnetite) mineralogy – is most common in clasts from matrix-dominated lithic breccias (31%). T_b spectra data suggest that compositions of titanomagnetite phases in these clasts range from TM28 to TM38 (estimated from Figure 3.9).

Twenty-three percent of clasts display type F behaviour (Table 3.3), i.e. they exhibit a sharp drop in intensity over a temperature range of ~100°C to ~200°C (e.g. Figure 6.19b). These clasts are all from unit TBUB1. The initial drop in intensity displayed by the T_b spectra for these clasts occurs over the same temperature range as the removal of the low-T component in these clasts. This suggests that low-T components are carried by a low T_c (i.e. between 100°C and 200°C) titanomagnetite phase, with a composition between TM58

and TM70 (estimated from Figure 3.9). Some clasts also display a high-T component, but this is typically carried by only a small fraction of the remanence. High-T components are inferred to be carried by magnetite or Ti-poor titanomagnetite. The fact that low-T components carry the majority of the NRM suggests that they are CRMs carried by titanomagnetite, which have partly or fully overprinted the primary magnetite components². Clasts from unit SF1 (Section 6.2) and from the Pourahu deposit in New Zealand (Section 3.7) display similar behaviour to that seen in clasts from TBUB1. An alternative origin for the low-T overprints in clasts from TBUB1 is that they are IRMs, formed by lightning striking the source deposit. This is a possibility as clasts from TBUB1 have amongst the highest NRM intensities of clasts from matrix-dominated lithic breccias.

Types A, B, D and C demagnetisation behaviour (Table 3.3) – which indicate single-phase magnetite (A), maghaemite (B), titanomagnetite (D) and haematite (C) are displayed by 13%, 8%, 8% and 5% of clasts respectively. As is seen in clasts from clast-dominated lithic breccias, haematite is the least common remanence carrier. Ten percent of clasts display a three-phase, or more complicated T_b spectra (Type G; Table 3.3).

Magnetic mineralogy and VRM

Around 40% of clasts from clast-dominated lithic breccias and 25% of clasts from matrix-dominated lithic breccias display an additional VRM component. The majority of these clasts are inferred to have a magnetite or two-phase titanomagnetite–magnetite mineralogy. The directions of some VRM components deviate from the GAD for Ascension, but this can be explained by the influence of the high-T component on the VRM component. Samples that show a high-Ti (low T_c) titanomagnetite mineralogy show no VRM component (e.g. Figure 6.19a,b).

6.3.4 Secular variation

Figure 6.21 shows low-T component mean directions for a) hot clast-dominated and b) hot matrix-dominated lithic breccias, with α_{95} values. Mean directions for units BX1, CGB1 and EB1 are calculated from low-T directions for type 1 clasts only.

Low-T component mean directions for clast-dominated lithic breccias approximate the GAD for Ascension and cannot be distinguished from one another at the 95% confidence level (Figure 6.21a). No inferences can therefore be made about the relative ages of these units. LF1 and PB are exceptions, as mean directions for these units are distinct from one another (but not from other clast-dominated lithic breccia units). This suggests LF1 and PB were not deposited contemporaneously.

Mean directions for MVF1 and NRF1 are similar within error (Figure 6.21b) and no

² N.B. In this case, CRM acquisition is inferred to have occurred in the deposit that *sourced* TBUB1 (TBUB1 contains clasts with *randomly orientated* low-T components).

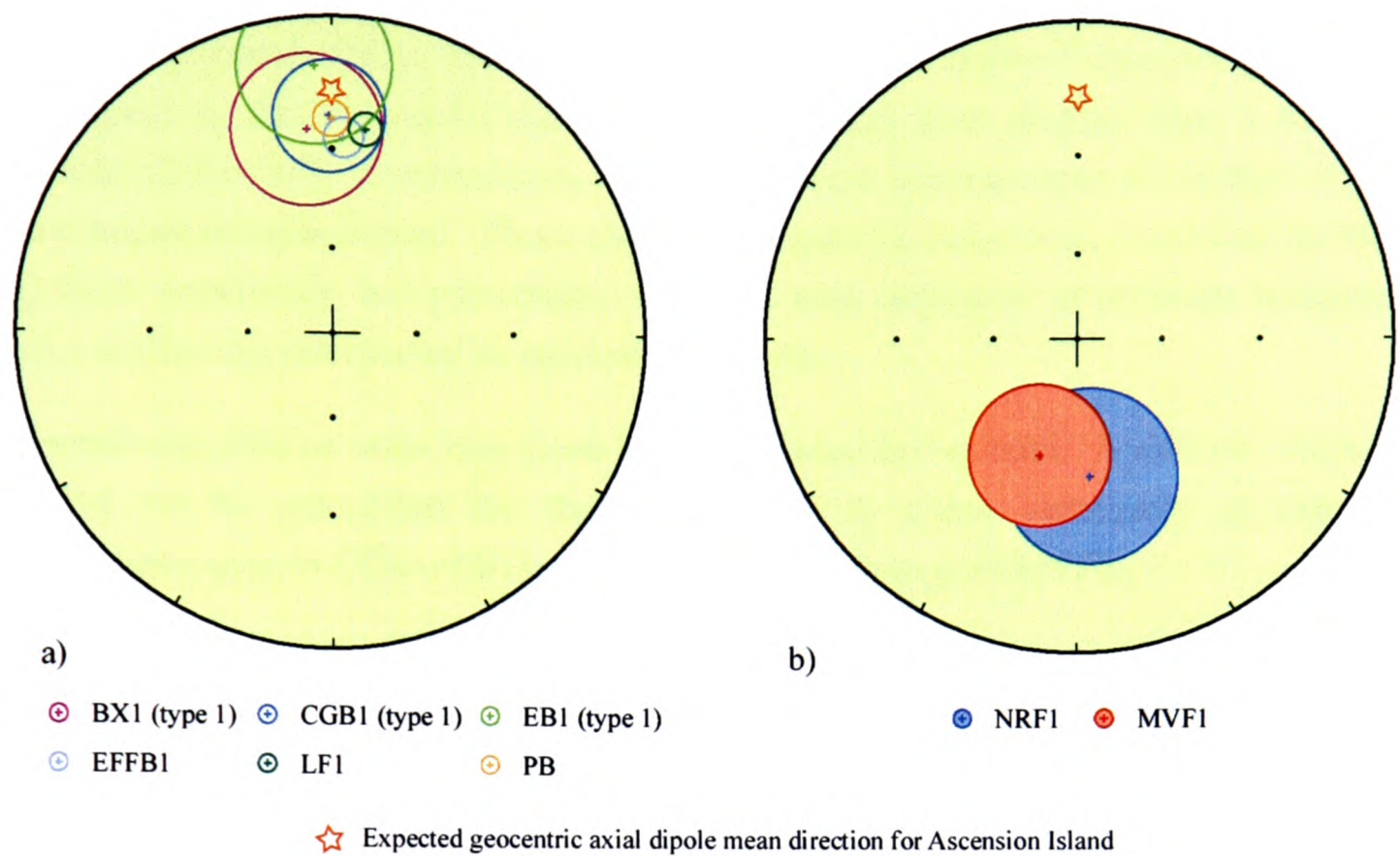


Figure 6.21: Equal area stereoplots showing site mean directions (small crosses) and a95 values (circles) for a) clast-dominated and b) matrix-dominated lithic breccias from Ascension. Mean directions for BX1, CGB1 and EB1 are for type 1 clasts only. All clast-dominated units display normal polarity and mean directions approximate the expected GAD mean direction for Ascension. No distinction can be made between mean directions at the 95% confidence level, except for units LF1 and PB1, which are distinct from one another. All matrix-dominated pumiceous breccia units display reversed polarity, but mean directions deviate from the expected opposite GAD for Ascension. Mean directions for NRF1 and MVF1 cannot be distinguished from one another at the 95% confidence level. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplots respectively.

inference can therefore be made about their relative ages. No reliable mean direction can be calculated for MVF2. MVF1, MVF2 and NRF1 all display reversed polarity, suggesting that they were deposited during a short-lived reversed event within the Brunhes normal epoch, or prior to the most recent magnetic reversal (within the Matuyama reversed epoch). Magnetostratigraphic data (Chapter 7) suggest that reversed units are likely to have been deposited during the Matuyama epoch and hence they are inferred to have ages of >0.78Ma.

6.3.5 Conclusions

Forty-two percent of the lithic breccias sampled on Ascension contain clasts in which low-T components lie sub-parallel to the expected GAD for Ascension, i.e. they display type 1 remanence behaviour (Table 3.2). They are therefore inferred to have been emplaced above ambient temperature (hot), at temperatures ranging from 313°C to >580°C (Table 6.3). The combination of palaeomagnetic data with field evidence suggests origins as pyroclastic flow deposits, co-ignimbrite breccias or brecciated lava flows are inferred for these units (see Sections 6.3.5.1., 6.3.5.2).

Thirty-three percent of lithic breccias contain clasts in which low-T directions are random with respect to the expected GAD for Ascension, i.e. they display type 2 remanence behaviour (Table 3.2). Furthermore, all of these units contain some clasts that display a multi-component remanence. These units are inferred to have been reworked (at least in part) from previously hot pyroclastic material, and emplaced at ambient temperature (cold), i.e. they are interpreted as epiclastic deposits.

The remaining 25% of units may have been emplaced hot or cold. A definite estimate of T_e could not be calculated for these units due to either ambiguity of remanence characteristics (e.g. in CGB1/EB1) or alteration of clasts (e.g. in MVF2).

In clast-dominated lithic breccias, the majority of clasts (86%) demagnetise over a wide temperature range, suggesting that magnetic minerals in these clasts have a wide range of grain sizes. The major remanence carrier in clast-dominated units is inferred to be magnetite, but titanomagnetite and maghaemite are inferred to carry remanence in 28% and 15% of clasts respectively. Titanomagnetite compositions range from TM02 to TM63 (estimated from Figure 3.9).

In matrix-dominated lithic breccias, almost 50% of clasts demagnetise over a narrow temperature range, producing a discrete T_b spectra. These clasts are interpreted to contain magnetic minerals with more restricted grain sizes. The major remanence carrier in clasts from matrix-dominated units is inferred to be titanomagnetite, with compositions ranging from TM28 to TM70 (estimated from Figure 3.9). Magnetite and maghaemite are also inferred to be remanence carriers.

6.3.5.1 Clast-dominated lithic breccias

Palaeomagnetic interpretations substantiate field interpretations for EFFB1, LF1 and UVB1 and clarify the interpretations of PB and UVB1. For BX1, EB1 and CGB1 palaeomagnetic data cannot aid interpretation.

Palaeomagnetic data suggests that EFFB1 was emplaced at $\sim 313^\circ\text{C}$. These data, in combination with field evidence, i.e. the fact that EFFB1 contains a substantial amount of juvenile material and exhibits a fine-grained basal layer, suggests that it is a pyroclastic flow deposit. Moreover, the coarse, lithic-rich nature of EFFB1 suggest that it may be a co-ignimbrite or lag breccia, formed by the fall-back of dense lithic clasts from the eruption column.

LF1 is comprised of angular, mainly non-vesicular juvenile clasts, with some ash and was therefore originally interpreted as a block-and-ash-flow. Palaeomagnetic analysis yields a T_e for LF1 of 417°C , which confirms this interpretation. LF1 contains clasts that display a single or two-component remanence (i.e. type 1a or 1b remanence behaviour; Table 3.2), both of which types would be expected in clasts from block-and-ash-flows (in non-

vesicular juvenile and accessory lithics respectively). However, directions of high-T components in 1b clasts are grouped (although less tightly than low-T components; Figure 6.14c) and may therefore be the product of slumping of parts of the deposit during cooling. This suggests that most clasts originally held a single-component remanence and are hence (non-vesicular) juvenile clasts, which are typically dominant in block-and-ash-flows (Cas and Wright, 1988). The true T_e for LF1 may therefore be $>580^\circ\text{C}$.

Most clasts from PB display a single-component remanence, in a direction sub-parallel to the expected GAD for Ascension, suggesting that they were emplaced $>580^\circ\text{C}$ and hence PB was emplaced at elevated temperatures. PB is pumice-rich but also lithic-rich and contains fragmented lava clasts and is therefore interpreted either as the deposit of a lithic-rich pumiceous pyroclastic flow (possibly a lag-breccia) or a brecciated or partially collapsed lava flow.

Units BX1 and EB1 were interpreted, from field characteristics as explosion breccias as they are poorly sorted and comprise large angular lithic clasts that have produced significant impact structures in the underlying deposits.

In BX1, low-T directions for clasts that exhibit type 1 remanence behaviour (Table 3.2) are grouped, whilst low-T components from the remaining clasts are random. The majority of type 1 low-T components persist to $>300^\circ\text{C}$, suggesting that these are not VRM components. There is also little evidence to suggest that these are CRM overprints, as the presence of a type 1 low-T component does not appear to be linked to mineralogy (and components do not display curved trajectories on vector plots). Type 1 low-T components are therefore interpreted as true TRM components. This suggests that half of the clasts in BX1 were emplaced hot and half were emplaced cold, or at a temperature below 100°C (the lower limit of resolution for the palaeomagnetic technique of T_e estimation). Cold (type 2) clasts all display a multi-component remanence, suggesting that they were sourced from a previously hot deposit.

Lithic clasts from explosion breccias are expected to vary in their remanence characteristics, depending on the initial temperature of the country rock that is fragmented during eruption. In addition, varying T_e s may be exhibited by clasts from the same deposit, as temperature equilibration is not expected to occur in explosion breccias (because clasts are transported ballistically rather than within a flow). Type 1 clasts from BX1 show a range of T_e s from 218°C to 502°C (Figure 6.20a). If clasts are hot when fragmentation and deposition occur, they will show a multi-component remanence with similarly directed low-T components and randomly orientated high-T components, as is exhibited by type 1 clasts from BX1. Where clasts are deposited cold, they will display a single or multi-component remanence (depending on pre-eruption history of the rock) in a random direction with respect to the ambient field direction. In multi-component clasts, both low and high-T components will be randomly orientated. This behaviour is

exhibited by type 2 clasts from BX1. The palaeomagnetic behaviour of BX1 thus substantiates field evidence that it is an explosion breccia.

Just over half of clasts from EB1 display type 1b remanence behaviour (Table 3.2), however, low-T components are carried by a small fraction of the total remanence and are typically removed by 160°C-263°C. T_e s for individual type 1 clasts from EB1 have a smaller temperature range than those from BX1 (Figures 20a,c). In addition, T_e for EB1 (185°C) is closer to 163°C (the temperature by which VRM components are expected to be removed in these deposits), than T_e for BX1 (218°C). This suggests that low-T components are likely to be VRMs. However, the palaeomagnetic technique cannot strictly determine the origin of low-T components in clasts from EB1 and two possible scenarios are therefore proposed. Assuming low-T components are TRMs, EB1 is interpreted to contain a mixture of hot and cold clasts, as in BX1. Assuming low-T components are VRMs, EB1 is interpreted to have been emplaced cold. Neither interpretation precludes an explosion breccia origin for EB1, because if no heating of the country rock occurs before fragmentation, explosion breccias may be comprised entirely of cold clasts.

Clasts from CGB1 display similar (ambiguous) palaeomagnetic characteristics to those displayed by EB1, i.e. it is not possible to distinguish between low temperature TRMs and VRMs in these clasts. Two possible T_e s are therefore proposed for CGB1 (Table 6.3): 1) 0°C (which assumes low-T components are VRMs) and 2) 217°C (which assumes low-T components are TRMs). CGB1 is poorly-sorted and lithic-rich, with a concentration of lithics at its base. Assuming low-T components are TRMs, CGB1 is therefore interpreted as a hot co-ignimbrite breccia. However, if low-T components are VRMs, CGB1 is interpreted as the product of epiclastic redeposition of primary pyroclastic material, as many clasts display a multi-component remanence (which suggests that they were previously hot). Furthermore, CGB1 may be a product of gravitational collapse (i.e. a debris avalanche) as it contains angular clasts and has a massive to diffusely layered nature.

6.3.5.2 Matrix-dominated lithic breccias

Palaeomagnetic data allow further interpretations of the matrix-dominated lithic breccias. Field evidence suggests that MVF1, MVF2 and NRF1 originated as flows, but allows no distinction between hot and cold flow types. Clasts from MVF1 and NRF1 display a single or two-component remanence with low-T components that lie in a direction sub-parallel or antipodal to the expected GAD for Ascension. This suggests that they were emplaced hot, furthermore at temperatures above 500°C (>580°C for MVF1). MVF1 and NRF1 are therefore interpreted as the products of hot pyroclastic flows as they are poorly sorted, contain abundant juvenile material and high proportions of fine material. Moreover, MVF1 contains semi-welded pumice clasts, which are commonly seen in

pyroclastic flow deposits emplaced at such elevated temperatures (Cas and Wright, 1988; Freundt et al., 2000).

MVF1 has similar field characteristics to MVF2 (e.g. semi-welded juvenile clasts, poor sorting, high proportion of fine material) and may therefore have a similar origin. However, palaeomagnetic analysis could not provide a reliable estimate of T_e for MVF2, because many of the clasts sampled are inferred to have been altered.

MVF1 and NRF1 have similar site mean directions and field characteristics, and are possibly therefore parts of the same deposit. Palaeomagnetic data suggest that MVF1 has a higher T_e than NRF1 (>580°C and 487°C respectively) and this is expected if they *are* part of the same deposit, as MVF1 is inferred to be the closer unit to the island's eruptive centres than NRF1 (see Chapter 7).

Clasts from TBUB1 and THB1 units typically display type 2 remanence behaviour (Table 3.2), substantiating field interpretations of these units as epiclastic deposits. Moreover, relict T_e s for TBUB1 and THB1 (Table 6.3) suggest that they have been reworked from previously hot pyroclastic units with temperatures of ~250°C. TBUB1 is interpreted as a probable mudflow, as it contains large boulders, a high proportion of fine material and exhibits features that suggest it contained water (i.e. where parts of the deposit appear to have been 'squeezed' up into the overlying unit; Section 2.2.3.3). THB1 is interpreted as a fluvially reworked deposit, as it contains rounded clasts and a sandy matrix and has an erosive base.

6.4 LAVA BRECCIAS

Lava breccias comprise 13% of the breccia units sampled on Ascension for palaeomagnetic analysis (Figure 2.20). Nine individual units were sampled, however analysis of the palaeomagnetic characteristics of clasts from these units suggests that they were sampled from five major units, some of which were sampled more than once (Section 6.4.4).

The lava breccia units are distinctive in that they are comprised mainly of non-vesicular juvenile material, which ranges in form from dense lava to less dense (poorly vesicular) pseudo-pumice, which may resemble pumice. Vesicular juvenile material (i.e. 'true' pumice) is typically absent from these units.

6.4.1 Remanence characteristics

Lithic clasts (of all forms) typically show a single-component TRM in a direction sub-parallel (or antipodal) to the expected GAD for Ascension, i.e. type 1a remanence behaviour (Table 3.2; e.g. Figure 6.22a). In addition to a TRM component, many samples also show a VRM, which is typically removed by ~150°C (e.g. Figure 6.23a).

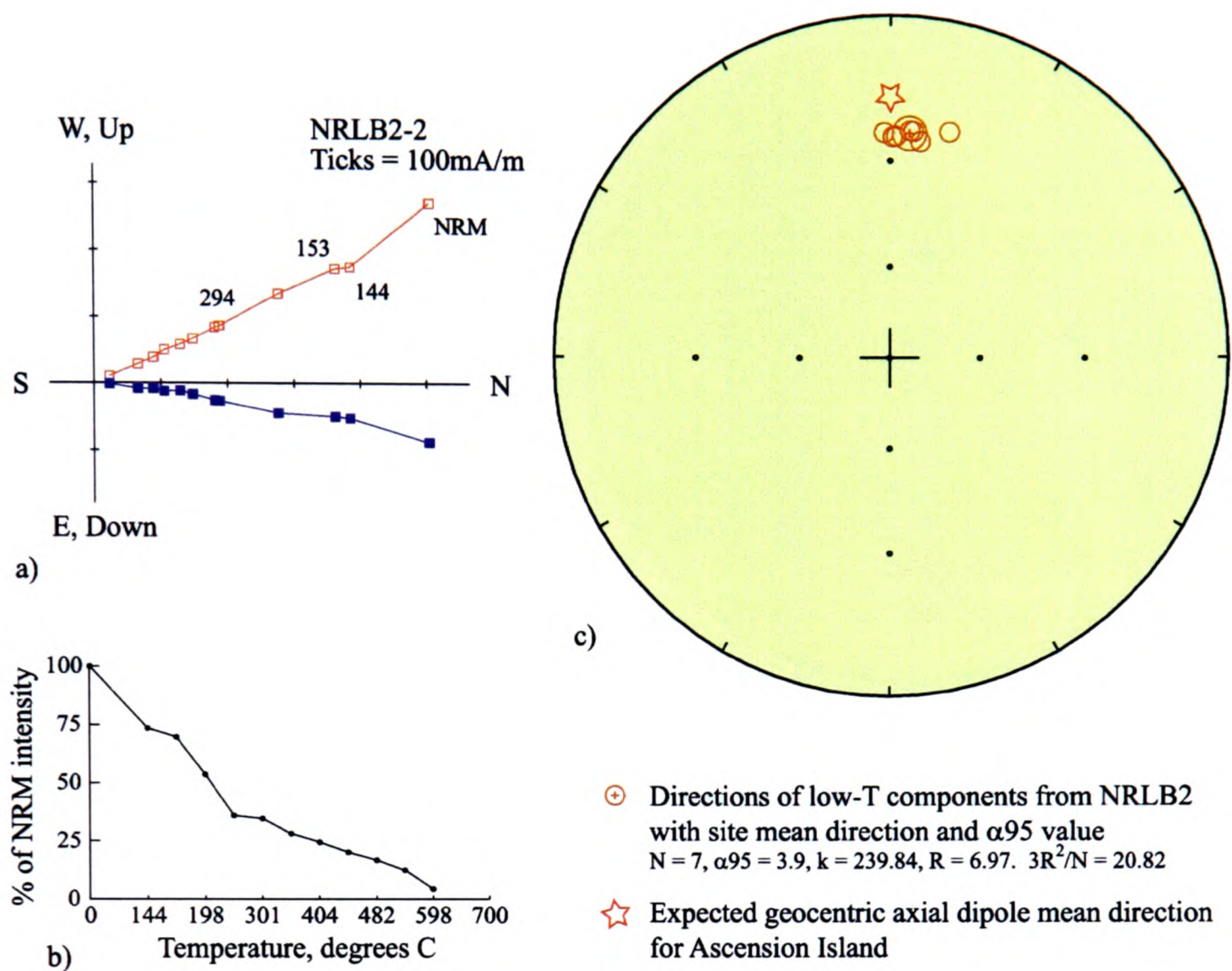


Figure 6.22: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot for samples from a lava breccia unit that shows normal polarity (NRLB2). NRLB2-2 displays type 1a remanence behaviour (Table 3.2) and is therefore interpreted to have been emplaced $>580^{\circ}\text{C}$. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for NRLB2-2 (plot b) is two-phase (type E2 demagnetisation behaviour; Table 3.3), with decreases in intensity seen at 294°C and $\sim 598^{\circ}\text{C}$ suggesting that titanomagnetite and maghaemite are the remanence carriers. Plot c) shows the distribution of individual ‘low-T’ components for clasts from NRLB2, with site mean direction (small cross) and α_{95} value (large circle). Low-T directions are tightly grouped and their mean direction deviates from the expected GAD for Ascension by $<9^{\circ}$. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

Directions of ‘low-T’ TRM components are tightly grouped for all lava breccia units (e.g. Figures 6.22c, 6.23c) and grouping is generally tighter than for other types of breccia deposit. Directions of VRM components are also typically grouped, although grouping is less tight than for TRM components (e.g. Figure 6.23c).

Nine lava breccia clasts (from five different units) show more than one component of magnetism with a low-T component that cannot be attributed to VRM. The majority of these exhibit a red coloration, suggesting that they are oxidised and have therefore undergone alteration and subsequently acquired a CRM.

The remaining multi-component samples are inferred to have rotated during deposition and compaction as they display sub-parallel low-T and high-T components, both with directions that approximate the GAD for Ascension.

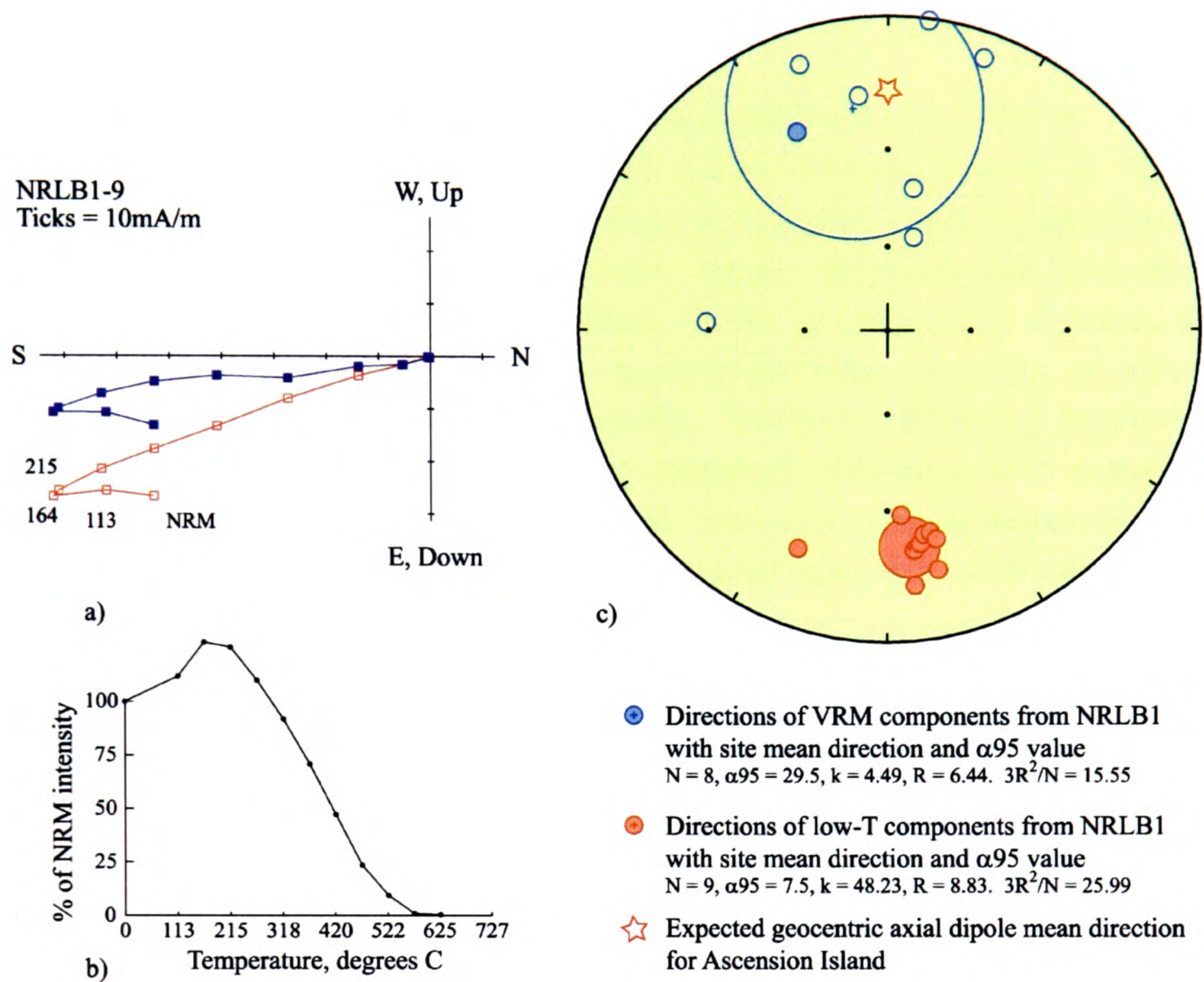


Figure 6.23: Zijderveld plot, T_b spectrum and equal area stereoplot for clasts from a lava breccia unit that displays reversed polarity (NRLB1). NRLB1-9 displays reversed polarity and type 1a remanence behaviour (Table 3.2), but exhibits an additional (normal) VRM component that persists to $\sim 164^\circ\text{C}$ (plot a). T_c for NRLB1-9 is inferred to be $>580^\circ\text{C}$. Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for NRLB1-9 (plot b) displays an apparent increase in intensity as the VRM component tracks away from the origin, followed by a decrease to $\sim 1\%$ of the NRM value by $\sim 580^\circ\text{C}$, suggesting that remanence is carried by magnetite (type A2 demagnetisation behaviour; Table 3.3). Plot c) shows the distribution of individual VRM and ‘low-T’ components for clasts from NRLB1, with site mean directions (small crosses) and α_{95} values (large circles). Low-T directions are tightly grouped and their mean direction approximates the expected reversed GAD for Ascension. VRM components are grouped (though more loosely than low-T components) and their mean direction approximates the expected GAD for Ascension. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

6.4.2 Emplacement temperatures

Eighty-six percent of clasts from lava breccias display a single-component remanence (not including VRM components), indicating that they have undergone heating to temperatures above T_c of their magnetic minerals. Magnetite is inferred to be the most common remanence carrier in clasts from these units (Section 6.4.3) and it can be assumed therefore that the lava breccias reached temperatures in excess of 580°C (T_c for magnetite). The remaining 14% of clasts from lava breccias display a multi-component remanence, however T_c estimates cannot be made for these clasts, as low-T components are not interpreted to be thermal in origin.

6.4.3 Magnetic mineralogy

NRM intensities in clasts from lava breccias range from 4mA/m to 14A/m. Magnetic mineralogy for these clasts was estimated mainly through analysis of blocking temperature T_b spectra, with high-T χ measurements carried out on selected clasts to corroborate conclusions drawn from T_b spectra. Seventy-five percent of clasts display well-distributed T_b spectra (e.g. Figure 6.22b). In the remaining 25% of clasts, most demagnetisation occurs over a narrow temperature range (typically at elevated temperatures), producing a discrete T_b spectrum. Maximum unblocking temperatures range from 374° to 688°, but in 48% of clasts, intensity is reduced to 1-2% of the NRM value by ~580° C, indicating that magnetite is the most common remanence carrier in lava breccias (e.g. Figure 6.23b). A summary of the different types of T_b spectra displayed by clasts from lava breccias is shown in Table 6.5.

T_b spectra type	% of clasts	INTERPRETATION
A	31	single-phase magnetite
B	15	single-phase maghaemite
C	3	single-phase haematite
D	5	single-phase titanomagnetite
E	34	two-phase
F	3	two/three phase (low T_c)
G	9	three+ phase

Table 6.5: Summary of T_b spectra types for clasts from lava breccias sampled on Ascension (with basic interpretation).

Two-phase, type E behaviour (Table 3.3) is most common in clasts from lava breccias, displayed by 34% of clasts (e.g. Figure 6.22b). This indicates that a two-phase mineralogy, comprising a titanomagnetite phase plus magnetite, maghaemite, haematite or a second titanomagnetite is most common in these clasts. Titanomagnetite compositions can be approximated from its T_c using a graph of T_c v titanomagnetite composition (Figure 3.9) and range from TM05 to TM57 (from T_b spectra data). A single-phase magnetite mineralogy (type A spectra; Table 3.3) is next most common, displayed by 31% of clasts (e.g. Figure 6.23b). Fifteen percent of clasts display a single-phase maghaemite mineralogy (type B spectra; Table 3.3). Single-phase titanomagnetite (type D spectra; Table 3.3) and haematite (type C spectra; Table 3.3) mineralogies are displayed by 5% and 3% of clasts respectively. The majority of the clasts that are inferred to contain maghaemite are found in units MVLB1 and NRF2 (which have been determined as being from the same deposit; Table 6.6). Three percent of clasts display type F demagnetisation

(Table 3.3) behaviour and 9% display type G demagnetisation behaviour (Table 3.3), i.e. they display a three-phase, or more complicated mineralogy.

6.4.3.1 Magnetic mineralogy and VRM

The majority of lava breccia units contain some samples that show a VRM. VRMs are typically removed by 150-200°C and are displayed most clearly by samples in which the characteristic remanence (TRM) is in a reversed direction (e.g. Figure 6.23a). VRM components cannot generally be isolated in clasts that display discrete T_b spectra, as the majority of demagnetisation occurs over a narrow temperature range, at elevated temperatures.

Samples that display a VRM component typically have either a magnetite mineralogy or a mixed (low-Ti titanomagnetite-magnetite) mineralogy. In addition, a number of magnetite samples from these units show *no* VRM component. It is clear therefore, that for these units, magnetic mineralogy cannot be used reliably to predict whether a VRM component will be present or absent.

6.4.4 Secular variation

Combination of secular variation, magnetic polarity and field and stratigraphic data has enabled correlation of the lava breccia units sampled on Ascension (see Chapter 7; Enclosure 1). Magnetostratigraphic correlation suggests that five distinct lava breccia deposits exist on Ascension, three of which were sampled at more than one location. Table 6.6 shows how individual sampling units relate to the five major lava breccia units.

major unit	polarity	sampled unit
1	normal	NRLB2, NRLB4, PPLB1
2	normal	SB4
3	normal	TV1
4	reversed	MVLB1, NRF2
5	reversed	NRLB1, NRLB3

Table 6.6: Relationships of individually sampled lava breccia units to the five major lava breccia units inferred to exist on Ascension.

Figures 6.24a, b and c show the directions of TRM components from individually sampled lava breccia units that are inferred to belong to the same major unit. Units that are inferred to belong to the same lava breccia unit have mean directions that are closely grouped. Figure 6.24d shows site mean directions for each of the *major* lava breccia units, three of which display normal polarity and two of which display reversed polarity. Mean directions for the five major units are distinct from one another at the 95% confidence

level. Mean declination (for units with the same polarity) varies by up to 23°. Less variation is seen in inclination, but directions vary by 5° in reversed units and as much as 13° in normally magnetised units. The variation in mean directions implies that these units were *not* deposited contemporaneously. Units that show reversed polarity are inferred to have ages >0.78Ma.

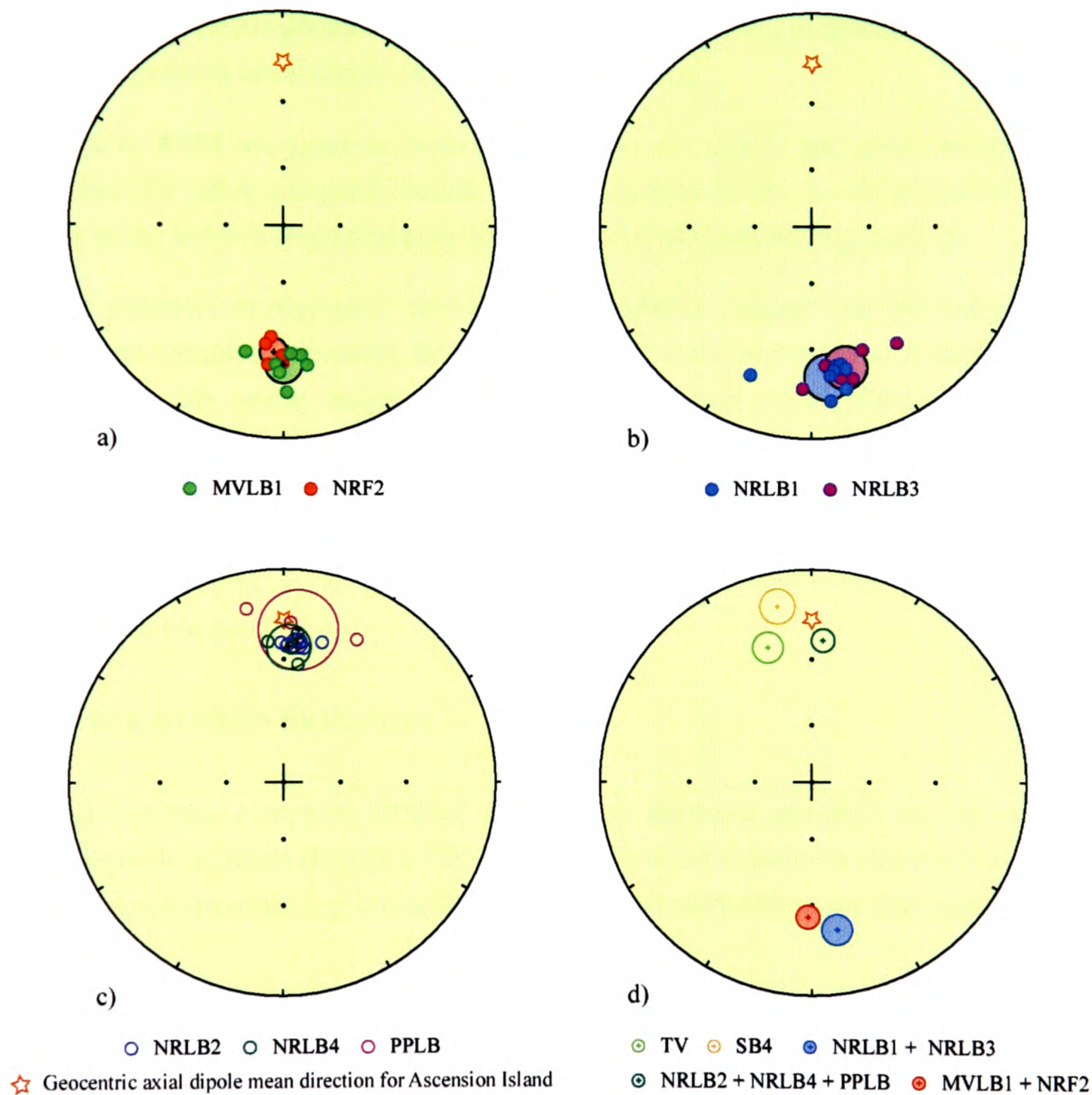


Figure 6.24: Stereoplots showing individual TRM directions, site mean directions (small crosses) and α_{95} values (large circles) for individually sampled lava breccia units (a, b, c) and site mean directions for the five major lava breccia units inferred to exist on Ascension (d). Plot a) shows data from sites that are inferred to comprise major unit 4, plot b) shows data for sites that comprise unit 5 and plot c) shows data for units that comprise unit 1. Mean directions for sites belonging to the same major unit are similar (i.e. they cannot be distinguished from one another at the 95% confidence level). TRM directions for all sites are tightly grouped and mean directions approximate the expected GAD or expected reversed GAD for Ascension. Plot d) shows site mean directions for the five major lava breccia deposits, which are distinct from one another at the 95% confidence level. Open and filled shapes represent points on the upper and lower hemispheres of the stereoplots respectively.

6.4.5 Conclusions

Clasts from lava breccia units typically display a single-component remanence in a direction sub-parallel, or antipodal to the expected GAD for Ascension, i.e. type 1a remanence behaviour (Table 3.2), indicating that the lava breccias were emplaced at temperatures in excess of 580°C. This substantiates field interpretations of these deposits. MVLB1 and NRF2 are interpreted as brecciated lava flows as they contain clasts with a narrow compositional range, and contain mafic inclusions. The remaining lava breccias are interpreted as hot pyroclastic flow deposits that display varying degrees of welding, as these display heterogeneous clast types, contain abundant juvenile material and may exhibit fine-grained basal layers or overlying ash layers.

Directions of TRM components from lava breccias are tightly grouped and grouping is tighter than for other sampled breccia units. This may be the result of partial welding, which is likely to have restricted possible movement of clasts during cooling.

Magnetic polarity, stratigraphic data and field evidence suggest that the individual lava breccia units sampled represent five distinct major units exposed on Ascension. Units belonging to the same major unit show similar site mean directions and field characteristics. Reversed units (units 4 and 5; Table 6.6) have mean directions that vary by up to 13°, suggesting that they were not deposited contemporaneously. Moreover, some time is likely to have separated their deposition, implying that they were deposited during the Matuyama reversed epoch, rather than during a brief event within the Brunhes normal epoch (Section 3.6.4).

6.5 STRATIFIED BRECCIAS

Stratified breccias comprise 29% of the breccia deposits sampled on Ascension for palaeomagnetic analysis (Figure 2.22). Fifteen individual units were sampled, all of which exhibit internal structure e.g. cross-stratification, ash interbeds, dune structures.

6.5.1 Remanence characteristics

The majority of clasts from stratified breccias carry a stable remanence. Stratified breccias can be divided into: units in which clasts typically display type 1 remanence behaviour (Table 3.2), i.e. low-T components lie sub-parallel (or antipodal) to the expected GAD for Ascension (e.g. Figure 6.25a), units in which clasts typically display type 2 remanence behaviour (Table 3.2), i.e. low-T components are randomly orientated with respect to the expected GAD (e.g. Figure 6.26), and units for which remanence characteristics are less straightforward (e.g. Figure 6.27).

Units EFS1/2, LA1/2 and LF2 are almost entirely comprised of clasts that show type 1

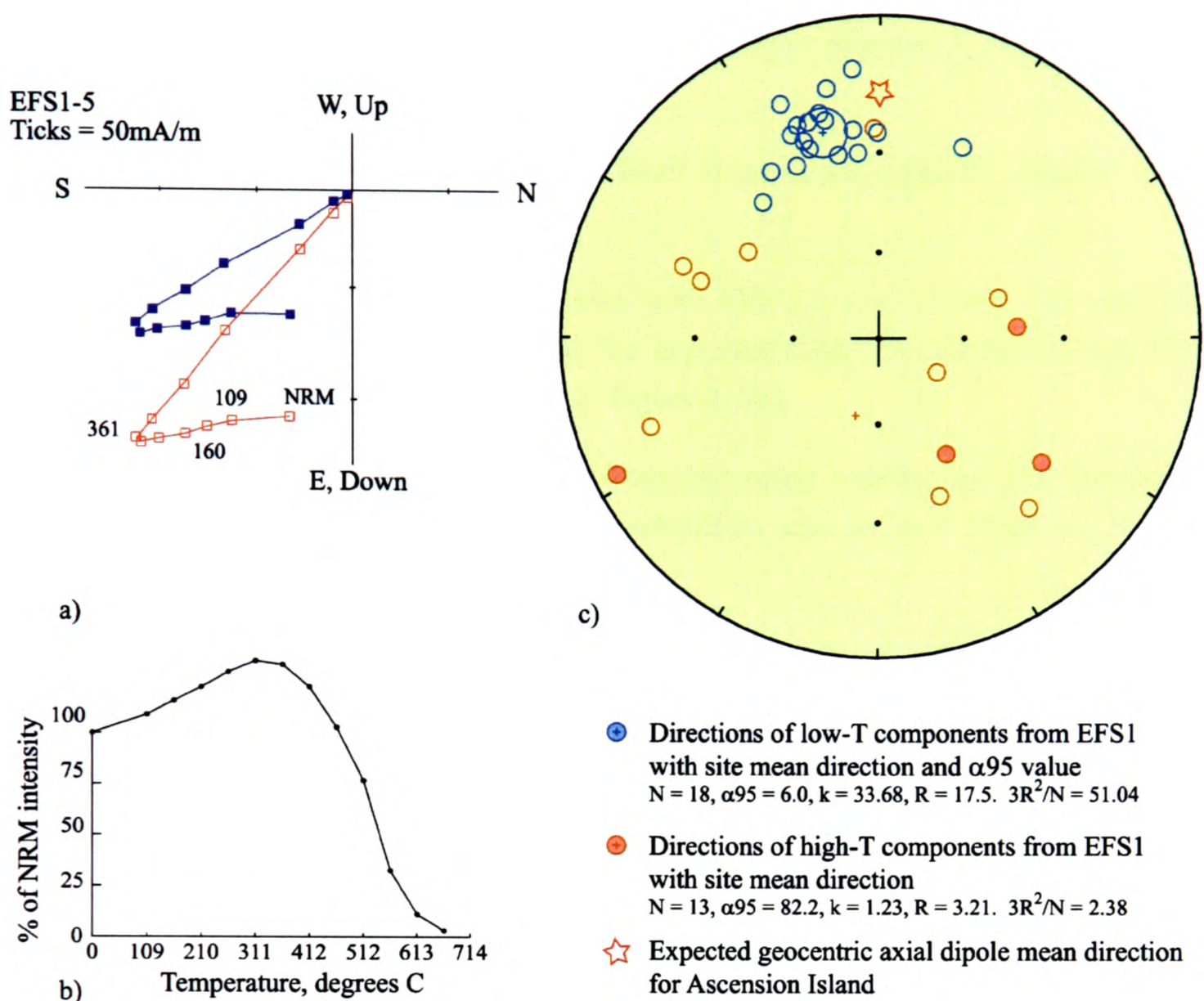


Figure 6.25: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot for samples from a stratified breccia that displays type 1 remanence behaviour (EFS1). EFS1-5 displays type 1b remanence behaviour (Table 3.2) and has a T_e of $\sim 361^\circ\text{C}$ (plot a). Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for EFS1-5 (plot b) displays an apparent increase in intensity as the low-T component tracks away from the origin, followed by a drop in intensity between $\sim 500^\circ\text{C}$ and 612°C , suggesting that remanence is carried by magnetite or maghaemite. Plot c) shows the distribution of individual low-T and high-T components for clasts from EFS1, with site mean directions (small crosses) and α_{95} value (large circle). Low-T directions are tightly grouped and their mean direction deviates from the expected GAD for Ascension by $\sim 15^\circ$. Directions of high-T components are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

remanence behaviour (Table 3.2). Most clasts from these units display type 1b remanence behaviour, i.e. a two-component remanence (e.g. Figure 6.25a), but some display type 1a (single-component remanence) and one clast displays type 1c behaviour (three-component remanence; Table 3.2). An additional VRM component is exhibited by five clasts from these units. The directions of VRM components may differ from the expected GAD for Ascension because of the influence of the low-T components.

In seven clasts from these units, low-T components lie in a direction distinct from the expected GAD for Ascension (i.e. they display type 2 remanence behaviour; Table 3.2) and in one clast, no magnetic components can be resolved. Type 2 behaviour can be attributed

to unstable clast mineralogy, or to the fact that clasts have discrete T_b spectra, which do not allow the isolation of a low-T component.

Juvenile (pumice) or pseudo-pumice clasts from these units typically display type 1a remanence behaviour (Table 3.2).

Low-T component directions for lithic clasts from EFS1/2, LA1/2 and LF2 are tightly grouped and mean directions approximate the expected GAD for Ascension (e.g. Figure 6.25c). High-T components are random (e.g. Figure 6.25c).

Unit P comprises pumice clasts sampled from the same locality as LF2 for polarity information. These clasts have low NRM intensities and in two clasts no magnetic

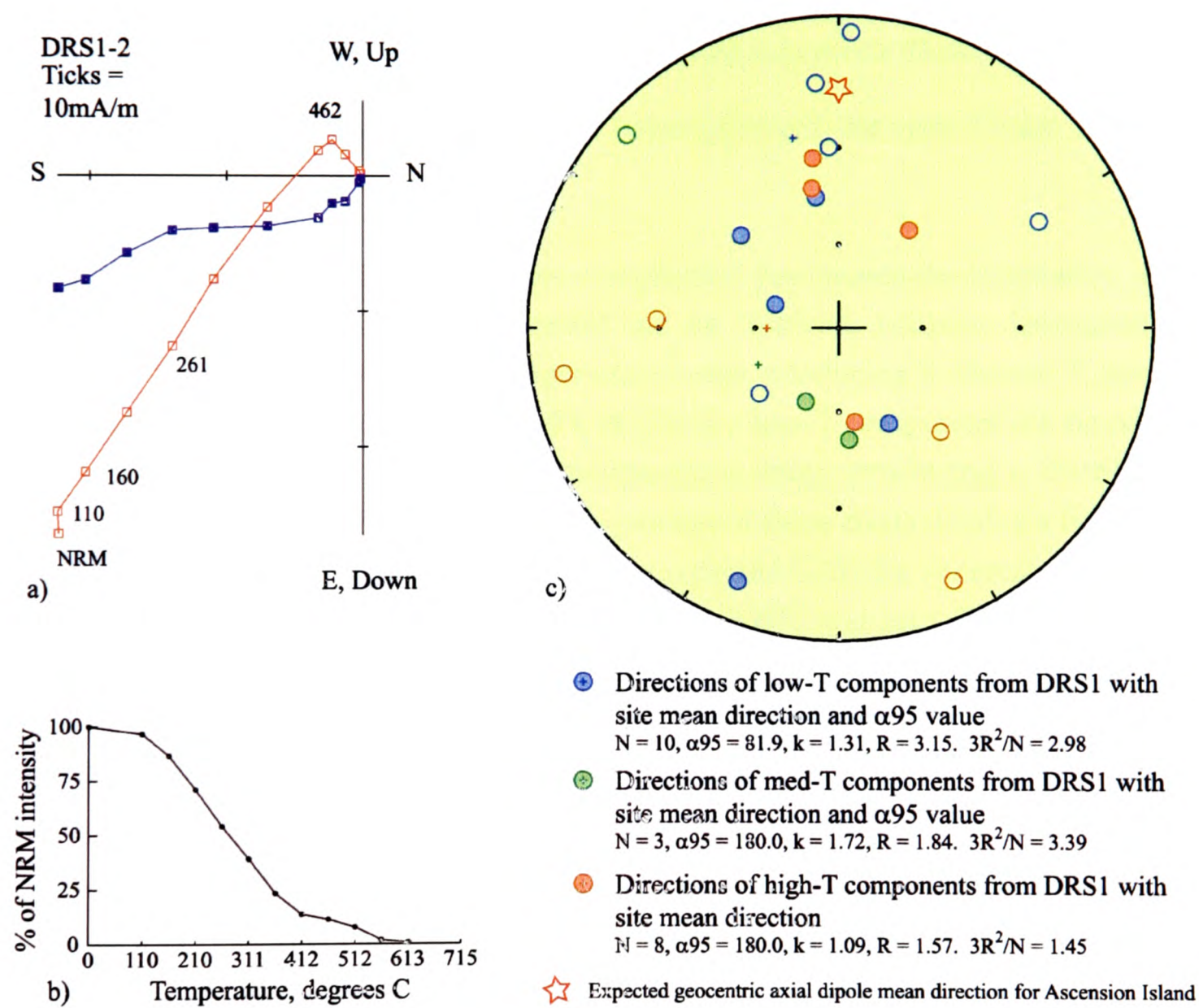


Figure 6.26: Zijderveld plot (z-plot), T_b spectrum and equal area stereoplot showing directions of low-T, med-T and high-T components for a stratified breccia (DRS1) that shows type 2 remanence behaviour (Table 3.2). DRS1-2 displays type 2c remanence behaviour (plot a; Table 3.2) and has relict T_b s of $\sim 261^\circ\text{C}$ and 462°C . Points represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. The T_b spectrum for DRS1-2 (plot b) is two-phase (type E1, Table 3.3), with drops in intensity at $\sim 412^\circ\text{C}$ and $\sim 580^\circ\text{C}$, suggesting that remanence is carried by titanomagnetite and magnetite. Plot c shows the distribution of individual low-T, med-T and high-T components for samples from DRS1, with site mean directions (small crosses). Low-T, med-T and high-T directions are all random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

components can be resolved. The remaining clasts display type 1a remanence behaviour (Table 3.2). Directions lie close to the low-T mean direction for clasts from LF2, however statistics cannot be calculated for unit P due to small clast population.

Units DRS1, EFB1, MRBB1, MRH1, SP1 and TBLB1 (Figure 6.1) contain mostly clasts that show type 2 remanence behaviour (Table 3.2; e.g. Figure 6.26a).

DRS1, EFB1 and MRBB1 contain type 2a, type 2b and type 2c clasts (e.g. Figure 6.26a). In MRBB1, SP1 and TBLB1, clasts typically display type 2a remanence behaviour (Table 3.2), though type 2b clasts are also displayed by MRBB1 and TBLB1.

An additional VRM component is displayed by seventeen clasts from type 2 units, but in all cases, this is removed by 100°C to 150°C. Type 1 remanence behaviour (where low-T components persist above 150°C) is displayed by six clasts from type 2 units. In all of these cases, low-T components are interpreted as CRM overprints (Section 6.5.3).

Directions of low-T and high-T components (where present) for type 2 units are random (e.g. Figure 6.26c).

Units CVS1, CVS2 and PPBB1 show more complicated remanence characteristics. In 56% of clasts from CVS1, no low-T component can be resolved, because demagnetisation occurs over a narrow and elevated temperature range, producing a discrete T_b spectrum (Section 6.5.3, e.g. Figures 6.27a,b). In 44% of clasts, a low-T component *can* be resolved, as demagnetisation occurs over a wide temperature range, producing a distributed T_b spectrum (e.g. Figures 6.27c,d). Seventy-five percent of these clasts display a type 1 low-T component (i.e. in a direction sub-parallel to the expected GAD for Ascension). However, low-T components are typically removed by 150°C to 200°C and may therefore be VRMs.

In the remaining 25% of clasts from this unit, 90% of demagnetisation occurs between 0°C and 100°C. This clast displays a type 1 low-T component that persists to 250°C, but this may be a CRM overprint.

In CVS2 and PPBB1, 70% of clasts show a type 1 low-T component (type 1b or type 1c remanence behaviour; Table 3.2). The remaining 30% of clasts display discrete T_b spectra, preventing the isolation of any low-T component. Directions of low-T components in clasts from CVS2 and PPBB1 are grouped, though grouping is relatively poor and mean directions deviate from the expected GAD for Ascension by 37°. Low-T components are typically removed by ~200°C and may therefore be TRM or VRM components.

6.5.2 Emplacement temperatures

Table 6.7 shows best estimates of equilibrium temperatures for stratified breccias. Five (33%) of the stratified breccias are interpreted as having been emplaced hot, with T_b s

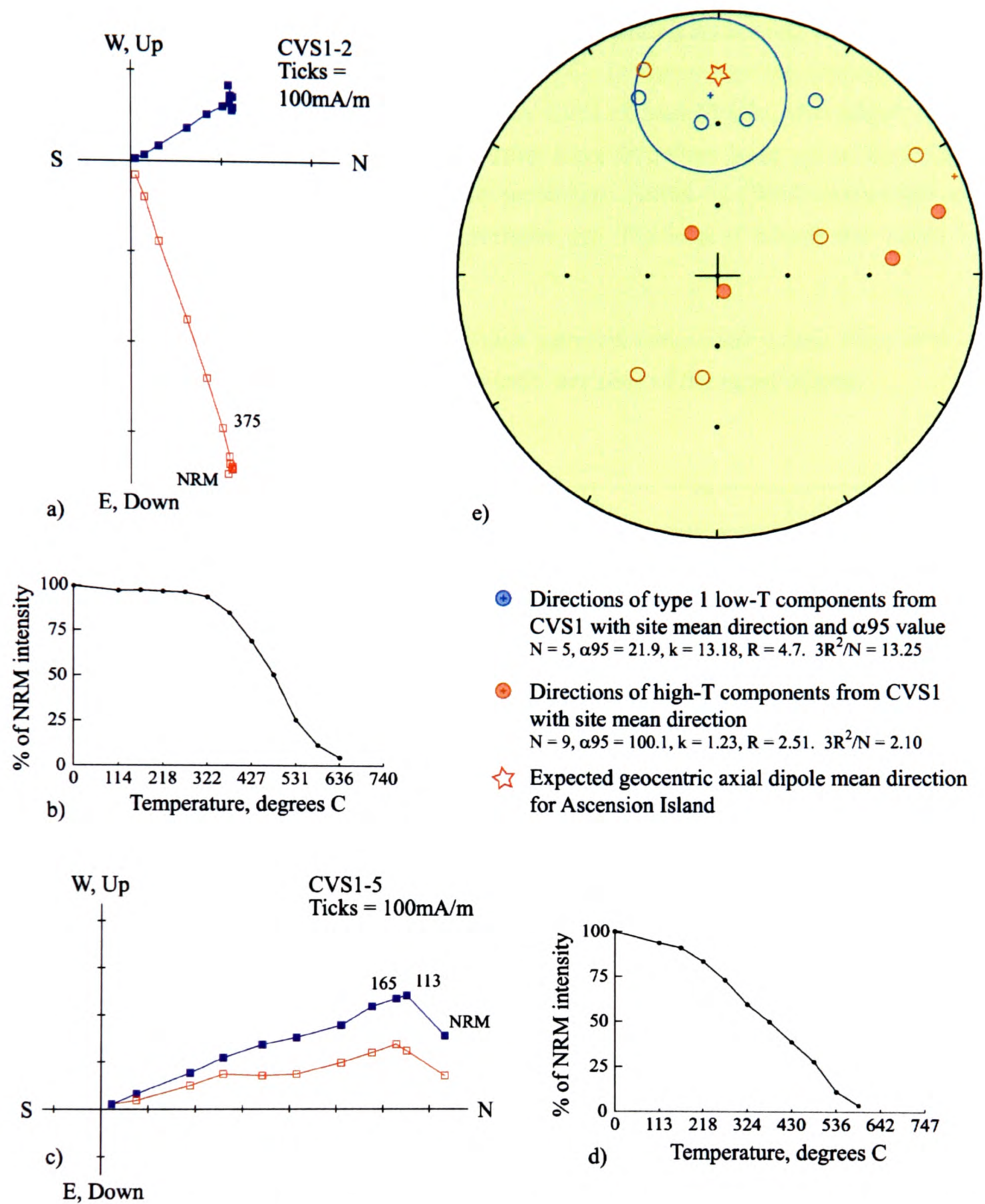


Figure 6.27: Zijderveld plots, T_b spectra and equal area stereoplot showing directions of low-T and high-T components for CVS1. CVS1-2 displays type 2a remanence behaviour (plot a; Table 3.2), however it is not possible to isolate a low-T component in CVS1-2, because of the shape of the T_b spectrum. The T_b spectrum for CVS1-2 (plot b) is discrete, with most demagnetisation occurring over a narrow temperature range between 350°C and ~600°C (type B1 demagnetisation behaviour; Table 3.3). Remanence is inferred to be carried by maghaemite. CVS1-5 displays type 1a remanence behaviour (plot c; Table 3.2) and demagnetisation occurs over a much wider temperature range (plot d). The T_b spectrum for CVS1-5 is distributed (type A2; Table 3.3) and full demagnetisation occurs at ~580°C, suggesting that magnetite is the remanence carrier. Points on z-plots represent heating steps of 50°C except where indicated otherwise and temperatures in a) and b) have been corrected to account for the thermal gradient of the furnace. Plot c shows the distribution of individual low-T components (from type 1 clasts only, i.e. clasts where a low-T component can be isolated) and high-T components for samples from CVS1, with site mean directions (small crosses) and α_{95} value (large circle). Low-T directions are grouped and high-T directions are random. Open and filled shapes on the stereoplot represent points on the upper and lower hemispheres respectively.

ranging from 291°C to 453°C. Six units (40%) are interpreted as having been emplaced at ambient temperature and these are given a T_e of 0°C. In the remaining four units (26%) a reliable estimate of T_e cannot be produced. In CVS1/2 and PPBB1, the origin of low-T components cannot be determined. These units have therefore been given two T_e s: 0°C, which assumes that low-T components are secondary (VRM or CRM) overprints and a $T_e > 0^\circ\text{C}$, which assumes that low-T components are TRMs and hence the units were emplaced hot.

No T_e can be calculated for unit P, as pumice samples only were taken from this unit, however it is grouped with unit LF2 as both units are part of the same deposit.

unit	T_e , °C	unit	T_e , °C
CVS1	0 ¹ , 161 ²	LA2	291
CVS2	0 ¹ , 164 ²	LF2 (P)	453
DRS1	0 (264, 349)	MRBB1	0 (161)
EFB1	0 (313)	MRH1	0 (214)
EFS1	311	PPBB1	0 ¹ , 160 ²
EFS2	287	SP1	0 (264)
LA1	293	TBLB1	0 (240)

Table 6.7: Best estimates of equilibrium emplacement temperature for stratified breccias sampled on Ascension. Values in brackets represent relict T_e s (i.e. the average T_e of the source deposit). ¹ T_e for the deposit assuming that low-T components are secondary (VRM or CRM) overprints. ² T_e for the deposit assuming that low-T components are thermal in origin.

6.5.2.1 Thermal stratification study

Additional samples were taken from EFS1 and EFFB1 for palaeomagnetic analysis, in order to carry out an investigation into thermal stratification within the deposit that they comprise. EFS1 is an inferred surge deposit that is overlain by a hot lava breccia unit (Figure 6.28). EFFB1 is inferred to be a hot pyroclastic

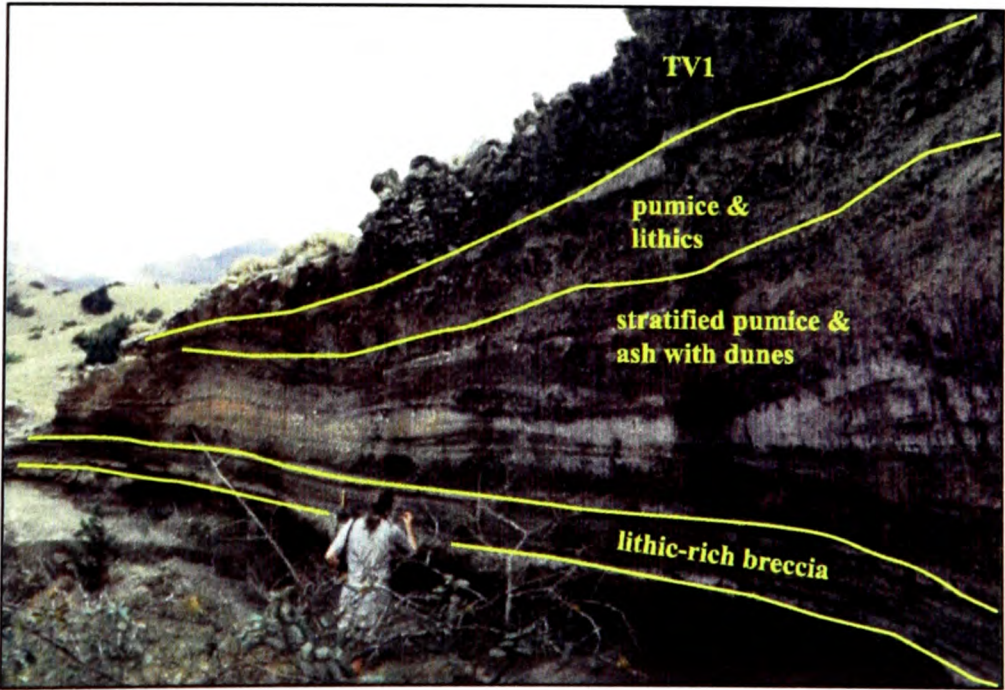


Figure 6.28: Photo of EFS1 showing the various different units that make up the deposit (see also Figure 6.29).

flow deposit and underlies EFS1 (Figure 6.29). The aim of this study was to determine whether clasts from EFS1 have been thermally affected by the emplacement of the overlying hot lava breccia. Such ‘thermal overprinting’ has been observed by Bardot (1997) in a number of pyroclastic deposits from Santorini (although this was only recognised in cases in which the overlying deposit was an order of magnitude thicker than the underlying deposit). Additional thermal modelling calculations by Bardot (1997) suggest that significant heating of deposits (to more than one tenth of the initial overlying deposit temperature) may occur up to a distance equivalent to the thickness of the overlying (cooling) deposit.

Samples were taken from different height intervals within EFS1 and EFFB1 and their emplacement temperatures plotted against stratigraphic height (Figure 6.29). Figure 6.29

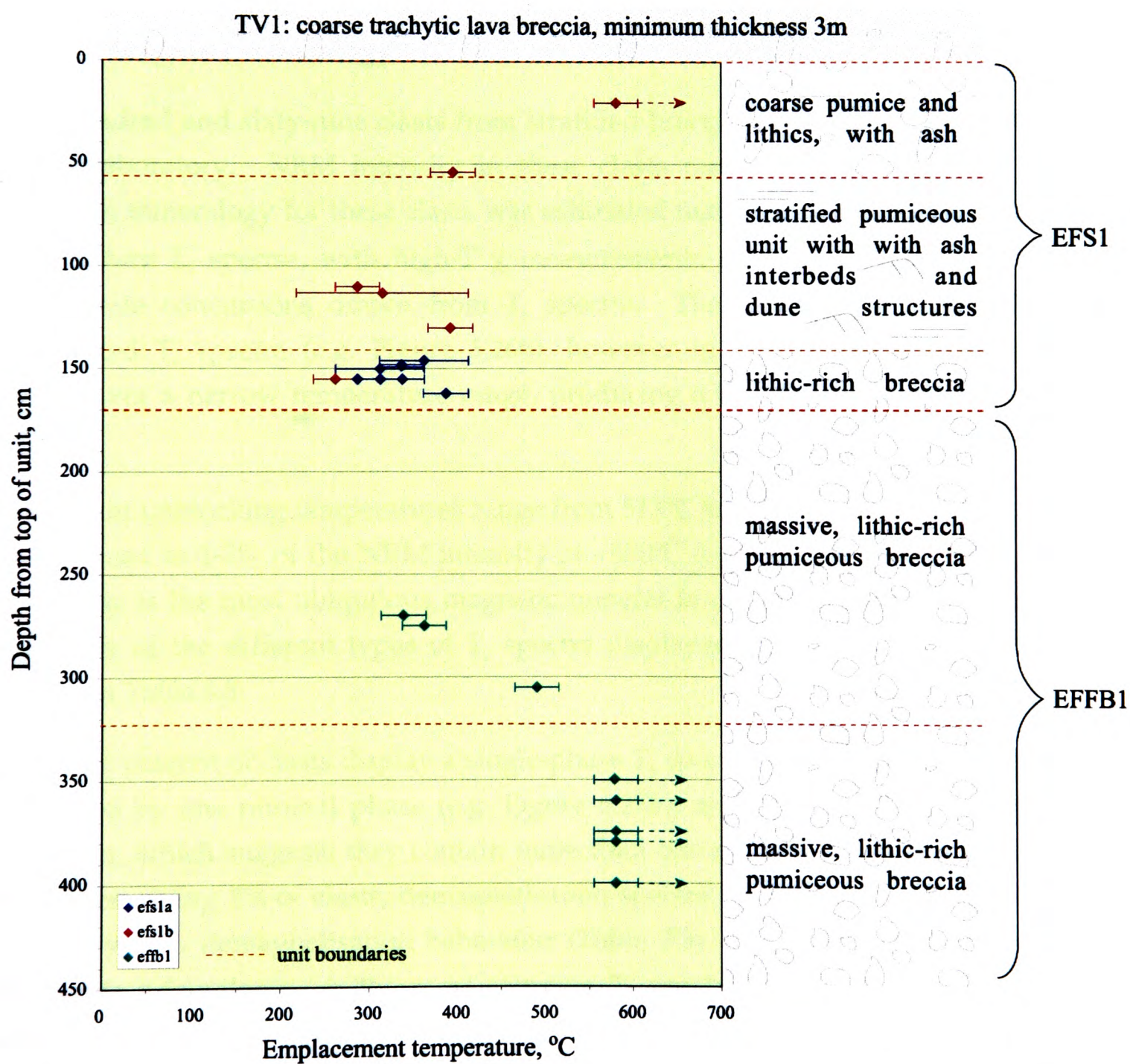


Figure 6.29: Plot of emplacement temperature v stratigraphic height for clasts from EFS1 (see Figure 6.28) and EFFB1, plus descriptions of their constituent stratigraphic units. In the upper 1.1m of the deposit (upper units of EFS1), T_e for clasts decreases with depth (i.e. distance from the base of TV1). From 1.1m to ~2.7m depth, T_e is relatively constant (and similar). Below 2.7m (EFFB1), T_e increases, until ~3.5m depth, below which all clasts have a $T_e > 580^\circ\text{C}$.

shows that T_e decreases (from $>580^\circ\text{C}$ to $\sim 275^\circ\text{C}$) from 0 to $\sim 1.1\text{m}$ depth, remains relatively constant between 1.1 and 2.7m depth and then increases from 2.7m to $\sim 3.5\text{m}$ depth. Below 3.5m all clasts have a $T_e > 580^\circ\text{C}$.

The fact that T_e increases with proximity to the top of the unit suggests that in the upper 1.1m of the unit, clasts may have been thermally affected (i.e. re-heated) by the overlying hot lava breccia. Below 1.1m, there is no thermal gradient, suggesting that the overlying unit has not affected clasts below this depth. The increase in T_e seen in clasts below $\sim 2.7\text{m}$ is interpreted to reflect changing flow processes during the eruption and deposition of the lower and upper units of EFFB1. For example, the incorporation of increased amounts of air (or water) into the flow as the eruption progressed, could have resulted in later erupted (stratigraphically higher) units, being cooled and hence having lower emplacement temperatures.

6.5.3 Magnetic mineralogy

One hundred and sixty-nine clasts from stratified breccias were thermally demagnetised in the laboratory. NRM intensity in these clasts ranges from 4mA/m to 18.9A/m. Magnetic mineralogy for these clasts was estimated mainly through analysis of blocking temperature T_b spectra, with high-T χ measurements carried out on selected clasts to corroborate conclusions drawn from T_b spectra. The majority of clasts (75%) show distributed T_b spectra (e.g. Figure 6.26b), however in 25% of clasts, demagnetisation occurs over a narrow temperature range, producing a discrete T_b spectrum (e.g. Figure 6.27b).

Maximum unblocking temperatures range from 513°C to 675°C , but the majority of clasts are reduced to 1-2% of the NRM intensity at $\sim 580^\circ\text{C}$ (e.g. Figure 6.27d), suggesting that magnetite is the most ubiquitous magnetic mineral in clasts from stratified breccias. A summary of the different types of T_b spectra displayed by clasts from lava breccias is shown in Table 6.8.

Fifty-one percent of clasts display a single-phase T_b spectrum, suggesting that remanence is carried by one mineral phase (e.g. Figure 6.27b), and 48% display a multi-phase T_b spectrum, which suggests they contain more than one mineral phase (e.g. Figure 6.26b). In the remaining 1% of clasts, demagnetisation spectra cannot be classified due to noisy data. Type A demagnetisation behaviour (Table 3.3) – which suggests a single-phase magnetite mineralogy – is the most common T_b spectra type displayed by clasts from stratified breccias (28% of clasts; Table 6.8). Next most common (24% of clasts; Table 6.8) is type E demagnetisation behaviour (Table 3.3), which indicates a two-phase mineralogy comprising low T_c titanium-rich (Ti-rich) titanomagnetite, plus magnetite (most common), maghaemite (next most common), haematite or a second titanomagnetite (5 clasts each). Compositions for Ti-rich titanomagnetite phases (estimated from Figure 3.9) range from

TM43 to TM68 and compositions for Ti-poor (i.e. low T_c) titanomagnetite phases range from TM02 to TM43 (from T_b spectra data).

Seventeen percent of clasts display a significant drop in intensity in the range 0°C to 200°C (type F demagnetisation behaviour; Table 3.3; Table 6.8). In the majority of these clasts, this drop in intensity corresponds to the removal of the low-T component, which is interpreted as a CRM overprint, carried by Ti-rich titanomagnetite.

T_b spectra type	% of clasts	INTERPRETATION
A	28	single-phase magnetite
B	11	single-phase maghaemite
C	7	single-phase haematite
D	5	single-phase titanomagnetite
E	24	two-phase
F	17	two/three phase (low T_c)
G	7	three+ phase

Table 6.8: Summary of T_b spectra types for clasts from stratified breccias sampled on Ascension (with basic interpretation).

Eleven percent of clasts display type B demagnetisation behaviour (Table 3.3), which suggests a single-phase maghaemite mineralogy. Single-phase haematite (type C demagnetisation behaviour; Table 3.3) and single-phase titanomagnetite (type D demagnetisation behaviour; Table 3.3) are inferred to be relatively rare in clasts from stratified breccias, displayed by only 7% and 5% of clasts respectively. Seven percent of clasts display type G demagnetisation behaviour (Table 3.3), which suggests a three-phase, or more complicated mineralogy.

6.5.4 Secular variation

Figure 6.30 shows site mean directions for low-T components from a) inferred hot stratified breccia units and b) for type 1 clasts from units CVS1, CVS2 and PPBB1.

All hot stratified breccias display normal polarity and site mean directions approximate the expected GAD for Ascension (Figure 6.30a). Mean directions cannot be distinguished from one another at the 95% confidence level and relative ages cannot therefore be inferred for these units. However, it is possible that some of these units were deposited contemporaneously.

Units CVS1, CVS2 and PPBB1 all display normal polarity. Site mean directions for CVS1 and PPBB1 approximate the expected GAD for Ascension, but the mean direction for

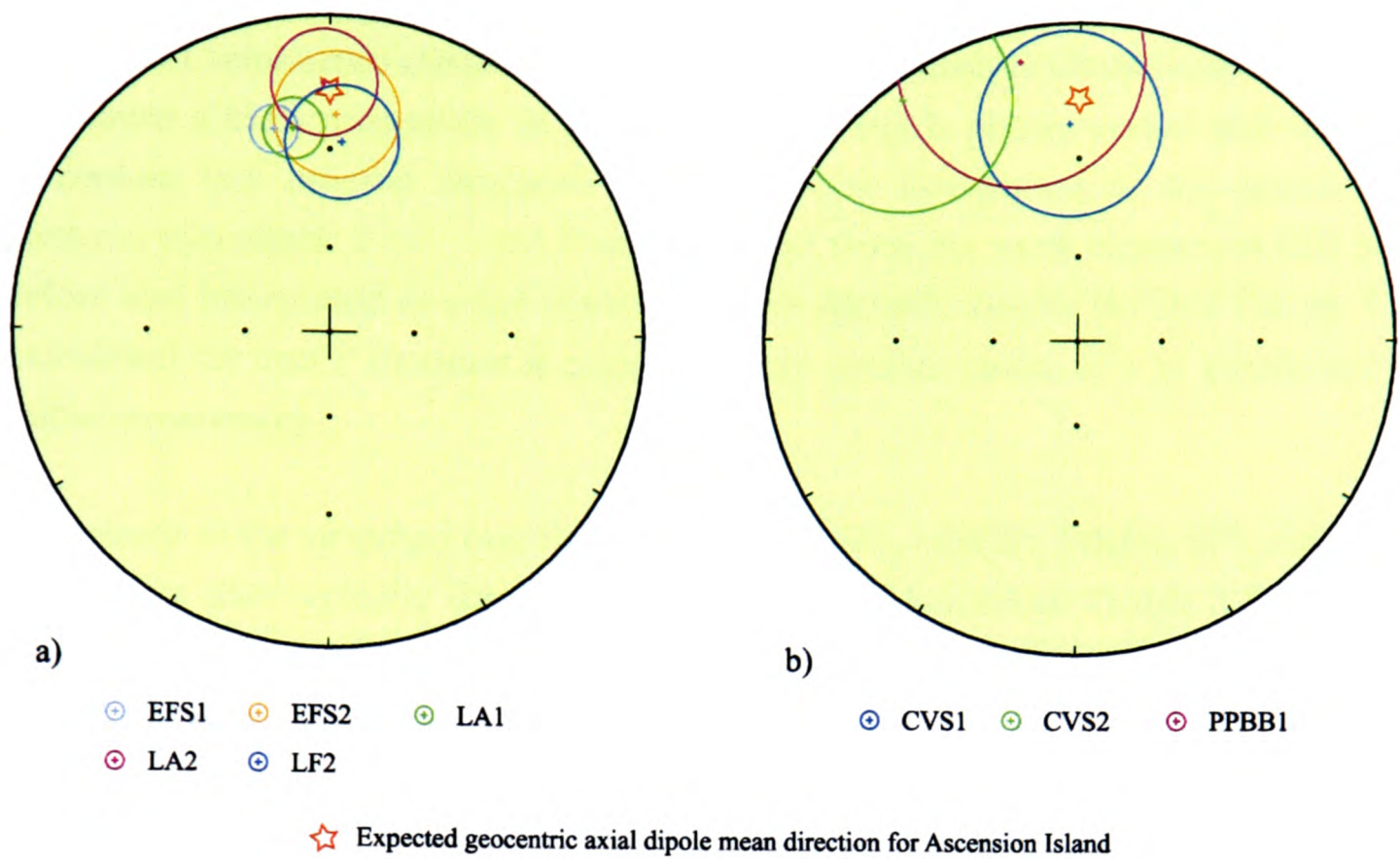


Figure 6.30: Equal area stereoplots showing site mean directions (small crosses) and a95 values (circles) for stratified breccias. All units display normal polarity. Plot a) shows units that are interpreted as hot and plot b) shows units for which the origin of low-T components is unclear. Mean directions for hot units approximate the expected GAD for Ascension and cannot be distinguished at the 95% confidence level. Mean directions for CVS1 and PPBB1 approximate the expected GAD for Ascension, but the mean direction for CVS2 is distinct from the GAD. However, mean directions of all sites in b) are similar (cannot be distinguished from one another) at the 95% confidence level. Open shapes represent points on the upper hemisphere of the stereoplot.

CVS2 deviates from the GAD by $>36^\circ$ in declination and $>11^\circ$ in inclination. However, α_{95} values for the units are relatively large (Figure 6.30b). Mean directions for the three units cannot therefore be distinguished from one another at the 95% confidence level and no inferences can therefore be made about their relative ages.

6.5.5 Conclusions

Thirty-three percent of the stratified breccias (EFS1/2, LA1/2, LF2) contain clasts that typically display type 1 remanence behaviour (Table 3.2), i.e. low-T components lie in a direction sub-parallel to the expected GAD for Ascension. These units are therefore interpreted as primary (hot) pyroclastic deposits, with T_s ranging from 287°C to 453°C . These data in combination with field evidence such as high juvenile (pumice) and ash content and internal structure such as dunes and ripples suggest that EFS1/2 and LA1/2 are pumiceous pyroclastic surge deposits. The pyroclastic surges that produced EFS1 and EFS2 are inferred to have been hot and dry, suggesting that they were ground surges as opposed to base surges. Base surges are often cold and wet (Cas and Wright, 1988) and their component clasts are expected therefore to display type 2 remanence characteristics (e.g. randomly orientated low-T components; Table 3.2). Ground surges are typically hot and dry (Cas and Wright, 1988) and their component clasts are therefore expected to

display type 1 remanence characteristics (Table 3.2), as is seen in clasts from EFS1/2. LF2 also contains a high proportion of pumice and ash, but is poorly sorted and individual beds contain less internal structure. It is therefore interpreted as the product of a pumiceous pyroclastic flow. Unit P was sampled from the same deposit as LF2 and is therefore also interpreted as a hot pyroclastic flow deposit, despite the fact that no T_e can be calculated for unit P (because it comprises only pumice clasts, 50% of which show an unstable remanence).

Forty percent of the stratified breccia units (DRS1, EFB1, MRBB1, MRH1, SP1 and TBLB1) contain clasts that typically display type 2 remanence behaviour (Table 3.2), i.e. low-T components lie in a direction distinct from the expected GAD for Ascension. This suggests that these units were emplaced at ambient temperature. Palaeomagnetic data for all of these units except MRH1 and SP1 concur with field evidence, such as sandy matrix, cross-bedding, trains or lenses of pumice and channel-fill features, which suggest that these are epiclastic deposits. A more precise interpretation cannot be made, but origins as mudflow, debris flow or fluvially reworked deposits are all possible.

Field evidence such as internal stratification, fiamme-like (flattened) juvenile clasts, accretionary lapilli and alteration to clays suggests that MRH1 is a hydromagmatic pyroclastic deposit. Palaeomagnetic data suggest that MRH1 was emplaced at ambient temperature, however this does not preclude a primary pyroclastic origin for MRH1. If water was involved in the eruption (as would be expected in a hydromagmatic eruption; Section 2.1.1), the eruptive material would have been cooled, reducing T_e , possibly to temperatures below the resolution of the palaeomagnetic emplacement temperature method (i.e. $<50^\circ\text{C}$). Clasts from such deposits would be expected to display low-T components with random directions, as is seen in MRH1.

SP1 displays similar field characteristics to units LA1 and LA2 (e.g. fine grain size, planar and cross-stratification), suggesting that it is either the distal equivalent of, or has been reworked from these units. Most clasts from SP1 display a multi-component remanence, with randomly orientated low-T components, suggesting that the unit was emplaced at ambient temperature. The estimated relict T_e for clasts from SP1 is 264°C , which is close to the estimated primary T_e s for LA1 and LA2 (293°C and 291°C respectively). This favours the suggestion that SP1 was reworked from the LA deposits, which in turn suggests that substantial amounts of water were present on Ascension in the past (as SP1 lies $\sim 2\text{km}$ from the LA deposits).

Origins of the remaining 20% of stratified breccia units (CVS1, CVS2 and PPBB1) cannot be clarified from palaeomagnetic data. This is because it is not possible to distinguish between VRM and TRM in low-T components from these units, or low-T components cannot be resolved due to discrete T_b spectra. However, the palaeomagnetic data suggests

that these units were either emplaced hot, at temperatures $\leq 200^{\circ}\text{C}$, or were emplaced at ambient temperature (cold) and have subsequently acquired VRM components.

Field evidence suggests that CVS1 and CVS2 are either base surge deposits or reworked (water-lain) deposits. Palaeomagnetic data for these units cannot clarify the origin of these units, because no distinction can be made between low temperature TRMs and VRMs in clasts from CVS1 and CVS2. If these deposits were emplaced at ambient temperature, this does not preclude a base surge origin, as many of such deposits are cold and wet (see Section 2.1.4.3). Clasts from the deposits of cold, wet base surges would be expected to display randomly orientated low-T components. If CVS1 and CVS2 are reworked deposits, this once more implies the presence of substantial volumes of water on Ascension in the past.

Field evidence (such as high matrix content, channel-like features) suggests that PPBB1 originated as a flow, but allows no distinction between hot and cold flow types. Palaeomagnetic data suggest that two T_e s are possible for PPBB1: 1) a T_e of 0°C , which suggests that low-T components in clasts from PPBB1 are VRMs, and 2) a $T_e \leq 200^{\circ}\text{C}$, which suggests that low-T components in clasts from PPBB1 are TRMs. Assuming PPBB1 was emplaced at ambient temperature ($T_e = 0^{\circ}\text{C}$), it is interpreted as a mudflow deposit. Assuming PPBB1 was emplaced at elevated temperature ($T_e \leq 200^{\circ}\text{C}$), it is interpreted as a pumiceous pyroclastic flow deposit.

The thermal stratification study carried out on EFS1 and EFFB1 suggests that the T_e of clasts from the upper ~1m of the deposit increases with proximity to the overlying hot unit and thus that thermal overprinting of the upper region of the deposit may have occurred. Such overprinting has been shown to be plausible by Bardot (1997), however the variation in clast T_e displayed by EFS1 may also be attributed to changing flow processes during the eruption and deposition of the deposit. A definitive origin for the temperature gradient displayed by EFS1 and EFFB1 cannot therefore be determined without further detailed sampling of the deposits.

6.6 MAJOR CONCLUSIONS

In the majority of cases, palaeomagnetic analysis has enabled the origins of breccia deposits sampled on Ascension to be clarified. Sixty-two percent of the breccia deposits sampled are interpreted as having been emplaced hot. Emplacement temperatures for these units range from 186°C to $>580^{\circ}\text{C}$. Twenty-three percent of units are interpreted as having been emplaced at ambient temperature (cold). The majority of these are inferred to have been reworked from previously hot pyroclastic material with T_e s ranging from 239°C to 427°C . In 15% of units, palaeomagnetic analysis cannot clarify modes of

formation, either because no distinction can be made between TRM and VRM components, or because no low-T components can be resolved.

Magnetic mineralogy in clasts from breccia deposits is variable, however clasts most commonly display a mixed mineralogy comprising a titanomagnetite phase plus magnetite, maghaemite, haematite or a second titanomagnetite. Titanomagnetite compositions range from TM02 to TM70. Haematite is the least common remanence carrier in these clasts.

Many two-phase clasts display a low-T CRM overprint. In these clasts, the overprint is typically carried by high-Ti titanomagnetite and the high-T component is carried by magnetite or low-titanium titanomagnetite. Clasts from reworked parts of the Pourahu deposit at Ruapehu (Section 3.7) also display this behaviour.

The thermal stratification study suggests that T_c s of clasts may be affected by thermal overprinting from overlying hot units. This highlights the importance of combining palaeomagnetic data with field evidence (e.g. deposit thickness, surrounding stratigraphy, stratigraphic height of individual clasts) in the interpretation of pyroclastic deposits.

The majority of breccia deposits sampled on Ascension display normal polarity, however 17% display reversed polarity. Reversed units are inferred to have been deposited during the Matuyama reversed epoch (rather than within a short-lived reversed event within the Brunhes normal epoch), suggesting that they have ages $>0.78\text{Ma}$. These units are interpreted as primary pyroclastic deposits and are hence well-preserved.

Chapter 7

CORRELATION AND ERUPTIVE HISTORY

This chapter combines the data obtained in this study (including magnetic polarity, emplacement temperatures, secular variation, geochemistry and volcanological data), in order to: a) correlate the major sequences of pyroclastic material on Ascension, b) evaluate the distribution of primary versus reworked material on Ascension, c) determine source areas for the pyroclastics, and d) place the pyroclastic sequences into a temporal framework.

7.1 REVERSAL STRATIGRAPHY

Ninety-seven individual stratigraphic units (from various different deposits) were sampled on Ascension for palaeomagnetic analysis. Seventy-two percent of the units sampled display normal polarity, whilst 5% of units display reversed polarity. Polarity could not be determined for 23% of units, due to insufficient or noisy data, or because units are interpreted as epiclastic and hence constituent clasts exhibit no preferred magnetic direction. The presence of reversed units within the pyroclastic stratigraphy of Ascension suggests that the eruption and subsequent reworking of the (exposed) pyroclastic deposits spanned a reversal of the Earth's magnetic field. The most recent major magnetic reversal (the Brunhes-Matuyama boundary) is dated at ~0.78Ma (Cande and Kent, 1995), but a number of short-lived reversals ('events') have also occurred within the Brunhes normal epoch (see Chapter 3, Figure 7.1). Based on magnetic polarity alone, there are therefore a number of possible dates that this boundary could represent. However, correlation of the pyroclastic sequence with a radiometrically dated unit constrains the age unambiguously (Figure 7.1). The boundary between reversed and

normal units can be most precisely located within the pyroclastic sequence exposed at NASA Road and Pyroclastic Plain (see Figure 1.8; Enclosure 1). Lower units in this sequence display reversed polarity and upper units display normal polarity, and the entire sequence is underlain by a rhyolite lava, which has been dated at $\sim 0.99 \pm 0.02 \text{ Ma}$ (Nielson and Sibbett, 1996¹). In addition, a basaltic dyke, dated at $\sim 0.80 \pm 0.03 \text{ Ma}$ (Nielson and Sibbett, 1996) cross-cuts the lower units of the sequence (Figure 7.1). The implication from these dates is that the reversal seen in the Ascension pyroclastic stratigraphy is younger than $\sim 0.80 \text{ Ma}$ and that it represents the *Brunhes–Matuyama boundary* (dated at $\sim 0.78 \text{ Ma}$; Cande and Kent, 1995).

The presence of the Brunhes–Matuyama boundary is also revealed by secular variation data for units sampled on Ascension (Figure 7.2). Figure 7.2 shows the variation in mean declination and inclination with depth for units from some of the major pyroclastic sequences on Ascension as well as the positions of some of the dated pyroclastic deposits. The B–M boundary is represented by the large deviation from the expected normal geocentric axial dipole mean declination and inclination values for Ascension (Figure 7.2).

7.2 CORRELATION

Stratigraphic logs were constructed for the major pyroclastic sequences exposed on Ascension. Magnetic polarity data proved invaluable for correlation, as in many cases, these logs could not be correlated from field evidence alone. For example, three individual lava breccia units are found within the NASA Road – Pyroclastic Plain – Middleton’s Valley sequence (see Figure 1.8), which cannot be distinguished by their field

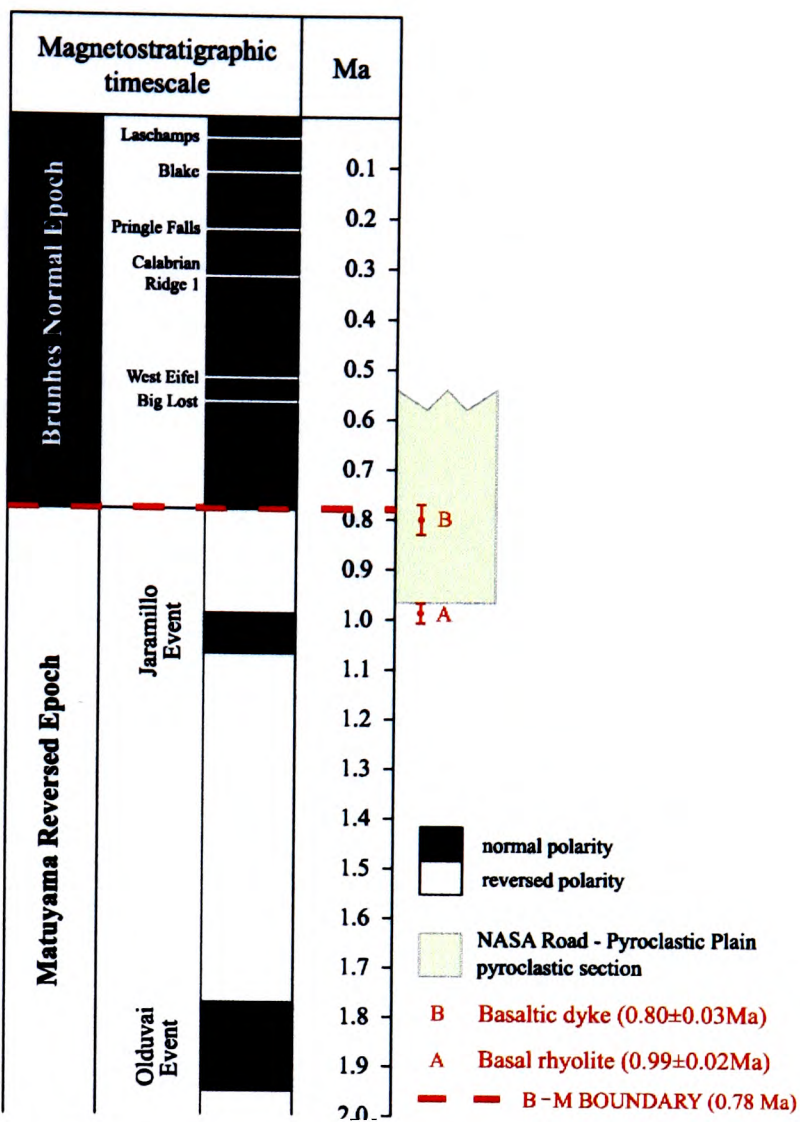


Figure 7.1: Magnetostratigraphic timescale for the last 2Ma, showing the positions of the Brunhes-Matuyama boundary and the basal rhyolite and cross-cutting dyke seen in the NASA Road – Pyroclastic Plain pyroclastic section. Timescale data from Cande and Kent (1995) and Opdyke and Channell (1996) and age data from Nielson and Sibbett, 1996.

¹ Dating carried out by M. Shafiqullah, University of Arizona and S. H. Evans Jr., University of Utah. Results published in Nielson and Sibbett, 1996.

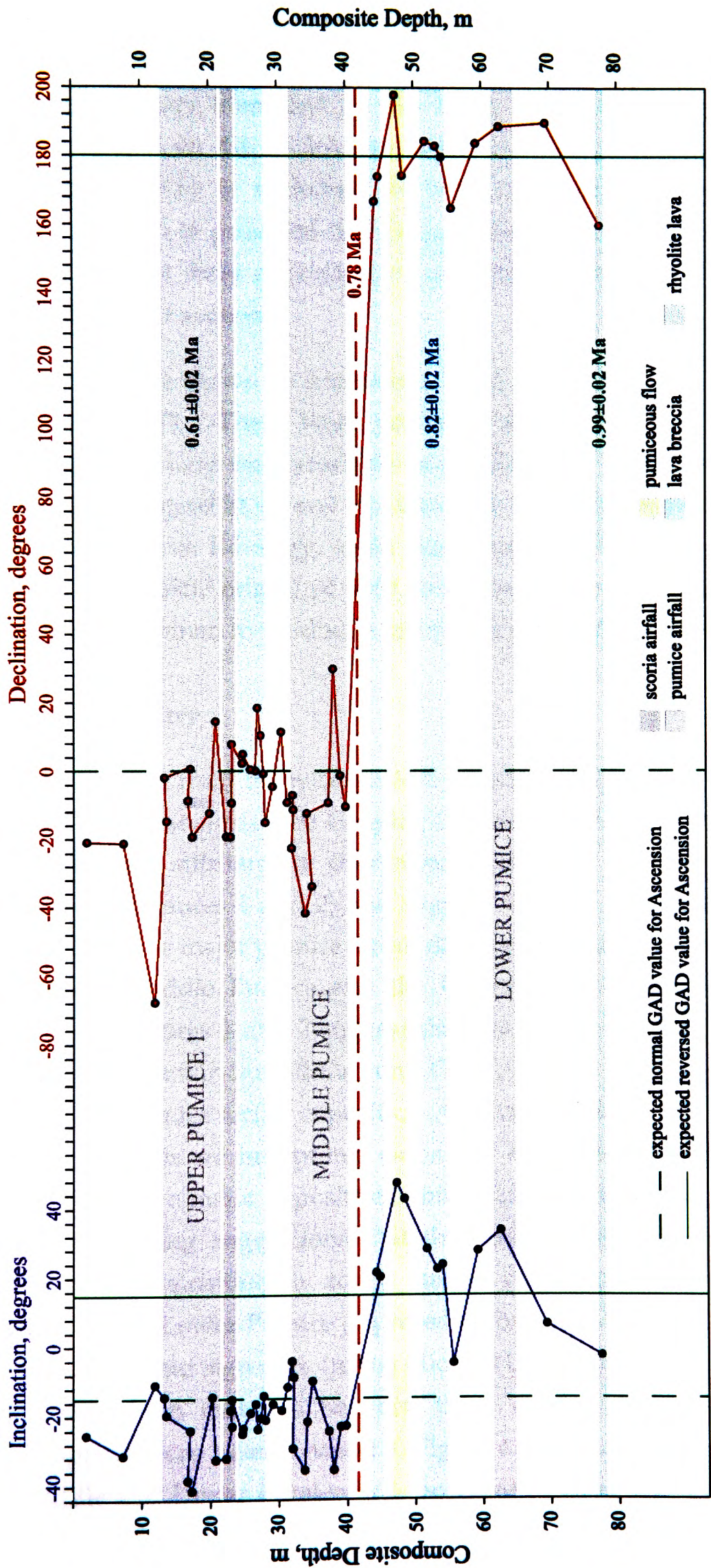


Figure 7.2: The variation in site mean declination (D) and inclination (I) with composite depth for pyroclastic deposits from Ascension. The expected normal geocentric axial dipole mean (GAD) D and I for Ascension (000/-15) are shown as the dashed green lines, and the expected reversed GAD D and I (180/15) are shown as the plain green lines. Also shown are the approximate positions of some of the units that can be correlated between sections (coloured bands), with K-Ar ages (where known). The location of the Brunhes-Matuyama boundary is shown as the red dashed line. The reversal in the stratigraphy can be seen as a large deviation from the expected GAD values. K-Ar dates are from Nielson and Sibbett (1996) and Kar et al., (1998).

characteristics. However, two of the lava breccias display reversed polarity and the remaining unit displays normal polarity.

Enclosures 1 and 2 show magnetostratigraphic sections (logs) for the major pyroclastic sequences exposed in central and eastern Ascension, respectively, and correlations based on the B–M boundary identified by this study. The inferred position of the reversal boundary is shown on the Enclosures as the red dashed line and the Mountain Road Section (Section 8/A) is included on both Enclosures for reference. A separate stratigraphic section is provided for the pyroclastic deposits exposed at Cricket Valley (Figure 7.3), because these deposits have a limited areal extent and cannot therefore be correlated with other sections.

Some of the Sections shown on Enclosures 1 and 2 are composite sections (e.g. Sections 2 and 8, Enclosure 1). These were produced for areas (e.g. Green Mountain Road, Pyroclastic Plain) where the pyroclastic sequence is not continuous. In these areas, the stratigraphy was logged at several localities and these logs were subsequently correlated according to the basic lithology, grain size, magnetic polarity and T_e (which indicates pyroclastic or epiclastic origin) of their constituent units (see Figures 7.4 and 7.5). The logs were then combined to produce a composite section for the area.

7.2.1 Geochemistry

Samples were taken from thirty-seven individual (mainly airfall) units on Ascension for geochemical (XRF) analysis (see Chapter 4, Section 4.15). Whole rock major and trace element signatures substantiate correlations based on magnetostratigraphic and field evidence (see Enclosures 1 and 2) and suggest that the units sampled for geochemistry belong to one of five major pumice airfall deposits exposed on Ascension, here named as: the Lower and Middle Pumice and the Upper Pumice 1, 2 and 3. The correlation proposed in Enclosures 1 and 2 suggest that the Upper Pumice 3 is associated with the welded Green Mountain ignimbrite (unit GMI1; Section C, Enclosure 2) and may be the youngest major pumice airfall deposit on Ascension. The majority of units sampled for geochemical analysis are interpreted as part of the Middle Pumice or Upper Pumice 1. Units from these two major deposits exhibit similar trace element signatures (see Figures 4.12a,b), contradicting suggestions that they the Ascension pyroclastic deposits were erupted from a compositionally zoned magma chamber (e.g. Harris, 1982; Nielson and Sibbett, 1996). The Lower Pumice (represented by unit MVA2 in Figure 4.13a) displays a different trace element signature (to the Middle/Upper Pumice 1), however it has a major element composition that lies between those of the scoria airfall deposits and the Middle/Upper Pumice 1 (see Chapter 4, Figure 4.12). This implies that the scoria airfalls, Lower, Middle and Upper Pumice 1/2 represent more or less differentiated varieties of the same magma source.

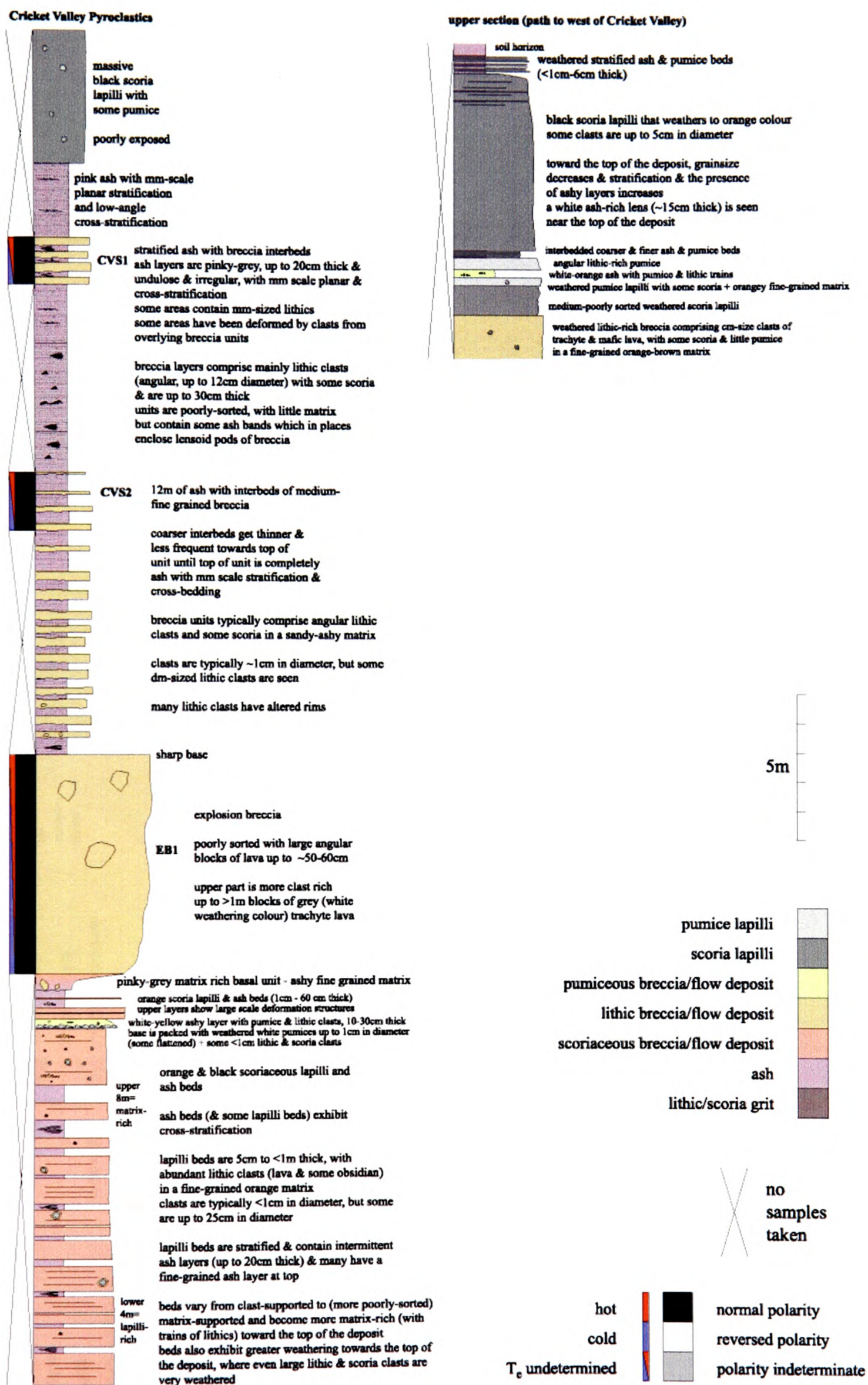


Figure 7.3: Stratigraphic section of the Cricket Valley Pyroclastic deposits, with lithological descriptions and palaeomagnetic (polarity and emplacement temperature) data.

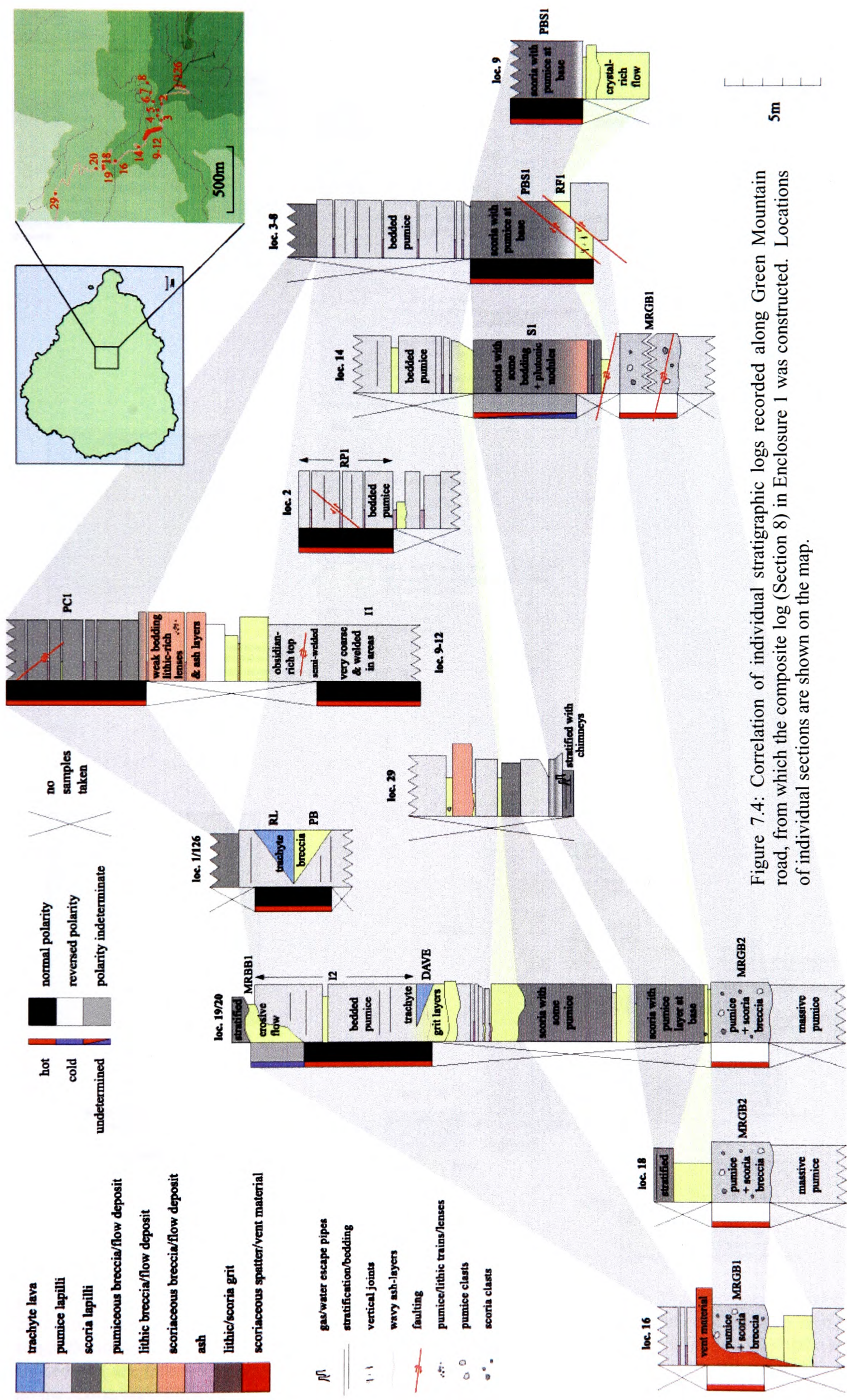


Figure 7.4: Correlation of individual stratigraphic logs recorded along Green Mountain road, from which the composite log (Section 8) in Enclosure 1 was constructed. Locations of individual sections are shown on the map.

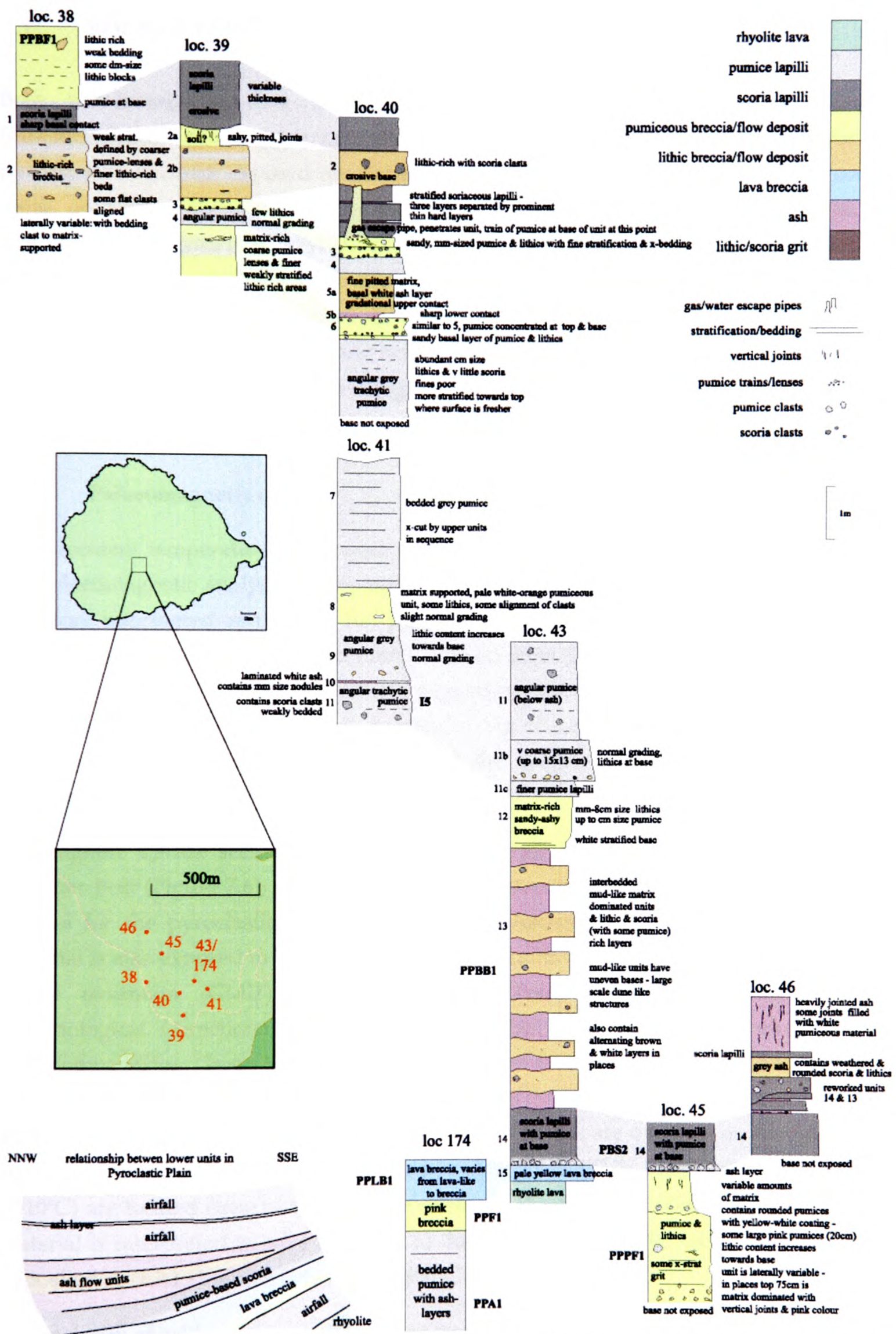


Figure 7.5: Individual (correlated) stratigraphic logs from which the Pyroclastic Plain composite section (Enclosure 1) was constructed. Log locations are shown on the map. The sketch diagram shows a section through the lower units in the sequence, indicating stratigraphic relationships; the PPBB1 ash flow units are localised and are inferred to have filled a topographic low (valley) in the middle of the plain, banking up onto the scoria unit (PBS2).

7.3 SOURCE AREAS

Both palaeomagnetic data (emplacement temperatures) and volcanological data (directional data and isopach/isopleth maps) were used to infer source areas for the pyroclastic sequences exposed on Ascension. These data suggest that two main source areas, or *eruptive centres* existed for the pyroclastic deposits exposed on Ascension: the *Central Felsic Complex* (CFC), which can be further divided into the Middletons Eruptive Complex (MEC) and Green Mountain Eruptive Complex (GEC), and the *Eastern Felsic Complex* (EFC), which encompasses the area to the east and northeast of Green Mountain (Cricket Valley to Weather Post and west of Little Ascension trachyte flow; see Figures 1.3, 1.6, 7.6). This concurs with the suggestions of previous workers such as Nielson and Sibbett (1996) and Kar et al. (1998).

7.3.1 Palaeomagnetic data

Emplacement temperatures (T_e s) were determined for seventy-two of the units sampled for palaeomagnetic analysis. Forty-nine of these (68%) exhibit a T_e above 100°C and are therefore interpreted as primary hot pyroclastic units (e.g. pyroclastic flows/surges or airfall deposits), or as lavas (seven units). Fifteen units (21%) exhibit a T_e of 0°C (i.e. they were emplaced at ambient temperature), suggesting that they are epiclastic in origin (e.g. debris/mud flows, lahars, fluvial deposits). For the remaining eight units (11%), a definitive T_e could not be determined and the origins of these units could not be categorically defined (i.e. they may be hot or cold).

The highest T_e s are seen in the vicinities of Middletons Ridge, Green Mountain and Weather Post (Figure 7.6), suggesting that these three areas comprise the major eruptive centres for the pyroclastic material exposed on Ascension. Hot (>400°C) pyroclastic material is also exposed to the west of White Hill (units LF1/2), on the northern flanks of Green mountain (GMI1) and at Hummock Point (NEB; Figure 7.6), however volcanological (directional) data suggest that this material was also sourced from Middletons Ridge, Green Mountain or Weather Post (see Figure 7.6). The distribution of emplacement temperatures in Figure 7.6 also shows the variation in temperature between proximal (EFS1/2) and more distal (LA1/2) deposits that are exposed on (overlie) Little Ascension trachyte flow. The hottest, proximal deposits (TV1: >580°C and EFS1/EFFB1: >310°C) are located close to the eruptive source at Weather Post/Devil's Cauldron. This material is interpreted to have travelled to the north, across Little Ascension Flow, to be deposited as (LA1/2 which exhibit T_e s <300°C).

The majority of cold units are more distant from the eruptive centres and in areas of lower relief (Figure 7.6), as would be expected if these units were epiclastic in origin. However, in the pyroclastic sequences located on the NASA Road and to the west of Little Ascension Flow (see Figure 7.6; Enclosure 1), cold units are found interbedded with hot

units, suggesting that epiclastic activity was occurring between eruptions.

7.3.2 Volcanological data

Where possible, the orientation of sedimentary structures such as bomb-sags and ripples were measured, in order to infer directions of transport (and hence source areas) for pyroclastic units. Bomb sags are common within ash-rich units such as LF2 and the Cricket Valley surge deposits (see Figures 1.8, 7.3) and are produced by the impact of ballistic pyroclasts onto unconsolidated or waterlogged material. This impact leaves an asymmetrical trail, from which the source direction of the pyroclast can be inferred. Asymmetrical ripples are commonly produced by pyroclastic surges and can also be used as palaeocurrent indicators (see for example, Fisher and Schminke, 1984). The directional data from such features were recorded at five individual localities (Table 7.1, Figure 7.6).

plot	deposits sampled
A	ash & grit conformably overlying Green Mountain Ignimbrite
B	EFS2 – pumice & ash deposits at top of Little Ascension Flow
C	EFS1 – pumice & ash deposits at top of Little Ascension Flow
D	LF2/P – interbedded breccias & ash, west of White Hill
E	CVS1/2 – Cricket Valley Surge deposits – stratified ash & breccia deposits

Table 7.1: Description of the deposits sampled to produce the rose diagrams shown in Figure 7.6.

Figure 7.6 suggests that the deposits measured at A (and hence possibly the Green Mountain Ignimbrite beneath?) were sourced from a vent on Green Mountain. The remaining plots (B-E) suggest that the deposits measured (EFS1/2, CVS1/2 and LF2) were sourced from the Weather Post – Devils Cauldron area (i.e. the Eastern Felsic Complex). The deposits sampled at LF2 are inferred to have been erupted from Weather Post (plot D, Figure 7.6), whereas the Cricket Valley ('surge') deposits (see Chapter 2, Figures 2.23, 2.24) appear to have been sourced from Devil's Cauldron (plot E, Figure 7.6). Plots B and C comprise data measured from individual units from the same eruptive sequence (units EFS1/2). The majority of measurements at C suggest that EFS1 was sourced from Devil's Cauldron. However, the bomb-sag directions recorded at B (from unit EFS2) indicate that the pyroclasts that formed them had a number of sources: Devil's Cauldron, Cricket Valley and possibly even Green Mountain. This may be a function of the proximity of EFS2 to the vent that sourced the pyroclasts; i.e. if the pyroclasts were erupted from a vent very close to EFS2, the resultant bomb-sags would display no preferred orientation. Alternatively, the variety of directions recorded at B may reflect the fact that eruptions were occurring contemporaneously from more than one source (e.g. from Devil's Cauldron, Cricket Valley and Green Mountain).

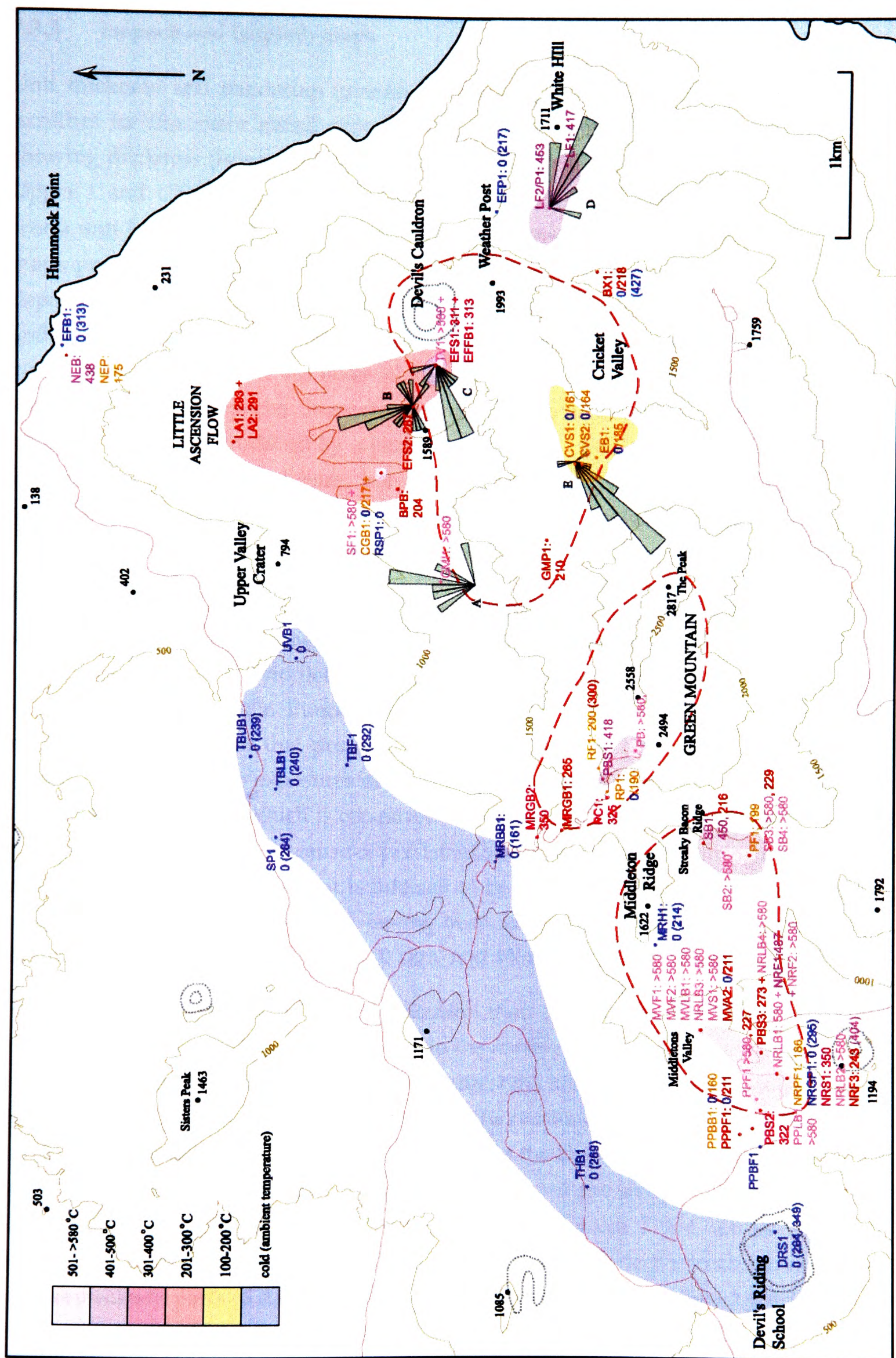


Figure 7.6: Map of Ascension showing emplacement temperatures of units sampled for palaeomagnetic analysis. Shading connects units with similar T_e . Also shown are volcanological directional data (rose diagrams) for five locations (labelled A-E). Petal length reflects the number of measurements recorded in a particular directional range. Red dashed lines show approximate locations of the main eruptive centres.

7.3.3 Isopach and isopleth maps

Unit thickness and maximum juvenile and lithic sizes were recorded at a number of localities for the major airfall deposits. These have been combined to construct maps showing thickness (isopach) and maximum pumice/lithic size (isopleth) for the Middle, Upper 1 and Upper 3 (normal polarity) pumice airfall deposits and the pumice-based scoria unit (isopach only) seen in Enclosure 1 (Figures 7.7 to 7.10). Isopach and isopleth maps provide information on the source area and transport direction of the measured deposit (and hence wind direction during eruption). In general, the greatest clast sizes and thicknesses are expected close to the volcanic vent (see for example Houghton et al., 2000), however if erosion has taken place, isopleths may be a more reliable indicator of vent location than isopachs. Isopach maps can also be used to provide an estimate of the volume of material produced by a particular eruption. Eruption volumes are estimated for the deposits discussed here, however it should be noted that volumes are only approximate because: a) the extent of erosion of the deposits is not known and b) calculations assume a circular geometry for the deposit and use an 'average' thickness.

The isopach and isopleth maps for the Middle Pumice (Figure 7.7; Enclosures 1 and 2) show that the greatest thicknesses and clast sizes for the deposit are recorded around the Lower NASA Road – Middletons Valley area (~1km from Middletons Ridge). This suggests that the Middle Pumice was a product of the Central Felsic Complex and moreover, that the vent that produced it was located west of Green Mountain around Middletons Valley. No exposures of the Middle Pumice are recorded further east of the Green Mountain Road, which is concurrent with preferential deposition of the deposit to the northwest of the vent, because of persistent southeasterly winds during eruption. The minimum volume of the deposit is inferred to be $\sim 0.11\text{km}^3$ (108m^3), which is in-keeping with the Middle Pumice eruption having been sub-plinian or Plinian in nature. Such eruptions typically produce between 0.1km^3 and 10km^3 of material (Cioni et al., 2000).

The Upper Pumice 1 has a wider distribution than the Middle Pumice and is exposed from the Devils Riding School in the west to the northern flanks of Green Mountain in the central part of the island (Figure 7.8). The greatest thicknesses and clast sizes (pumice and lithic) for the Upper Pumice 1 are recorded on the northern flanks of Green Mountain (on the Mountain Road; Figure 7.8). This suggests that the Upper Pumice 1 was erupted from a vent on Green Mountain and the partial welding of the deposit in this area further substantiates this. Lithic isopleths for the Upper Pumice 1 are concurrent with a southeasterly wind direction during eruption, however the lack of pyroclastic exposure in the northeastern parts of Ascension (as a result of covering by later lavas) precludes more accurate analysis. The minimum volume of the Upper Pumice 1 deposit is inferred to be $\sim 0.27\text{km}^3$ (271m^3), more than twice the volume of the Middle Pumice. This suggests that the Upper Pumice 1 eruption was more substantial than the Middle Pumice eruption.

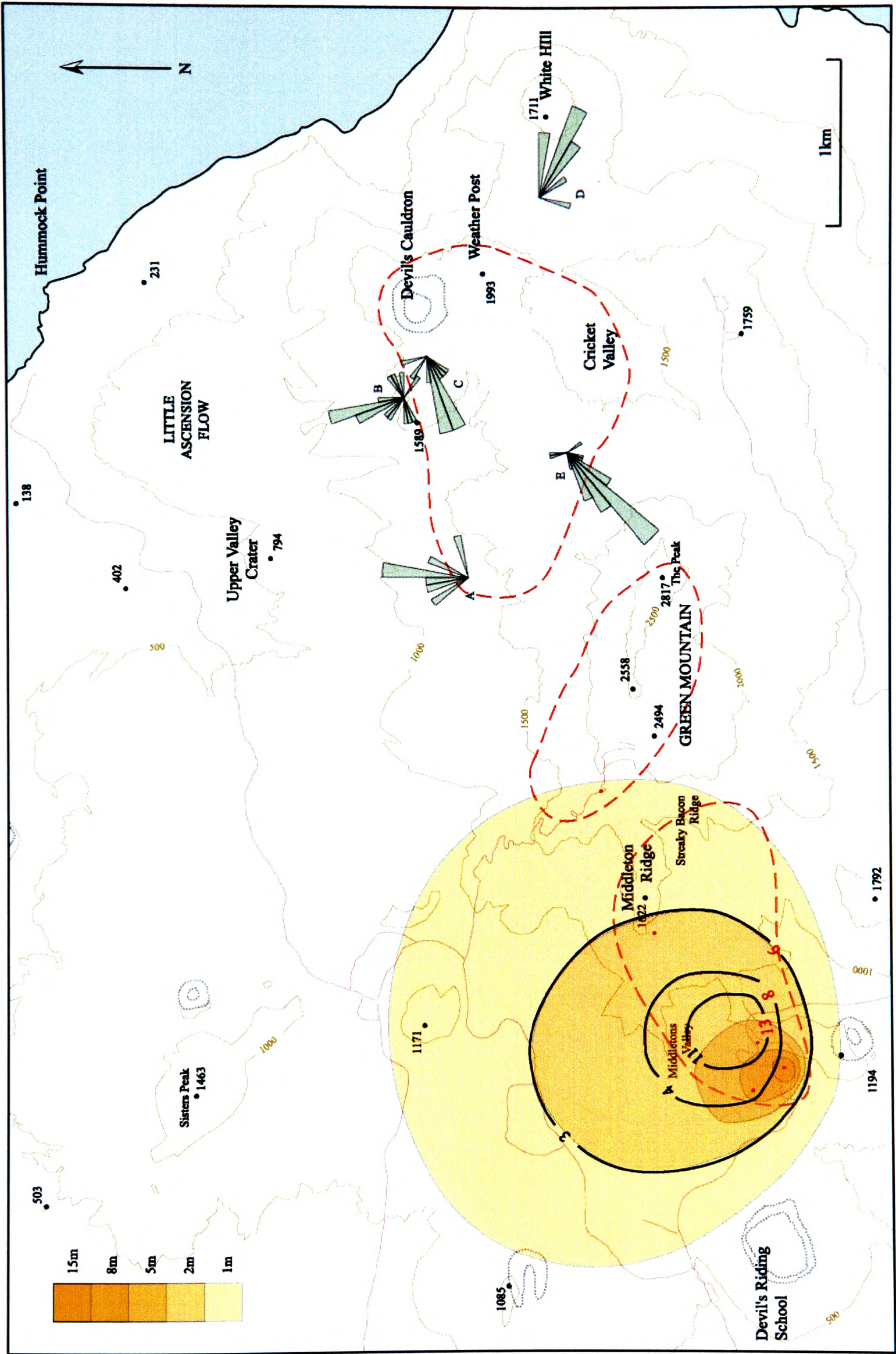


Figure 7.7: Isopach (shaded) and isopleth (lines) map for the Middle Pumice airfall. Lithic and pumice clast diameters (in centimetres) are shown in black and red (respectively) and red dots indicate measuring sites. Red dashed lines represent approximate locations of the main eruptive centres. Also shown for reference are the volcanological directional data from Figure 7.6 (labelled A–E).

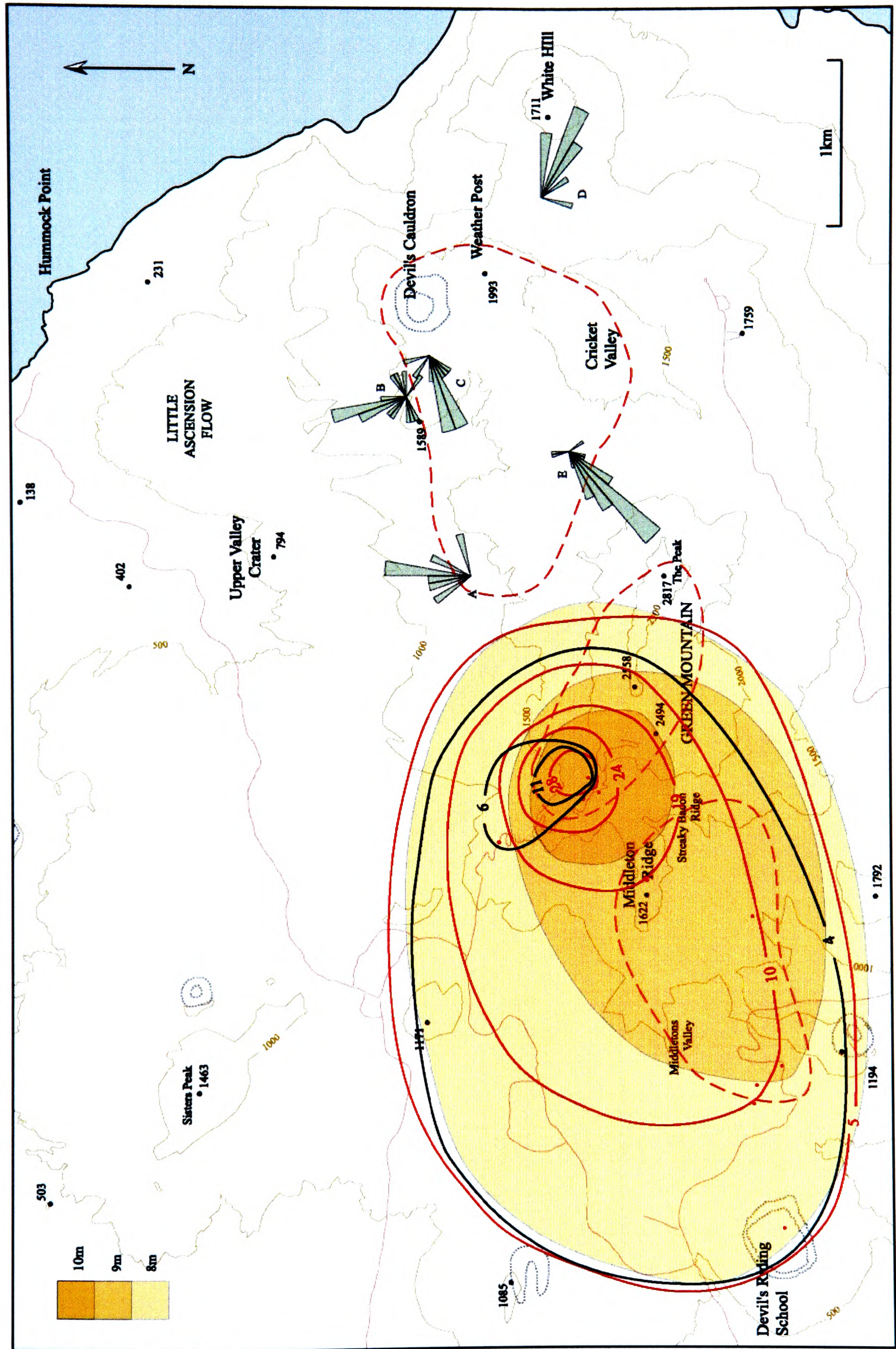


Figure 7.8: Isopach (shaded) and isopleth (lines) map for the Upper Pumice 1 airfall. Lithic and pumice clast diameters (in centimetres) are shown in black and red (respectively) and red dots indicate measuring sites. Red dashed lines represent approximate locations of the main eruptive centres. Also shown for reference are the volcanological directional data from Figure 7.6 (labelled A–E).

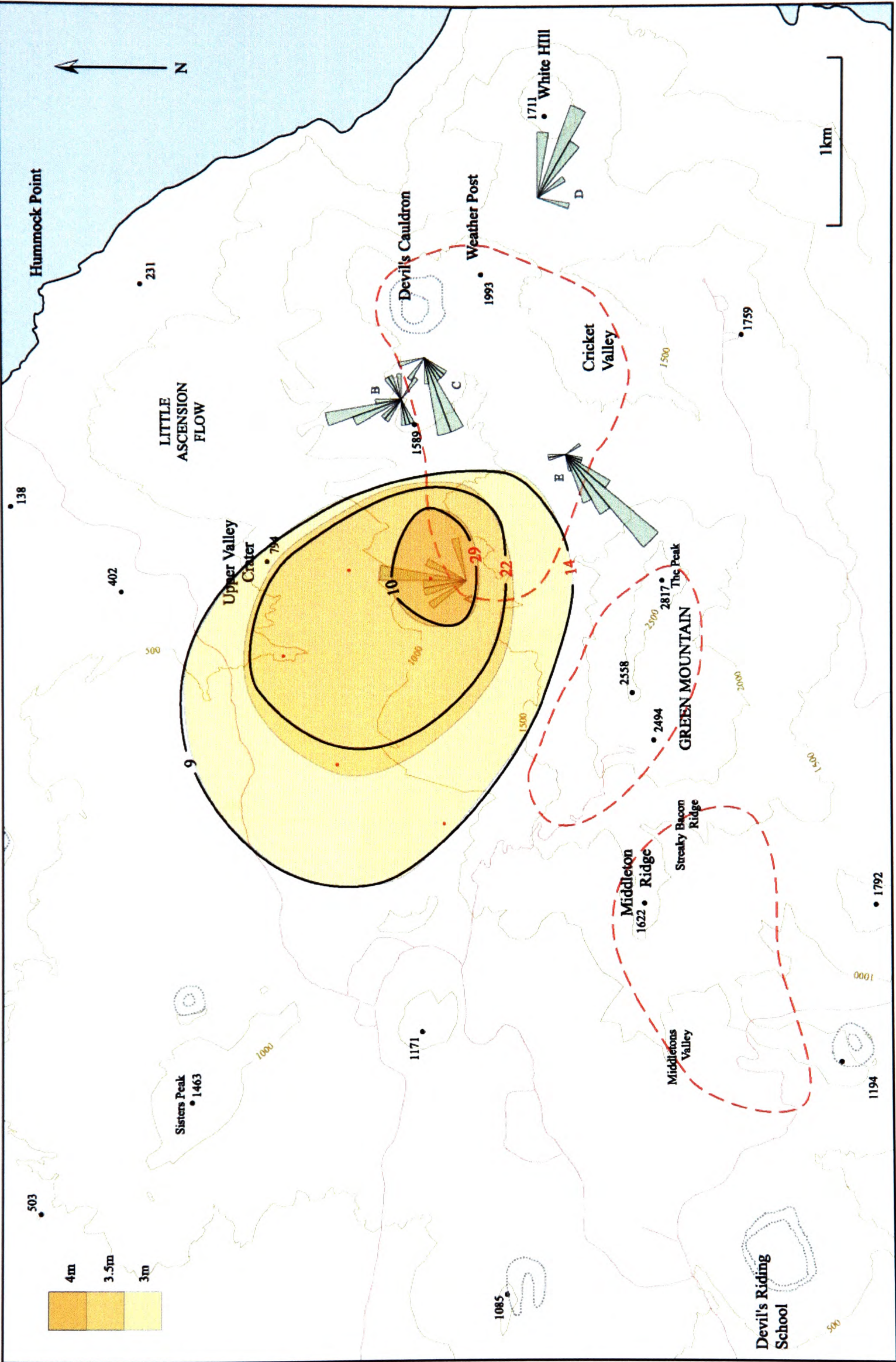


Figure 7.9: Isopach (shaded) and isopleth (lines) map for the Upper Pumice 3 airfall. Lithic and pumice clast diameters (in centimetres) are shown in black and red (respectively) and red dots indicate measuring sites. Red dashed lines show the approximate locations of the main eruptive centres. Also shown for reference are the volcanological directional data from Figure 7.6 (labelled A–E).

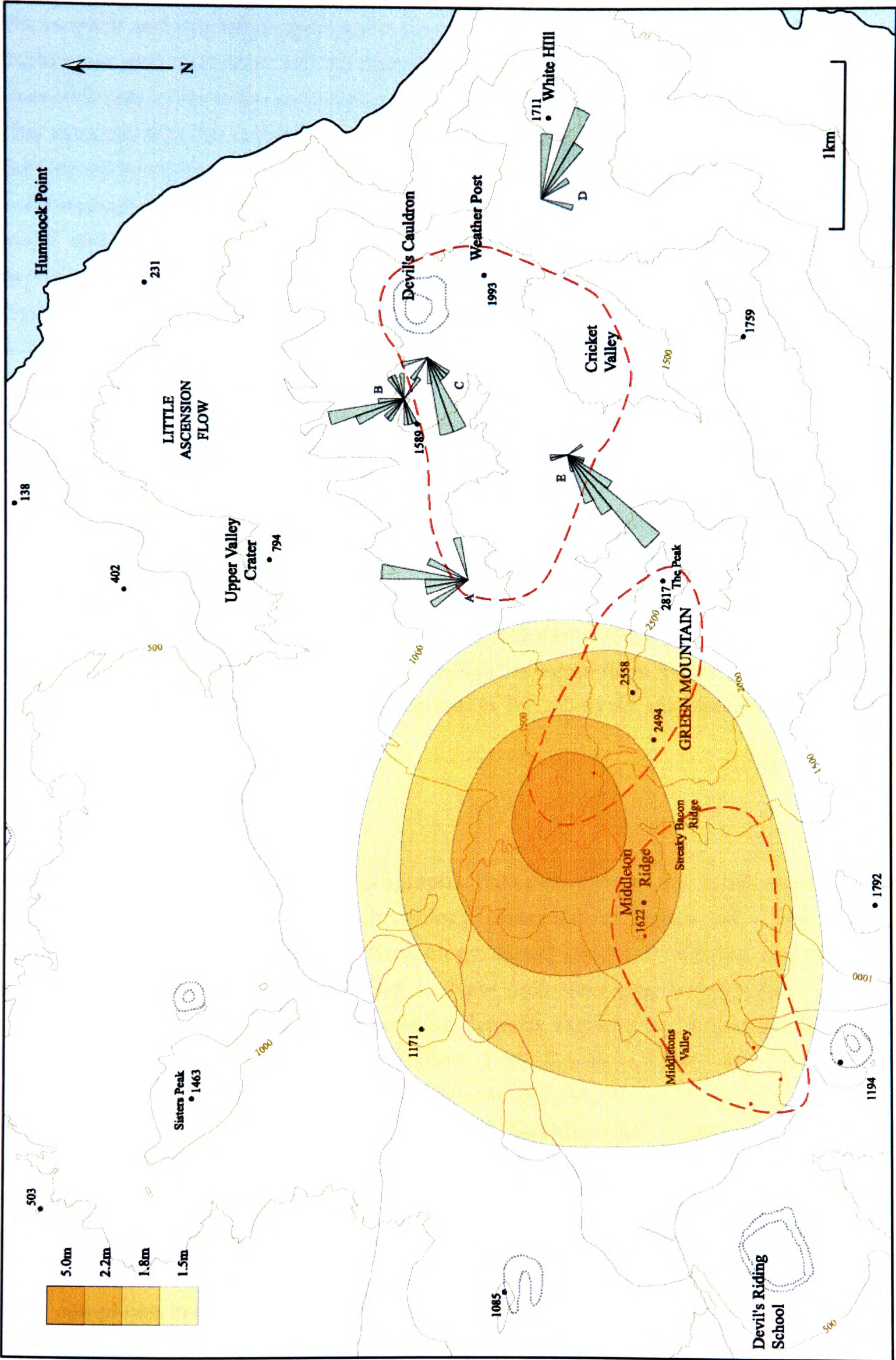


Figure 7.10: Isopach map for the pumice-based scoria airfall deposit shown in Enclosure 1. Red dots represent measuring localities. Red dashed lines show the approximate locations of the main eruptive centres. Also shown for reference are the volcanological directional data from Figure 7.6 (labelled A–E).

The isopach and isopleth maps for the Upper Pumice 3 (Figure 7.9) show that the largest thicknesses and clast sizes for the deposit were recorded on the north-eastern flanks of Green Mountain, far to the east of the centres of the Middle and Upper Pumice 1 isopachs. This suggests that the deposit was sourced from the Eastern Felsic Complex, rather than the Central Felsic Complex although the location of the vent is uncertain. This conclusion is substantiated by geochemical data, which suggests that the deposit exhibits a different major and trace element signature to the Middle and Upper 1 Pumice deposits. The deposit is exposed in the area between Two Boats Village and Upper Valley Crater (see Figures 1.3, 1.8), but is absent from localities further to the east. This is again concurrent with a southeasterly wind direction during eruption. The minimum volume for the Upper Pumice 3 deposit is calculated as $\sim 0.04\text{km}^3$ (39m^3). This is an order of magnitude less than the volumes of the Middle and Upper Pumice 1 deposits, which implies that the Upper Pumice 3 eruption was less substantial – possibly sub-plinian in nature.

The isopach map for the pumice-based scoria airfall deposit (PBS; Figure 7.10; Enclosure 1) suggests that this unit was erupted from a vent between Middleton's Ridge and Green Mountain. The minimum volume for the Pumice-Based Scoria deposit is calculated as 0.02km^3 (23m^3), which is approximately half the volume of the Upper Pumice 3 deposit. The relatively small volume of the PBS deposit in comparison to the pumice deposits discussed here is consistent with its formation by relatively non-violent Strombolian eruptions.

7.4 ERUPTION HISTORY

The palaeomagnetic and magnetostratigraphic data presented in this study improves the resolution of the basic eruption chronology presented in Figure 1.6. This section documents the improved eruption chronology, based on the correlation of pyroclastic sections proposed in Enclosures 1 and 2. New data presented here confirm that two major source areas exist for the pyroclastic deposits exposed on Ascension Island (as previously suggested by Nielson and Sibbett, 1996; Kar et al., 1998): the *Central Felsic Complex* (CFC), which comprises the Middletons Eruptive Complex (MEC) and Green Mountain Eruptive Complex (GEC), and the *Eastern Felsic Complex* (EFC), which encompasses the area to the east and northeast of Green Mountain (Cricket Valley–Weather Post and west of Little Ascension trachyte flow; see Figures 1.3, 1.6). Radiometric dating of the products of the Central and Eastern complexes is limited and consequently their relative ages are uncertain. The histories of the Central and Eastern felsic complexes are therefore discussed separately with associations made between the two complexes where possible. The histories have been split (loosely) into eruptive 'phases' for ease of reading.

7.4.1 The Central Felsic Complex

Phase 1: 1Ma – 0.78Ma

Felsic pyroclastic activity on Ascension began with the build-up of the Middletons Eruptive Complex (MEC). The oldest (exposed) unit erupted from the MEC is inferred to be the rhyolite that underlies sections 2 and 5 (Pyroclastic Plain and Middleton's Valley) shown on Enclosure 1. This rhyolite exhibits reversed polarity (see Section 2, Enclosure 1) and has been dated at $0.99 \pm 0.02\text{Ma}$ (Nielson and Sibbett, 1996). Overlying this is a coarse ash-rich breccia unit that may have been derived from the rhyolite (through brecciation or later reworking). Following the eruption of the rhyolite, a sequence of felsic and some mafic pyroclastic deposits were erupted from the MEC. All of the units sampled from this sequence display reversed polarity. Individual deposits include: a semi-welded scoria and pumice deposit of airfall or pyroclastic flow origin (MVS2, Enclosure 1), which in places has been altered to clay (see Section 7, Enclosure 1), at least two matrix-rich pumice and lithic lapilli breccias, which may be pyroclastic or epiclastic (e.g. laharcic) in origin, and the *Lower Pumice* airfall deposit (Sections 4 and 8, Enclosure 1), which has an intermediate (trachyandesite) composition (see Chapter 4, Figure 4.12) and is exposed on the Mountain Road (Section 8, Enclosure 1). Some epiclastic activity followed, with the reworking of (part of) the Lower Pumice to form unit MVA2, which was emplaced at ambient temperature (see Section 5, Enclosure 1). Activity resumed with the eruption of semi-welded scoria and pumice flow deposit MVS1 (Sections 5, 7, Enclosure 1), which has a T_e of $>580^\circ\text{C}$ and covers an area from Middletons Valley to Streaky Bacon Ridge ($\sim 1\text{km}$; see Figure 1.3; Section 7, Enclosure 1). This was followed by the eruption of the Middleton Ridge trachyte (MRT), which extends from Middletons Ridge (from where it is inferred to have been sourced) to Middletons Valley and the upper NASA road to the southwest, where it is inferred to have become brecciated, to form lava breccias NRF2 and MVLB1² (Sections 4–6, Enclosure 1). The trachyte is dated at $0.82 \pm 0.02\text{Ma}$ (Nielson and Sibbett, 1996) and MRT, NRF2 and MVLB1 all display reversed polarity and T_e s of $>580^\circ\text{C}$ (see Enclosure 1). A major eruption of trachytic pyroclastic deposits followed. The first products of this eruption were the pumice airfall MVA1 and stratified ash and pumice and lithic flows of MRH1 (Sections 5, 6, Enclosure 1). Many of these units have altered to clay and some contain accretionary lapilli or display soft-sediment deformation structures, suggesting that water was involved in the eruption and hence that these are *hydromagmatic* deposits. This concurs with the palaeomagnetic data, which suggest that the MRH1 deposits were emplaced at ambient temperature (Section 6, Enclosure 1), and substantiates the work of Sheppard and Harris (1985), who suggest that the interaction of magma with seawater may have played an important role in the felsic pyroclastic eruptions of Ascension. After the eruption of the MRH1 deposits, a lithic-rich pyroclastic flow with a T_e of 487°C to $>580^\circ\text{C}$ (NRF1/MVF1) and a trachytic-rhyolitic lava breccia

² This may be the 'volcanic breccia' described in Nielson and Sibbett (1996).

NRLB1/NRLB3 (Sections 4,5, Enclosure 1) were erupted from a vent in the vicinity of Middletons Valley and travelled southwest to the Upper NASA Road area. The lava breccia displays reversed polarity and is the youngest reversed unit sampled on Ascension for palaeomagnetic analysis. Following this, or roughly contemporaneous was the eruption of the extensive 'Middletons ignimbrite' (see Chapter 2, Section 2.3.2; unit MRH, Appendix C) which is exposed in the ridges and valleys to the south of Middletons Ridge. Alteration precluded sampling of this deposit and its magnetic polarity is consequently unknown.

Phase 2: 0.78Ma – 0.65Ma

After the deposition of the MRH deposits and the NRLB lava breccia, a large sub-plinian or Plinian eruption occurred from the MEC, producing the major *Middle Pumice* airfall deposit. This deposit is inferred to have extended from the Pyroclastic Plain in the southwest to Little Ascension trachyte flow in the northeast and it is likely that it originally covered an even greater area. Major thicknesses of the Middle Pumice are exposed in the Pyroclastic Plain and NASA Road sections (Sections 2–4, Enclosure 1), however the unit is thinner or absent in the Middletons Ridge and Mountain Road sections, suggesting that considerable erosion of the deposit occurred from areas of higher topography. The present-day minimum volume of the deposit is estimated as $\sim 0.1\text{km}^3$. The Middle Pumice comprises a number of individual fall units (which vary in lithic content and grain size), suggesting that the eruption was sporadic and not sustained. Furthermore, in the Lower NASA Road Section, a thin pumiceous flow unit is interbedded with the airfall, suggesting that minor column collapse forming pyroclastic flows may also have occurred during this eruption. This is consistent with the eruption being sub-plinian, as the deposits of such eruptions commonly display stronger stratification than Plinian deposits (Cioni et al., 2000) and eruption columns are less sustained (Morrissey and Mastin, 2000). The Middle Pumice was sampled for palaeomagnetic analysis at several locations (e.g. I3, NRA1, NRA2, PPA1), all of which display normal polarity.

The deposits of the Streaky Bacon Ignimbrite/Formation (which comprises over 10m of semi-welded to welded ignimbrite and pumice; see Chapter 2, Section 2.2.2.1) are exposed on the western flanks of Green Mountain (south of Middletons Ridge). All units sampled for palaeomagnetic analysis display normal polarity and were emplaced hot, at T_g s between 450°C to $>580^\circ\text{C}$. These deposits are inferred to overlie the Middle Pumice and may therefore have been produced by major collapse of the eruption column that produced the Middle Pumice.

After the eruption of the Middle Pumice, hydromagmatic activity from the MEC produced further stratified ash and lapilli breccia deposits of pyroclastic flow and surge origin (Section 6, Enclosure 1). Pencontemporaneously, a pumiceous pyroclastic flow

(NRF3/PPF1) and a third lava breccia (NRLB2/PPLB1) were erupted from a vent in the NASA Road – Pyroclastic Plain area. Both of these deposits display normal polarity and a T_e of $>580^\circ\text{C}$ (Sections 2–4, Enclosure 1). A major Strombolian eruption followed from a vent on Green Mountain, producing the far-reaching mafic airfall deposit, PBS (pumice-based scoria). This deposit is exposed in the sections of Pyroclastic Plain, NASA Road, Middletons Ridge (where it is exposed between layers of stratified hydromagmatic deposits, suggesting contemporaneity with the hydromagmatic eruptions from the MEC) and on the Mountain Road, where it is up to 5m thick. The present-day minimum volume of the PBS deposit is estimated to be $\sim 0.023\text{km}^3$, which is considerably less than the volume of the Middle Pumice (and is in-keeping with the less-violent nature of the PBS eruption). Units sampled from the PBS deposit display normal polarity (see Enclosure 1) and T_e s of 273°C – 418°C (with the hottest temperatures measured on the Mountain Road).

Hydromagmatic eruptions continued from the MEC, producing further stratified lapilli and ash deposits (exposed above PBS in Section 6, Enclosure 1). These were followed by a minor mafic eruption from a vent at Middletons Ridge or Green Mountain, which produced the erosive scoria flow that is exposed in the Middletons section, and the fine-grained scoria unit exposed above PBS on the Mountain Road (see Sections 6 and 8, Enclosure 1). Epiclastic activity (e.g. lahar formation and reworking by water) is likely to have been associated with and probably continued some time after the hydromagmatic eruptions from the MEC, resulting in the erosion and redeposition of primary pyroclastic material in the surrounding area, for example: the erosion of several metres of the pyroclastic sequence at Middletons Valley, along with the redeposition of material in the Pyroclastic Plain (as e.g. the interbedded ash and breccia deposits of PPBB1; Section 2, Enclosure 1), on the Mountain Road (where a number of matrix-rich flow deposits are exposed), on Middletons Ridge and in Streaky Bacon Valley.

Phase 3: 0.65Ma –

The next major activity to take place from the Central Felsic Complex incorporated the eruptions of the trachyte flows and domes exposed on the western flank of Green Mountain (dated at $\sim 0.650 \pm 0.017\text{Ma}$; Nielson and Sibbett, 1996), and another large Plinian-style eruption, which produced the extensive Upper Pumice 1 airfall deposit and was probably the largest explosive eruption to occur on Ascension. The Upper Pumice 1 deposit is interpreted as equivalent to the 'Devils Riding School pumice' of Kar et al. (1998), which is the only pyroclastic unit on Ascension to have been dated, with an age of $0.61 \pm 0.02\text{Ma}$ (Kar et al., 1998). The vent for the Upper Pumice 1 eruption is inferred to have been located on the northwestern flanks of Green Mountain, where the deposit is extremely thick and exhibits welding, and the largest (pumice and lithic) clast sizes are recorded (see Figure 7.6). The deposit maintains considerable thickness ($>6\text{m}$) up to 3km from the (inferred) vent, with significant thicknesses present at Middletons Valley, NASA Road and Devils Riding School. The present-day volume of the deposit is estimated to be

~0.27km³. Like the Middle Pumice, the Upper Pumice 1 is comprised of several individual fall units, suggesting that the eruption was sporadic and may therefore have been sub-plinian rather than Plinian in nature. Furthermore, periodic minor collapses of the eruption column are inferred to have occurred (particularly near the end of the eruption), resulting in the deposition of minor pyroclastic flow deposits in the Mountain Road section and producing the 'flow-like' field characteristics (e.g. undulose bedding, cross-stratification and mantling of steep slopes) that are displayed by many of the upper flow units.

Some epiclastic activity is inferred to have accompanied and followed the eruption of the Upper Pumice 1, in the form of mudflow/lahar formation and reworking by water or gravity, particularly in areas where the Upper Pumice 1 was deposited on steep slopes (e.g. at the lower NASA Road section, see Figure 2.5), where slumping is inferred to have occurred (see upper units, Section 3, Enclosure 1). However, it is surmised, from the presence of such thicknesses of the deposit, that reworking was relatively insignificant.

A second major mafic (Strombolian-type) eruption from the Central Felsic Complex, produced a second substantial scoriaceous airfall deposit that is exposed in the Mountain Road, Middletons Ridge, Pyroclastic Plain and Devils Riding School sections (Sections 1, 2, 6, 8, Enclosures 1), as well as to the north of Green Mountain (Turtles Back, Section D, Enclosure 2). On the Mountain road, this deposit is more than 5m thick and is inferred to have been emplaced at ~325°C (PC1). Here, the deposit comprises stratified lithic-rich scoria airfall and flow units (the latter display features such as undulose bedding, cross stratification and lithic-rich lenses), implying that the periodic collapses of the eruption column occurred. Epiclastic activity followed, with lahars eroding and re-depositing material on the Mountain road and in the valleys to the south of Turtle's Back (e.g. units TBLB1, TBUB1, which both have T_gs of 0°C; Section D, Enclosure 2).

A third and final mafic eruption from Green Mountain produced the thick (5m minimum) scoria airfall that caps (and forms the peak of) Green Mountain (Green Mountain Scoria). This eruption is inferred to have occurred from a vent on the southeastern flank of Green Mountain (Nielson and Sibbett, 1996) and also to have produced minor scoria flows. The airfall deposit blanketed a minimum area from the Devils Riding School in the southwest to Turtle's Back in the centre of the island and also caps the pyroclastic sequence exposed to the west of (and covers the area to the south of) Cricket Valley.

7.4.2 The Eastern Felsic Complex

The correlation of units from the Eastern Felsic Complex (EFC) is difficult in comparison to the correlation of units from the Central Felsic Complex, due to limited dating and complex field relationships. For example, much of the pyroclastic sequence is inferred to be missing in areas such as that to the west of Little Ascension flow, where units cross-cut

one another and significant erosion is inferred to have occurred (see Chapter 2, Figure 2.36). Furthermore, palaeomagnetic data from this study suggest that the majority of the pyroclastic deposits sampled from the Eastern Felsic Complex display normal polarity and hence magnetic polarity cannot aid correlation in this area (except to suggest that the pyroclastic deposits from this area are younger than 0.78Ma).

According to Nielson and Sibbett (1996), the oldest (non-pyroclastic) felsic activity to occur from the Eastern Felsic Complex was the eruption of the trachytic–rhyolitic domes exposed to the west of Spire Beach, in the Letterbox area and probably those of Wig Hill, Little White Hill and possibly White Hill. New data presented in this study (see Enclosure 2) suggest that the oldest *pyroclastic* deposits exposed in this area are the thick, bedded pumice deposits of RSP1 and EFP1 (Sections G, J, Enclosure 2). However these units are given a T_e of 0°C, suggesting that they are epiclastic in origin, and hence their magnetic polarity cannot be determined³. The deposits are 'cemented' with a sticky ash matrix, suggesting that they were in contact with water on deposition and they are inferred to have been reworked from a pre-existing pumice airfall deposit – possibly the Lower Pumice airfall, or an older pumice airfall sourced from the Eastern Felsic Complex. In addition, EFP1 contains continuous ash layers, suggesting that its deposition was sporadic and reworking may therefore have been contemporaneous with eruptions from one of the felsic sources.

Initial Weather Post eruptions – Cricket Valley and White Hill

Eruptions from Weather Post probably began some time after the deposition of EFP1 and are inferred to have produced: the Cricket Valley Pyroclastics (CVP), the pseudo-pumice and ash breccias (e.g. LF2) exposed to the west of White Hill (see Sections J–L, Enclosure 2) and northwest of Weather Post, and the Little Ascension trachyte flow. The earliest activity from Weather Post may have involved both mafic and felsic eruptions forming the Cricket Valley Pyroclastics. These deposits have a limited areal extent and it has been suggested that they were deposited in a pre-existing caldera (Nielson and Sibbett, 1996). Formation of such a caldera may have been associated with the eruption of the Streaky Bacon ignimbrite (see Section 10, Enclosure 1), or the Green Mountain Ignimbrite (Sections B, C, Enclosure 2). The CVP deposits include: ~10m of thick basaltic lapilli and ash beds of airfall or flow origin, a possible pyroclastic flow or pumice airfall deposit (thin pumice and ash deposit) and a 5m thick explosion breccia. These units are overlain by over 15m of stratified ash deposits (with breccia interbeds) of base-surge or epiclastic origin, which are in turn overlain by 4–5m of mafic airfall that, which is interpreted as the Green Mountain Scoria. The stratified ash deposits of the CVP exhibit distinctive ripples and cross-bedding and have previously been interpreted as reworked material, deposited in standing water (David Bell, personal communication; Nielson and Sibbett, 1996).

³ Juvenile clasts from these units display normal polarity, however, they may have been affected by VRM and hence cannot be used to infer true polarity.

However, I have proposed a possible alternative origin for these deposits as pyroclastic (base) surge deposits. Palaeomagnetic data from this study are inconclusive in determining between these two proposed origins, as no definite T_e could be determined for samples from these deposits (see Figure 7.4). Moreover, base-surges are commonly cold on deposition (Cas and Wright, 1988), as are water-lain (epiclastic) deposits. A base-surge origin for these deposits is in keeping with the conclusions of Sheppard and Harris (1985) that seawater was involved in many of the pyroclastic eruptions on Ascension. In addition, the upper ash and breccia units contain bomb-sags sourced from Weather Post, suggesting that the deposits were contemporaneous with eruptions from Weather Post. However, accretionary lapilli (which are common in hydromagmatic deposits such as those exposed on Middletons Ridge) are absent from these deposits. A reworked origin for these deposits requires a substantial source of water, though this may have been produced by storms associated with eruptions.

After the eruption of the CVP deposits, the Little Ascension trachyte flow was erupted from a vent at Weather Post or Devils Cauldron and extended out toward North East Point, probably accompanied by an explosion, which distributed trachytic explosion breccia over the surrounding area (Nielson and Sibbett, 1996).

Ash-rich pyroclastic flow and possibly surge deposits were also produced from Weather Post, forming the 'pseudo-pumice' and ash breccias (including LF2) that are exposed to the west of White Hill (see Sections J–L, Enclosure 2). LF2 contains bomb-sags sourced from Weather Post, displays normal polarity and has a T_e of 453°C. Before the eruption of these pyroclastic flow deposits, part of the dome of White Hill is inferred to have collapsed, producing a block-and-ash-flow that was deposited as LF1 (see Section L, Enclosure 2). LF1 contains abundant obsidian and displays normal polarity and a T_e of 417°C and lies beneath the breccias of LF2.

Initial Weather Post eruptions – west of Little Ascension Flow

Weather Post or Devils Cauldron was probably the source for much of the pyroclastic material exposed to the west of Little Ascension Flow. This pyroclastic material lies beneath Little Ascension Flow and has epiclastic deposit RSP1 at its base. After the deposition of RSP1, hot pumiceous pyroclastic flows were erupted from the Eastern Felsic Complex, producing a coarse semi-welded pumice deposit that has incised RSP1 (Section G, Enclosure 2). Overlying the semi-welded pumice deposit is bedded pumice airfall that is interpreted as the Middle Pumice. The presence of the Middle Pumice in this section suggests that the Eastern and Central complexes were (at least partly) contemporaneous. Following the eruption of the Middle Pumice, epiclastic activity in the Eastern Felsic Complex resulted in erosion of the pumice airfall and deposition of a number of lithic-rich poorly-sorted flow deposits. Further epiclastic activity, in the form of lahars or debris avalanches, formed coarse lithic-breccia CGB1, for which a definitive T_e could not be defined. A mafic pyroclastic eruption occurred next, possibly from a vent located at

Upper Valley Crater, producing a coarse erosive scoria flow (SF1; Section G, Enclosure 2) which has a T_e of $>580^\circ\text{C}$ and eroded several metres into the pyroclastic sequence. Similar though smaller scale scoriaceous flows are exposed in Section F, in Upper Valley.

After the mafic eruption of SF1, felsic pyroclastic eruptions continued from the Eastern Felsic Complex, producing the coarse stratified pumice and ash breccias of BPB1. These contain very coarse pumice blocks (up to 50cm diameter), ash and obsidian and are interpreted as pyroclastic flow deposits. Two units were sampled at BPB1. They display normal polarity and yield T_e s of 204°C and 356°C , respectively. These pyroclastic flow deposits were the last pyroclastics to be deposited in this area before the extrusion of the Little Ascension flow. In places, where Little Ascension Flow overlies them, the BPB1 deposits exhibit a pink colouration due to oxidation on heating (by Little Ascension Flow). The BPB1 deposits may be equivalent to the NEB1 deposits sampled at Hummock Point (which also lie beneath the Little Ascension flow; see Section N, Enclosure 2), in which case the pyroclastic flows that produced them are interpreted to have travelled a minimum of $\sim 2.5\text{km}$ from source (assuming a source of Weather Post/Devils Cauldron). The NEB1 deposits at Hummock Point exhibit a T_e of 438°C and are interbedded with inferred pyroclastic surge deposits. A pumice airfall deposit lies beneath the NEB1 deposits that is not exposed at other localities, suggesting that it may have had a local source. The pumice airfall overlies a scoria airfall deposit, which has a layer of pumice at its base. This unit may represent a distal (and hence finer-grained) equivalent of the pumice-based scoria airfall that is exposed in many of the sections on Enclosure 1 (which was sourced from the Central Felsic Complex). Before the eruption of the pumice-based scoria unit (from the Central Felsic Complex), epiclastic activity at Hummock Point formed unit EFB1. EFB1 is a lithic-rich breccia that was emplaced at ambient temperature and exhibits cross-bedding, suggesting that it was reworked by water, possibly from the material deposited to the west of Little Ascension flow. The pyroclastic section exposed at Hummock Point rests upon a basaltic lava flow (NELL; Section N, Enclosure 2), that has a T_e of $>580^\circ\text{C}$, but for which magnetic polarity could not be determined.

Later Weather Post/Devils Cauldron eruptions

Felsic eruptions from the Weather Post – Devils Cauldron area continued after the eruption of the Little Ascension trachyte flow. These eruptions produced the trachyte dome of Weather Post (Nielson and Sibbett, 1996) and a sequence of pumiceous pyroclastic flows and surges that are exposed to the west and northwest of the area (the Eastern Felsic Surges or EFS deposits). The EFS deposits were erupted from a vent at Devils Cauldron (see Section 7.3; Figure 7.5) and travelled at least 1km to the northwest, out onto the 'plain' of Little Ascension flow. In proximal areas (e.g. units EFS1/2, EFFB1; Sections H and I, Enclosure 2), the Eastern Felsic Surge deposits exhibit characteristic ripple/dune structures, and many of the younger surges have eroded several metres of underlying (older) surges. Surge deposits sampled in this area display normal polarity

and T_e s of 287°C–313°C. More distal surge deposits (e.g. LA1/2; Section M, Enclosure 2) are finer-grained and display T_e s of 291°C–293°C. Eruption of the EFS deposits was followed by the explosive formation of Devils Cauldron and an accompanying eruption of a 'volcanic flow breccia', which is possibly the youngest felsic pyroclastic material on Ascension⁴ (Nielson and Sibbett, 1996). This breccia unit was sampled in this study as 'lava breccia' TV1 (Sections H, I, Enclosure 2) and displays a T_e of >580°C.

Reworking of the EFS deposits some time after eruption, caused them to be re-distributed further to the north on the Little Ascension flow and as far to the west as Butt Crater, where they exist as fine-grained, flat-lying ash deposits (e.g. SP1, which displays a T_e of 0°C; Section D, Enclosure 2).

The directions of bomb-sags measured from EFS2 (see Figure 7.6) suggest that the pyroclasts that formed them were sourced not only from Devils Cauldron but also from Cricket Valley and possibly from Green Mountain (or another vent in the Central Felsic Complex). This suggests that eruptions were occurring from these three sources at the same time. Moreover, over half of the bomb-sags measured are sourced from Cricket Valley (see Figure 7.5), which suggests that the phreatic or phreatomagmatic explosion (Nielson and Sibbett, 1996) that formed the crater may have occurred contemporaneously with the eruptions from Devils Cauldron. This explosion distributed trachytic and basaltic rubble over the surrounding area.

Upper Pumice 2 and 3 eruptions

Significant sequences of pyroclastic material are exposed in the area between Two Boats Village and Upper Valley Crater, and on the north flanks of Green Mountain (see Figure 1.3; Sections B–F, Enclosure 2). These sections are inferred to include material sourced from both major Felsic Complexes, though their correlation with other sections is difficult and hence the relative ages of these eruptions is unknown. Field and geochemical evidence from these sections imply that two major sub-plinian style eruptions occurred from the Eastern Felsic Complex, producing the two pumice airfall units exposed in Sections C–F (the Upper Pumice 2 and 3). The Upper Pumice 2 and Upper Pumice 3 display different trace (and major) element chemistry to the airfalls sourced from the Central Felsic Complex (see Section 7.2.1) and are not seen in other sections from either Enclosure 1 or 2 (except possibly in Section N, Enclosure 2). The lack of exposures of the Upper Pumice 2 and 3 in the Central Felsic Complex is concurrent with their eruption from the Eastern Felsic Complex, and preferential deposition to the northwest due to persistent southeasterly (trade) winds. The location of the vent(s) for the pumice airfall units is unknown; isopleth maps for the Upper Pumice 3 (Figure 7.9) show that the largest clast sizes are recorded on the north flanks of Green Mountain (west of Devils Cauldron),

⁴ Nielson and Sibbett (1996) found no detectable radiogenic argon in samples from this unit, suggesting that it is very young.

suggesting that the vent may have been near here (rather than at Weather Post/Devils Cauldron/Cricket Valley), however these airfalls are not exposed in sections to the east of Upper Valley and hence may have been eroded from these localities. Both airfall deposits display normal polarity and the Upper Pumice 3 has a minimum T_e of 210°C.

Some time separated the eruption of the two pumice airfall units from the Eastern Felsic Complex, during which epiclastic activity prevailed, and the lower airfall unit was eroded and reworked as finer-grained, stratified surge-like deposits (see Section E, Enclosure 2). Lahar formation probably also occurred (e.g. unit TBF, which has a T_e of 0°C, Section D, Enclosure 2).

The present-day volume of the Upper Pumice 3 airfall deposit is considerably less than that of the Upper Pumice 1 or Middle Pumice deposits (~0.04km³), which suggests that the Upper Pumice 3 eruption was less violent. However, it is interpreted to have ended with major eruption column collapse, producing the thick Green Mountain ignimbrite formation that is exposed on the northern flanks of Green Mountain. The location of the vent for the UP3 eruption is uncertain, as is the timing of the event relative to other eruptions on Ascension. However, this activity occurred before the formation of the Green Mountain cinder cone, as the Green Mountain Scoria overlies the ignimbrite at higher elevations to the south. Between the eruption of the Green Mountain ignimbrite and the Green Mountain Scoria, a basaltic lava flow (BILL) – which displays normal polarity and a T_e >580°C – was extruded from a vent on Green Mountain. This activity may have been associated with the eruption of the Green Mountain scoria.

After the eruption of the upper pumice airfall in this area, further epiclastic activity occurred in the Turtles Back–Upper Valley area, with the deposition of material reworked from the deposits on Little Ascension flow (e.g. EFS1/2, LA1/2) and deposition of cross-stratified units such as TBLB1 and TBUB1 (which display T_e s of 0°C) by lahars or mudflows. This activity was contemporaneous with the Strombolian eruptions from Green Mountain that produced the two most recent scoria airfall deposits. These scoria units are found interbedded with mudflow/lahar deposits in the Turtles Back area.

Chapter 8

CONCLUSIONS

The data presented in this study comprise the first detailed documentation of the pyroclastic deposits exposed on Ascension Island. The study has examined the distribution, field characteristics, magnetic polarity, emplacement temperatures and geochemistry of the deposits, allowing origins and source areas to be proposed for them. This has made it possible to place the pyroclastic deposits into a temporal framework and hence to better understand the eruptive history of the island. This study provides the first stratigraphic correlation of individual pyroclastic sequences exposed on the island (Enclosures 1 and 2), and also includes a brief discussion of secular variation within the pyroclastic stratigraphy. The conclusions that can be drawn from the investigation of the pyroclastic deposit are presented here and can be divided loosely into palaeomagnetic and volcanological conclusions.

8.1 PALAEOMAGNETIC CONCLUSIONS

Ninety-seven individual units were sampled on Ascension for palaeomagnetic analysis to provide information on magnetic polarity, emplacement temperature, magnetic mineralogy and secular variation.

8.1.1 Magnetic polarity

Magnetic polarity data from this study reveal the presence of a magnetic reversal within the stratigraphy. These data (in combination with field data) have enabled construction of the first stratigraphic correlation for the Ascension pyroclastic deposits (Enclosures 1 and 2). Stratigraphic relationships suggest that the reversal represents the Brunhes–

Matuyama boundary, which is dated at 0.78Ma (Cande and Kent, 1995). Moreover, the position of the reversal within the stratigraphy indicates that much of the pyroclastic material exposed on Ascension (i.e. all material that displays reversed polarity) is older than 0.78Ma. This is in contrast to the conclusions of some previous workers (on account of the typically 'fresh' appearance of the pyroclastic material) that it was deposited only in the last few thousand years (David Bell, pers. comm.).

The record of the B–M boundary on Ascension is significant, as records of this reversal boundary at low-latitude locations such Ascension are limited.

8.1.2 Emplacement temperatures

Emplacement temperatures (T_e s) were determined for the majority (seventy-two) of the units sampled on Ascension for palaeomagnetic analysis. Emplacement temperatures suggest that over half (68%) of the units sampled on Ascension were emplaced hot, i.e. they are *primary pyroclastic units*. Proposed origins for these units include pyroclastic flow deposits, pyroclastic surge deposits and pyroclastic airfall deposits. Fifteen of the units sampled for palaeomagnetic analysis (21%) were emplaced at ambient temperature (i.e. cold), suggesting that they are epiclastic in origin or *hydromagmatic* pyroclastic deposits, that were emplaced cold due to the incorporation of water during eruption. Proposed origins for epiclastic deposits include debris/mud flows or lahars, fluvially reworked deposits and debris avalanches. Origins for the remaining 11% of units sampled on Ascension could not be determined.

8.1.3 Magnetic mineralogy

The majority of samples taken from pyroclastic units on Ascension carry a stable remanence. Samples most commonly display a mixed mineralogy comprising high-titanium titanomagnetite plus one or more other mineral phases (typically low-titanium titanomagnetite, magnetite and maghaemite). However, magnetite, maghaemite, haematite and titanomagnetite are all recognised. Titanomagnetites display a wide range of compositions from TM02 to TM70 (calculated mainly from T_b spectra data). Where samples contain maghaemite, this may be a weathering product of magnetite (which is consistent with the relatively old age of the primary pyroclastic material on Ascension). However, in most cases, maghaematization is not interpreted to have significantly affected the primary magnetisation.

8.1.3.1 Titanomagnetite and CRM

Many of the samples analysed in this study have acquired a CRM some time after deposition. Palaeomagnetic data for these samples suggest that in many cases, the CRM is carried by titanium-rich (Ti-rich) titanomagnetite, whilst the primary (TRM) component is carried by magnetite or titanium-poor (Ti-poor) titanomagnetite. These results suggest

that in these clasts, the titanomagnetite phase is an alteration product. This is enigmatic, as the literature suggests that magnetite may be formed through alteration of titanomagnetite as a result of heating, but the reverse is not common (see for example Dunlop and Özdemir, 1997). It is proposed that in these clasts, the titanomagnetite phase results from the homogenisation of original Ti-rich titanomagnetite and magnetite (or Ti-poor titanomagnetite) phases, on heating and therefore carries the CRM. The magnetite/Ti-poor titanomagnetite phase displayed by these samples is interpreted a remanent of the original mineralogy, which retains the original TRM. Homogenisation of Ti-poor and Ti-rich phases on heating has been observed in the laboratory by McClelland (Elizabeth McClelland, personal communication, work in progress).

8.1.4 Clast type as a measure of reliability for use in T_c studies

Palaeomagnetic analysis of clasts from this study – particularly those sampled from part of the Pourahu Formation, New Zealand – suggest that juvenile material (i.e. pumice or scoria) is not reliable for use in emplacement temperature determination studies using partial thermal demagnetisation. The palaeomagnetic data from this study substantiate conclusions of Zlotnicki et al. (1984) and McClelland and Druitt (1989) that juvenile clasts typically acquire a chemical remanent magnetisation (CRM), soon after eruption that will overprint their original (TRM) magnetisation. This CRM will typically record the local geomagnetic field direction and can therefore be mistakenly identified as a primary TRM, resulting in erroneous identification of the deposit (i.e. as primary pyroclastic rather than epiclastic material). This highlights the problems with using a fluxgate magnetometer to differentiate pyroclastic and epiclastic deposits in the field and has important implications where the fluxgate method is used in hazard mapping.

Data from units sampled on Ascension suggest that composition may also play a role in the ability of a sample (or clast) to carry an intelligible, unadulterated primary magnetic signal. Comparison of the remanence characteristics of mafic (basaltic) and felsic (trachytic/rhyolitic) lavas sampled on Ascension suggests that mafic compositions are more prone to alteration and acquisition of CRM than felsic compositions. Each of the mafic lavas sampled is inferred to have acquired a CRM as a result of alteration and consequently displays a two-component remanence. High-temperature components in these samples are inferred to represent original TRMs and their directions are similar between samples. However, directions of low-T CRM components from these samples vary and deviate from the TRM direction, in some cases by a greater degree than can be accounted for by secular variation. In the latter case, CRM directions are inferred to have been influenced by the magnetisation of the host rock rather than the external (geomagnetic) field. In contrast to mafic lavas, felsic lavas do not typically display CRM or evidence of alteration (except in the case of one sample).

Comparison of the remanence characteristics of mafic (scoria) and felsic (pumice) *juvenile* clasts supports results from the lavas. Many of the scoria clasts sampled have been affected by CRM, and in addition, more scoria clasts than pumice clasts display data that are sufficiently noisy that no component of magnetism can be determined. Noise displayed by pumice clasts is typically attributed to background interference due to low intensities. However this explanation is not invoked for scoria clasts, which are expected to contain a higher percentage of magnetic minerals, and hence to display higher intensities than their felsic equivalents. The noise exhibited by scoria clasts is therefore attributed to contamination of the magnetic signal due to alteration caused by weathering or during laboratory experiments. Many scoria clasts also display discrete demagnetisation spectra, i.e. demagnetisation occurs over a narrow temperature range, limiting the information that can be retrieved from these samples. Such clasts are inferred to contain magnetic minerals with a narrow range of grain sizes.

8.2 VOLCANOLOGICAL CONCLUSIONS

8.2.1 Eruption history and source areas

The felsic pyroclastic deposits exposed on Ascension were sourced from two major eruptive complexes: the Central Felsic Complex – which comprises the Middletons eruptive centre and the Green Mountain eruptive centre – and the Eastern Felsic Complex. Eruptions from the Eastern Felsic Complex occurred from a number of centres, including Weather Post, Devils Cauldron and Cricket Valley (see Figure 1.3). Relative dating of the eruptions from the two major complexes is poor, however some of the eruptions are interpreted to have occurred contemporaneously. Felsic activity on Ascension begun from the Central Felsic Complex, with the eruption of a sequence of felsic lavas and pyroclastic deposits from the Middletons Eruptive Centre. This activity included the eruption of pyroclastic flow deposits (of both felsic and mafic composition), a major felsic airfall deposits (the Lower Pumice), and hydromagmatic eruptions that produced a sequence of pyroclastic surge deposits. This activity was followed by a major Plinian-style (sub-plinian?) eruption from the Central Complex, which produced a far-reaching pumice airfall deposit (the Middle Pumice) and is inferred to have culminated with major eruption column collapse, forming the pumice pyroclastic flows of the Streaky Bacon Formation (which include a welded ignimbrite unit, SB2). Hydromagmatic eruptions continued from the Middletons area at the same time as the major build up of the Green Mountain pyroclastic sequence begun with the eruption of the pumice-based scoria airfall deposit. The mixing of mafic and felsic magmas possibly triggered this eruption. However, the dual composition of the deposit may reflect tapping of a compositionally zoned magma chamber (Sheppard and Harris, 1983; Nielson and Sibbett, 1996). Further eruptions from Green Mountain included a second major Plinian-style event, which produced the Upper Pumice 1 major airfall deposit and involved periodic

minor eruption column collapse, various epiclastic activity, including the formation of lahars or mudflows and two further Strombolian mafic eruptions, which produced the two major scoria airfall deposits seen on Enclosures 1 and 2.

Eruptions from the Eastern Felsic Complex were likely to be (at least in part) contemporaneous with activity from the Central Felsic Complex, but there is little evidence to allow correlation of pyroclastic sequences sourced from the two complexes. However, comparison with the pyroclastic sequence exposed to the west of Little Ascension trachyte flow (see Figure 1.8) indicates that much of the pyroclastic sequence in the Eastern Felsic Complex may have been eroded.

The Weather Post – Devils Cauldron area is interpreted to have been the major source of the pyroclastic material of the Eastern Felsic Complex, although Cricket Valley and a vent on the northeastern flanks of Green Mountain are inferred to have been secondary source areas. The pyroclastic deposits exposed in the area include semi-welded pumice deposits, mudflow deposits, a major scoria flow and several pumiceous pyroclastic flow deposits. Two major pumice airfall deposits are exposed in the Turtle's Back – Upper Valley area and on the northeastern flanks of Green Mountain (the Upper Pumice 2 and 3). A thick sequence of pumiceous pyroclastic flow deposits (including the welded ignimbrite GMI1 – the Green Mountain Ignimbrite) overlies the Upper Pumice 3 and is inferred to reflect major column collapse at the climax of the Upper Pumice 3 eruption. The sequence of pyroclastic flow and surge deposits exposed on the Little Ascension trachyte flow may also be associated with this column collapse. A thick sequence of pyroclastic deposits is exposed to the west of Cricket Valley (the Cricket Valley Pyroclastics), which are also inferred to have been sourced from the Weather Post centre. These deposits cover a limited area and may have been deposited in a pre-existing caldera. Deposits include mafic lapilli breccia deposits, a phreatic or phreatomagmatic explosion breccia and extensive stratified ash deposits with interbedded breccias. The mechanism by which the upper ash units were deposited is not clear, but origins as reworked (epiclastic) deposits (Atkins et al., 1964; Nielson and Sibbett, 1996) or pyroclastic base-surges are proposed on account of the striking sedimentary-style bedforms (e.g. ripples, dunes and cross-bedding) that they display. Deposition of such an extensive sequence of deposits by epiclastic processes would have required substantial volumes of water, which are not prevalent on Ascension today. Palaeomagnetic analysis has not been able to distinguish between the two proposed origins because: a) definitive T_c s could not be determined for these units and b) both epiclastic and base-surge deposits may be emplaced at ambient temperature. A later phreatic or phreatomagmatic explosion formed the crater of Cricket Valley and deposited trachytic and basaltic rubble over the surrounding area.

8.2.2 Preservation of primary pyroclastic material on Ascension

Emplacement temperature and field data from this study suggest that a significant

percentage of the volcanoclastic material exposed on Ascension is *primary pyroclastic material*. Less than one third of the units sampled for palaeomagnetic analysis are inferred to have been emplaced at ambient temperature, implying that epiclastic deposits are less prevalent on the island than has been previously suggested (by e.g. Darwin, 1876; Atkins et al., 1964; David Bell, personal communication; Weaver, 2001). The extent to which epiclastic activity affects a stratovolcano is dependent on the composition of the edifice (for example unconsolidated material is more easily eroded, lavas will encourage run-off) but more importantly, on climate (Davidson and De Silva, 2000). Much of the pyroclastic material on Ascension is unconsolidated (e.g. airfall deposits), however the high ratio of primary pyroclastic to epiclastic material on Ascension implies that the amount of epiclastic activity (i.e. degradation of the volcanic edifice) has been relatively low in comparison to other stratovolcanoes (e.g. Mount Pinatubo, where pyroclastic flow deposits produced by the 1991 eruption were incised by several metres within days of eruption; Davidson and De Silva, 2000). In contrast, much of the pyroclastic material exposed on Ascension remains *in situ* despite ages greater than 0.78Ma for some of the material. In addition, there is no field evidence to suggest that major collapses of the volcanic edifice have occurred either on Ascension Island itself, or from parts of the submerged volcanic edifice (Neil Mitchell, personal communication). It is surmised from these data that continued high aridity prevailed on Ascension over the last ~1Myr, resulting in relatively low erosion rates.

8.2.3 Pyroclastic stratigraphy

8.2.3.1 Airfall deposits

Five major felsic airfall deposits are inferred to exist on Ascension (Enclosures 1 and 2), which are named here as the Lower Pumice, Middle Pumice and Upper Pumice 1, 2 and 3. The Lower, Middle and Upper Pumice 1 were sourced from the Central Felsic Complex and the Upper Pumice 2 and 3 were sourced from the Eastern Felsic Complex. Units sampled from the five major felsic airfall deposits display four distinct geochemical signatures (from whole rock major and trace element analysis). The Lower Pumice airfall displays a discrete geochemical signature and is transitional in composition between the scoria airfalls sampled on Ascension and the Middle and Upper Pumice 1. The compositional association of these deposits confirms conclusions that the felsic magmas on Ascension were derived by fractional crystallisation of the mafic (alkali-basalt) magmas (Harris, 1983; Weaver et al., 1996, Kar et al., 1998). However, the fact that the Lower Pumice is older, but less differentiated than the Middle and Upper Pumice 1, contradicts suggestions by Harris (1982) and Nielson and Sibbett (1996) that a compositionally zoned magma chamber was present beneath Ascension¹. Samples taken from the Middle and Upper Pumice 1 deposits display similar geochemistry, further

¹ This model implies that the erupted pyroclastics will become increasingly more mafic with time.

opposing the presence of zoned magma chamber and moreover implying that the felsic magma system that produced the deposits may have undergone a repose period of up to 0.17 Myr. The geochemical signatures of the Upper Pumice 2 and 3 deposits are distinct from those of the Lower, Middle and Upper Pumice 1 (reflecting their different sources), but also from one another. The difference between the chemistry of the Upper Pumice 2 and 3 supports field evidence, which shows them to be individual stratigraphic units (the Upper Pumice 3 overlies the Upper Pumice 2).

Emplacement temperatures for the felsic airfall deposits sampled on Ascension (for palaeomagnetic analysis) range from 175°C to 210°C. However, higher emplacement temperatures are inferred for deposits that were *not* sampled, as some of these display welding. Proximal welding of silicic and intermediate airfall deposits is only developed where magmatic temperature is >850°C (Thomas and Sparks, 1992). This is applicable to trachytic airfalls (such as the Ascension airfalls), which are expected to exhibit eruption temperatures of at least 900°C (see Table 4.4). The large discrepancy between eruption temperature (~900°C) and the T_e s of the felsic airfalls sampled on Ascension (~200°C) suggests that significant cooling of pyroclasts occurred during transport/fall from the eruption column. This in turn implies that major Plinian-style eruptions occurred on Ascension, producing eruption columns tens of kilometres in height (and depositing the pumice airfall deposits exposed on the island). However, these eruptions are inferred to have been sporadic, with repose periods during which ash layers settled over the area, as well as intermittent blocking and clearing of the vent, resulting in the deposition of more lithic-rich fall units. Periodic collapses of the eruption column also occurred (particularly toward the end of these eruptions), producing minor pyroclastic flows which deposited units that display mixed airfall and flow characteristics. In the case of the Middle Pumice and Upper Pumice 3 deposits (see Enclosure 1), the eruption is inferred to have culminated in major column collapse, forming the pumiceous Streaky Bacon and Green Mountain ignimbrites.

Many of the felsic airfall deposits on Ascension contain clasts of banded pumice, comprising streaky light grey, felsic (trachytic) and darker grey, more intermediate (trachyandesite?) material. These are interpreted as the product of magma mingling, which is common at stratovolcanoes and is best understood in the context of shallow magmatic systems (Davidson and De Silva, 2000). The fact that two distinct compositions are discernable within the pumice clasts suggests that intermingling rather than physical mixing of the magmas occurred, i.e. mixing was limited or incomplete (Donoghue et al., 1995). Mixing of magmas is considered to be an important factor in triggering of volcanic eruptions (Sparks et al., 1977; Huppert et al., 1984; Sparks and Marshall, 1986; Robin et al., 1990) and may have instigated some of the major Plinian-style eruptions on Ascension.

Three major mafic (scoria) airfalls have been distinguished on Ascension, which each

exhibit different trace element signatures. Emplacement temperatures for the mafic airfalls sampled on Ascension are higher than those of the felsic airfalls, ranging from 273°C to >580°C. This reflects the higher eruption temperature of mafic magmas and is true despite the smaller grain size of the mafic airfalls in comparison to their felsic (pumice) equivalents. The higher T_e s of the mafic airfalls also indicates that less heat was able to escape from airfall pyroclasts during transport (i.e. fall from the eruption column), which in turn implies that the eruptions that produced the mafic airfalls were considerably less vigorous than those that produced the their felsic equivalents, i.e. Strombolian or Hawaiian in nature. Nevertheless, some of the mafic airfalls exposed on Ascension are thick (5m minimum) and widespread, suggesting that the mafic eruptions involved energetic explosive activity.

The dual-composition pumice-based scoria (PBS) airfall deposit exposed on Ascension provides further evidence of eruptions involving different magma compositions.

8.2.3.2 Welded deposits and lavas

Two major exposures of welded ignimbrite are exposed on Ascension, on the northern and western flanks of Green Mountain. These are interpreted as the deposits of pumiceous pyroclastic flows, but the association between these two exposures is not clear. Emplacement temperatures for the welded deposits sampled on Ascension are all interpreted to be greater than 580°C; all samples display a single-component remanence (sub-parallel to the expected GAD for Ascension) and this indicates that they have been heated to a temperature above the Curie temperature of their magnetic minerals, i.e. above 580°C (the Curie temperature for magnetite).

8.2.3.3 Breccia deposits

Breccias comprise the majority of units sampled on Ascension. Palaeomagnetic analysis of clasts from these breccias has allowed the origins of most units to be clarified. The data indicate that 62% of the breccia units sampled were emplaced hot. Emplacement temperatures for the units range from 186°C to >580°C and inferred origins include pyroclastic pumice and scoria flow deposits, a block-and-ash-flow deposit, pyroclastic surge deposits (ground or ash-cloud surge), pyroclastic lag breccias, and autobrecciated lava flows. Twenty-three percent of the units sampled were emplaced at ambient temperature (i.e. cold) and the majority of these are inferred to have been reworked from previously hot pyroclastic material, either by water, mudflows (or lahars), by gravitational collapse (debris avalanches) or by phreatic or phreatomagmatic explosions. Origins of the remaining 15% of the breccia units sampled are unclear, as palaeomagnetic analysis cannot produce a definitive T_e for these units.

8.2.4 VOLCANIC HAZARDS

Several large pyroclastic eruptions have occurred on Ascension. The most violent eruptions occurred from the felsic centres in the central and eastern parts of the island and produced large volumes of tephra (pumice and scoria lapilli and ash) and substantial pumiceous ignimbrite deposits. The distribution of the airfall tephra in the northwestern parts of the island is difficult to ascertain, as younger lava flows and scoria cones have covered this area. Nonetheless, it is likely that airfall material blanketed a considerable part of the island and was probably deposited in the surrounding ocean. Estimates (from this study) of the minimum volumes of airfall deposits on Ascension suggest that the largest eruptions (deposit volumes $>0.2\text{km}^3$) were sub-plinian or Plinian in nature and may therefore have produced eruption columns of more than 10km in height. Recurrence of such activity on Ascension would pose a major threat to the safety of the island's residents, as well as causing potential damage to property and rendering the island's runway (used frequently by the RAF and USAF) inoperative. Potentially more hazardous, though, is the eruption of pyroclastic flows and surges, both of which have occurred on Ascension. The deposits of such flows and surges sampled on Ascension typically display emplacement temperatures in excess of 300°C (and several in excess of 580°C), demonstrating that they have great destructive power. However, the most recent activity has been the eruption of minor localised deposits associated with the formation of scoria cones from satellite vents, particularly in the northwestern parts of the island, and stratigraphic relationships suggests that Plinian-style activity has not occurred on Ascension for more than 0.5Myr. In addition, the major population centres on Ascension (with the exception of Two Boats Village) are located some distance from the felsic eruptive centres and field mapping suggests that even the major pyroclastic flow deposits exposed on Ascension do not cover extensive areas and perhaps travelled only as far as a few km from source. Moreover, Nielson and Sibbett (1996) suggest that little surface hydrothermal alteration has occurred on Ascension and they find no evidence of hot spring or fumarolic activity, suggesting that the magma chamber that fed the felsic pyroclastic eruptions may no longer be active.

BIBLIOGRAPHY

- ARAMAKI, S. & AKIMOTO, S. (1957). Temperature estimation of pyroclastic deposits by natural remanent magnetism. *American Journal of Science*, **255**: 619-627.
- ARGUDEN, A.T. & RODOLFO, K.S. (1990). Sedimentologic and dynamic differences between hot and cold laharc debris flows of Mayon Volcano, Philippines. *Geol. Soc. Am. Bulletin*, **102**: 865-876.
- ATKINS, F.B., BAKER, P.E., BELL, J.D. & SMITH, D.G.W. (1964). Oxford expedition to Ascension Island. *Nature*, **204** (4960): 722-724.
- BARDOT, L. (1997). *Explosive volcanism on Santorini: palaeomagnetic estimation of emplacement temperatures of pyroclastics*. Unpublished DPhil thesis, Oxford University.
- BARDOT, L., THOMAS, R. & MCCLELLAND, E. (1996). Emplacement temperatures of pyroclastic deposits on Santorini deduced from palaeomagnetic measurements: constraints on eruption mechanisms. *Palaeomagnetism and Tectonics of the Mediterranean Region*, Geol. Soc. Special Publication **105**: 345-357.
- BOND, A. & SPARKS, R.S.J. (1976). The Minoan eruption of Santorini, Greece. *Journal of the Geological Society of London*, **132**: 1-16.
- BRANNEY, M. J. & KOKELAAR, P (1992). A reappraisal of ignimbrite emplacement; progressive aggradation and changes from particulate to non-particulate flow during emplacement of high-grade ignimbrite. *Bulletin of Volcanology*, **54** (6): 504-520.
- BROZENA, J.M. (1986). Temporal and spatial variability of seafloor spreading processes in the Northern South Atlantic. *Journal of Geophysical Research*, **91** (B1): 497-510.
- BUTLER, R.F. (1992). *Palaeomagnetism: Magnetic Domains to Geologic Terranes*. Blackwell Scientific Publications, Oxford.
- CANDE, S.C. & KENT, D.V. (1995). Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, **100**: 6093-6095.

- CAS, R.A.F. & WRIGHT, J.V. (1988). Volcanic successions - modern and ancient: A geological approach to processes, products and successions. Chapman & Hall, London.
- CHADWICK, R.A (1962). Paleomagnetic criteria for volcanic breccia emplacement. *Geological Society of America Bulletin*, **82** (8): 2285-2293.
- CIONI, R., MARIANELLI, P., SANTACROCE, R. & SBRANA, A. (2000). Plinian and sub-plinian eruptions. In *An Encyclopedia of Volcanoes* (Ed H. Sigurdsson), Academic Press, San Diego: 477-494.
- COLLINSON, D.W. (1983). *Methods in rock magnetism and palaeomagnetism - techniques and instrumentation*. Chapman & Hall, London.
- COX, K.G., BELL, J.D. & PANKHURST. (1979). *The interpretation of igneous rocks*. George Allen and Unwin, London.
- CRONIN, S.J., HODGSON, K.A., NEALL, V.A., PALMER, A.S. & LECOINTRE, J.A. (1997). 1995 Ruapehu lahars in relation to the late Holocene lahars of Whangaehu River, New Zealand. *N.Z. Journal of Geology and Geophysics*, **40**: 507-520.
- DALY, R.A. (1925). The geology of Ascension Island. *Proceedings of the American Academy of Arts & Sciences*, **60** (1).
- DARWIN, C. (1876). *Geological observations on the volcanic islands (2nd edition)*. Smith, Elder and Co., London.
- DASH, B.P. & MILSOM, J. (1973). Gravity field of Ascension Island, South Atlantic. *Earth and Planetary Science Letters*, **21**: 79-84.
- DAVIDSON, J. & DE SILVA, S. (2000). Composite volcanoes. In *An Encyclopedia of Volcanoes* (Ed H. Sigurdsson), Academic Press, San Diego: 663-681.
- DONOGHUE, S.L., GAMBLE, J.A., PALMER, A.S. & STEWART, R.B. (1995). Magma mingling in an andesite pyroclastic flow of the Pourahu Member, Ruapehu volcano, New Zealand. *Journal of Volcanology and Geothermal Research*, **68**: 177-191.
- DONOGHUE, S.L., NEALL, V.E. & PALMER, A.S. (1995). Stratigraphy and chronology of late Quaternary andesitic tephra deposits, Tongariro Volcanic Centre, New Zealand. *Journal of the Royal Society of New Zealand*, **25** (2): 115-206.
- DONOGHUE, S.L., NEALL, V.E. & PALMER, A.S. (1997). The volcanic history of Ruapehu during the past 2 millennia based on the Tufa Trig tephra. *Bulletin of Volcanology*, **59**: 136-146.
- DONOGHUE, S.L., PALMER, A.S., MCCLELLAND, E., HOBSON, K., STEWART, R.B., NEALL, V.E., LECOINTRE, J. & PRICE, R. (1999). The Taurewa Eruptive Episode: evidence for climactic eruptions at Ruapehu volcano, New Zealand. *Bulletin of Volcanology*, **60**: 223-240.
- DUNLOP, D.J. & ÖZDEMİR, Ö. (1997). *Rock magnetism: fundamentals and frontiers*. Cambridge University Press, Cambridge: 573.

- ERWIN, P. (2001). *Palaeomagnetic investigations of volcano instability*. Unpublished DPhil thesis, Oxford University.
- FISHER, R.A. (1953). Dispersion on a sphere. *Proceedings of the Royal Society A*, **217**: 295-305.
- FISHER, R.V. (1966A). Mechanism of deposition from pyroclastic flows. *Am. J. Sci.*, **264**: 350-63.
- FISHER, R.V. (1979). Models for pyroclastic surges and pyroclastic flows. *Journal of Volcanology and Geothermal Research*, **6**: 305-18.
- FISHER, R.V. & SCHMINCKE, H. -U. (1984). *Pyroclastic rocks*. Springer-Verlag, Berlin.
- FLEET, S.G. & CANN, J.R. (1967). Vlasovite: a second occurrence and a triclinic to monoclinic inversion. *Mineralogical Magazine*, **36** (278): 233-241.
- FRIEDMAN, I., LONG, W. & SMITH, R.L. (1963). Viscosity and water contents of rhyolite glass. *Journal of Geophysical Research*, **68**: 6523-35.
- GAST, P.W. (1969). The isotopic compositions of lead from St. Helena and Ascension Islands. *Earth and Planetary Science Letters*, **5**: 353-359.
- GUBBINS, D. (1999). The distinction between geomagnetic excursions and reversals. *Geophysical Journal International*, **137**: F1-F3.
- HACKETT, W.R. & HOUGHTON, B.F. (1989). A facies model for a Quaternary andesitic composite volcano: Ruapehu, New Zealand. *Bulletin of Volcanology*, **51**: 51-68.
- HANSON, J.A., GIVEN, H.K. & BERGER, J. (1996). Earthquake activity near Ascension Island, South Atlantic Ocean, as seen by a combined seismic/ hydrophone array. *Geothermics*, **25** (4/5): 507-519.
- HARRIS, C. (1982). *Coarse-grained rocks of Ascension Island*. Unpublished DPhil thesis, Oxford University.
- HARRIS, C. (1983). The petrology of lavas and associated plutonic inclusions of Ascension Island. *Journal of Petrology*, **24** (4): 424-470.
- HARRIS, C. (1986). A quantitative study of magmatic inclusions in the plutonic ejecta of Ascension Island. *Journal of Petrology*, **27** (1): 251-276.
- HARRIS, C. & BELL, J.D. (1982). Natural partial melting of syenite blocks from Ascension Island. *Contributions to Mineralogy and Petrology*, **79**: 107-113.
- HARRIS, C., BELL, J.D., & ATKINS, F.B. (1982A). Isotopic composition of lead and strontium in lavas and coarse-grained blocks from Ascension Island, South Atlantic. *Earth and Planetary Science Letters*, **60**: 79-85.
- HARRIS, C., CRESSEY, G., BELL, J.D., ATKINS, F.B. & BESWETHERICK, S. (1982B). An occurrence of rare-earth-rich eudialyte from Ascension Island, South Atlantic. *Mineralogical Magazine*, **46**: 421-425.

- HOBLITT, R.P. & KELLOGG, K.S. (1979). Emplacement temperatures of unsorted and unstratified deposits of volcanic rock debris as determined by palaeomagnetic techniques. *Geol. Soc. Am. Bulletin*, **90** (1): 633-642.
- HOBLITT, R.P., REYNOLDS, R.L. & LARSON, E.E. (1985). Suitability of nonwelded pyroclastic-flow deposits for studies of magnetic secular variation; a test based on deposits emplaced at Mount St. Helens, Washington, in 1980. *Geology (Boulder)*, **13** (4): 242-245.
- HOUGHTON, B.F., LATTER, J.H. & HACKETT, W.R. (1987). Volcanic hazard assessment for Ruapehu composite volcano, Taupo Volcanic Zone, New Zealand. *Bulletin of Volcanology*, **49**: 737-751.
- HOUGHTON, B.F., WILSON, C.J.N. & PYLE, D.M. (2000). Pyroclastic fall deposits. In *An Encyclopedia of Volcanoes* (Ed. H. Sigurdsson), Academic Press, San Diego: 555-570.
- HOUGHTON, B.F., WILSON, C.J.N., MCWILLIAMS, M., LANPHERE, M.A., WEAVER, S.D., BRIGGS, R.M. & PRINGLE, M.S. (1995). Chronology and dynamics of a large silicic magmatic system: central Taupo Volcanic Zone, New Zealand. *Geology*, **23**: 13-16.
- HUNT, C., BANERJEE, S.K. & MARVIN, J. (1986). Magnetite exsolution in oceanic basalts lead to CRM controlled by ambient field, not host-rock magnetisation. *Eos, Transactions of the American Geophysical Union*, **67** (44): 923.
- HUPPERT, H.E., SPARKS, R.S.J. & TURNER, J.S. (1982A). Effects of volatiles on mixing in calc-alkaline magma systems. *Nature*, **297**: 554-557.
- HUPPERT, H.E., SPARKS, R.S.J. & TURNER, J.S. (1984). Some effects of viscosity on the dynamics of replenished magma chambers. *Journal of Geophysical Research*, **89** (B8): 6857-6877.
- KAR, A., WEAVER, B., DAVIDSON, J. & COLUCCI, M. (1998). Origin of differentiated volcanic and plutonic rocks from Ascension Island, South Atlantic Ocean. *Journal of Petrology*, **39** (5): 1009-1024.
- KENT, D.V., NINKOVICH, D., PESCATORE, T. & SPARKS, R.S.J. (1981). Palaeomagnetic determination of emplacement temperature of Vesuvius AD 79 pyroclastic deposits. *Nature (London)*, **290** (5805): 393-396.
- KENT, J.T., BRIDEN, J.C. & MARDIA, K.V. (1983). Linear and planar structure in ordered multivariate data as applied to progressive thermal demagnetization of palaeomagnetic remanence. *Geophysical Journal of the Royal Astronomical Society*, **75**: 593-621.
- KIRSCHVINK, J. L. (1980). The least-squares line and plane in analysis of palaeomagnetic data. *Geophysical Journal of the Royal Astronomical Society*, **62**: 699-718.
- LIPMAN, P.W. & MULLINEAUX, D.R. (EDS). (1981). The 1980 eruptions of Mount St. Helens, Washington. *US Geol. Survey Prof. Pap.*, **1250**.
- LIRER, L., PESCATORE, B., BOOTH, B. & WALKER, G.P.L. (1973). Two Plinian pumice-fall deposits from Somma Vesuvius, Italy. *Geol. Soc. Am. Bull.*, **84**: 759-72.

- MCCLELLAND, E.A., BARDOT, L. & WILSON, C.J.N. (2000). Emplacement temperatures of the 1800 BP Taupo ignimbrite, New Zealand: implications for flow transport mechanism. *Geophysical Research Abstracts*, **2** (European Geophysical Society 25th General Assembly) Session 25: 96.
- MCCLELLAND, E.A. & DRUITT, T.H. (1989). Palaeomagnetic estimates of emplacement temperatures of pyroclastic deposits on Santorini, Greece. *Bulletin of Volcanology*, **51**: 16-27.
- MCCLELLAND, E.A. & ERWIN, PATRICK SEUMAS. (2000). Was a dacite dome implicated in the 9,500 BP collapse of Mt Ruapehu? A palaeomagnetic investigation. *Submitted to Bulletin of Volcanology*.
- MCCLELLAND, E., KONDOPOULOU, D., WESTPHAL, M. & SOPHOS, P. (1997). Palaeomagnetic estimation of emplacement temperatures of plinian airfalls on Santorini, Greece. In: *The European Laboratory Volcanoes*, (Eds. Casale, R., Fytikas, M, Sigvaldasson, G., Vougioukalakis, G.), EU Special Publication, European Volcanological Programme EUR 18161 EN.
- MCCLELLAND, E. & SHCHERBAKOV, V.P. (1995). Metastability of domain state in multidomain magnetite; consequences for remanence acquisition. *Journal of Geophysical Research, B, Solid Earth and Planets*. **100**: (3): 3841-3857.
- MCDONOUGH, W.F. & SUN, S.S. (1995). The composition of the Earth. *Chemical Geology*, **120** (3-4): 223-253.
- MCELHINNEY, M.W. (1983). *The Earth's Magnetic Field*. Academic Press, London and New York.
- MAJOR, J.J., PIERSON, T.C., DINEHART, R.L. & COSTA, J.E. (2000). Sediment yield following severe volcanic disturbance--a two-decade perspective from Mount St. Helens. *Geology*. **28**: (9): 819-822.
- MILLS, M.J. (2000). Volcanic aerosol and global atmospheric effects. In *An Encyclopedia of Volcanoes* (Ed H. Sigurdsson), Academic Press, San Diego: 931-943.
- MINSHULL, T.A. & BROZENA J.M. (1997). Gravity anomalies and flexure of the lithosphere at Ascension Island. *Geophysical Journal International*, **131**: 347-360.
- MOORE, J.G. & PECK, D.L. (1962). Accretionary lapilli in volcanic rocks of the western United States. *Journal of Geology*, **70**: 182-93.
- MOORE, J.G. (1967). Base surges in recent volcanic eruptions. *Bull. Volcanol.* **30**: 337-63.
- MORRISSEY, M. M. & MASTIN, L. G. (2000). Vulcanian eruptions. In *An Encyclopedia of Volcanoes* (Ed H. Sigurdsson), Academic Press, San Diego: 463-475.
- MORRISSEY, M. M., ZIMANOWSKI, B., WOHLTZ, K. & BUETTNER, R. (2000). Phreatomagmatic fragmentation. In *An Encyclopedia of Volcanoes* (Ed H. Sigurdsson), Academic Press, San Diego: 431-445.
- MULLINEAUX, D.R. & CRANDELL, D.R. (1962). Recent lahars from Mount Saint Helens, Washington. *Geological Society of America Bulletin*, **73** (7): 855-869.

- MUXWORTHY, A.R. (1997). *Stability of multidomain magnetite*. Unpublished DPhil thesis, Oxford University.
- NAIRN, I.A. & SELF, S. (1978). Explosive eruptions and pyroclastic avalanches from Ngauruhoe in February 1975. *Journal of Volcanology and Geothermal Research*, **3** (1-2): 39-60.
- NÉEL, L. (1949). Theory of magnetic after effect in ferromagnetic in the form of small particles, with applications to baked clays. *Annales Géophysiques*, **5**: 99-136.
- NIELSON, D.L. & SIBBETT, B.S. (1996). Geology of Ascension Island, South Atlantic Ocean. *Geothermics*, **25** (4/5): 427-448.
- NIELSON, D.L. & STIGER, S.G. (1989). Geothermal exploration of Ascension Island, South Atlantic Ocean. *Transactions of the Geothermal Resource Council*, **11**: 187-191.
- NIELSON, D.L. & STIGER, S.G. (1996). Drilling and evaluation of Ascension #1, a geothermal exploration well on Ascension Island, South Atlantic Ocean. *Geothermics*, **25** (4/5): 543-560.
- O'HARA, M.J. & MATTHEWS, R.E. (1981). Geochemical evolution in an advancing, periodically replenished, periodically tapped, continuously fractionated magma chamber. *Journal of the Geological Society of London*, **138**: 237-77.
- O'NIONS, R.K. & PANKHURST, R.J. (1974). Petrogenetic significance of isotope and trace element variations in volcanic rocks from the Mid Atlantic. *Journal of Petrology*, **15**: 603-634.
- OPDYKE, N.D. & CHANNELL, J.E.T. (1996). *Magnetic Stratigraphy (International Geophysics Series Vol. 64)*. Academic Press, San Diego.
- O'REILLY, W. (1984). *Rock and mineral magnetism*. Blackie & Sons Ltd, Glasgow.
- PALMER, B.A. & NEALL, V.A. (1989). The Murimotu Formation - 9500 year old deposits of a debris avalanche and associated lahars, Mount Ruapehu, New Zealand. *N.Z. Journal of Geology and Geophysics*, **32**: 477-486.
- PALMER, B.A., PURVES, A.M. & DONOGHUE, S.L. (1993). Controls on accumulation of a volcanoclastic fan, Ruapehu composite volcano, New Zealand. *Bulletin of Volcanology*, **55**: 176-189.
- PEREZ TORRADO, F.J., SOLER, V., CARRACEDO, J.C. & MANGAS, J. (1994). Temperatura de emplazamiento de las ignimbritas Roque Nublo (Gran Canaria, Islas Canarias) mediante técnicas paleomagnéticas. *Estudios Geol.*, **50**: 9-17.
- POTTS, J. P. (1987). *A handbook of silicate rock analysis*. Blackie & Sons Ltd., Glasgow.
- RAYLEIGH, LORD (1919). On the problem of random vibrations and random flights in one, two and three dimensions. *Phil. Mag.*, **37**: 321-346.
- ROBIN, C., KOMOROWSKI, J-C., BOUDAL, C & MOSSAND, P. (1990). Magma Mixed-magma pyroclastic surge deposits associated with debris avalanche deposits at Colima volcanoes, Mexico. *Bulletin of Volcanology*, **52**: 391-403.

- RODOLFO, K. S. (2000). The hazard from lahars and jökulhlaups. In *An Encyclopedia of Volcanoes* (Ed H. Sigurdsson), Academic Press, San Diego: 973-995.
- ROEDDER, EDWIN & COOMBS, D.S. (1967). Immiscibility in granitic melts, indicated by fluid inclusions in ejected blocks from Ascension Island. *Journal of Petrology*, **8** (3): 417-451.
- ROLF, T.C. (1997). An investigation of the magnetic variation within two recent lava flows. *Geophysical Journal International*, **130**: 125-136.
- ROSS, H.P., GREEN, D.J. & MACKELPRANG, C.E. (1996a). Electrical resistivity surveys, Ascension Island, South Atlantic Ocean. *Geothermics*, **25** (4/5): 489-506.
- SELF, S. & SPARKS, R.S.J. (1978). Characteristics of widespread pyroclastic deposits formed by the interaction of silicic magma and water. *Bull. Volcanol.* **41**: 196-212.
- SHEPHERD, J.B. & SIGURDSSON, H. (1982). Mechanism of the 1979 explosive eruption of Soufrière volcano, St. Vincent. *J. Volcanol. Geotherm. Res.*, **13**: 119-30.
- SHEPPARD, SIMON M.F. & HARRIS, CHRIS (1985). Hydrogen and oxygen isotope geochemistry of Ascension Island lavas and granites: variation with crystal fractionation and interaction with seawater. *Contributions to Mineralogy and Petrology*, **91**: 74-81.
- SHERIDAN, M.F. (1979). Emplacement of pyroclastic flows: a review. In *Chapin & Elston* (1979): 125-36.
- SIEBERT, L. (1984). Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions. *Journal of Volcanology and Geothermal Research*, **22**: 163-197.
- SMITH, G.A. (1986). Coarse-grained nonmarine volcanoclastic sediment: terminology and depositional process. *Geol. Soc. Am. Bulletin*, **97**: 1-10.
- SMITH, R.L. (1960a). Ash flows. *Geol. Soc. Am. Bulletin*, **71**: 795-842.
- SPARKS, R.S.J. (1976). Grain size variations in ignimbrites and implications for the transport of pyroclastic flows. *Sedimentology*, **23**: 147-88.
- SPARKS, R.S.J. (1986). The dimensions and dynamics of volcanic eruption columns. *Bulletin of Volcanology*, **48** (1): 3-15.
- SPARKS, R.S.J. & MARSHALL, L.A. (1986). Thermal and mechanical constraints on mixing between mafic and silicic magmas. *Journal of Volcanology and Geothermal Research*, **29**: 99-124.
- SPARKS, R.S.J., SIGURDSSON, H. AND WILSON, L. (1977). Magma mixing: a mechanism for triggering acid explosive eruptions. *Nature*, **267**: 315-318.
- SPARKS, R.S.J., TAIT, S.R. & YANEV, Y. (1999). Dense welding caused by volatile resorption. *Journal of the Geological Society, London*, **156**: 217-225.

- SPARKS, R.S.J., WILSON, L. & HULME, G. (1978). Theoretical modelling of the generation, movement and emplacement of pyroclastic flows by column collapse. *J. Geophys. Res.* **83**: 1727-39.
- SUN, S.S. & McDONOUGH, W.F. (1989). Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: *Magmatism in Ocean Basins*, Geol. Soc. London Special Publication, **42**: 313-345.
- TARLING, D.H. (1971). *Principles and Applications of Palaeomagnetism*. Chapman and Hall, London.
- TAUXE, LISA (1998). *Palaeomagnetic Principles and Practice*. Kluwer Academic Publishers, Dordrecht/Boston/London.
- THELLIER, E. (1937). Aimantation des terres cuites; application a la recherche de l'intensite du champ magnetique terrestre dans la passe. *Comptes Rendes Acad. Sciences Paris*, **204**: 184-186.
- THELLIER, E. & THELLIER, O. (1959). Sur l'intensite du champ magnetique terrestre dans le passé historique et geologique. *Annales de Geophysiques*, **15**: 285-376.
- THOMAS, R.M.E. & SPARKS, R.S.J. (1992). Cooling of tephra during fallout from eruption columns. *Bulletin of Volcanology*, **54**: 542-553.
- TOPPING, W.W. (1973). Tephrostratigraphy and chronology of Late Quaternary eruptives from the Tongariro Volcanic Centre, New Zealand. *N.Z. Journal of Geology and Geophysics*, **16** (3): 397-423.
- TOPPING, W.W. & KOHN, B.P. (1973). Rhyolitic tephra marker beds in the Tongariro area, North Island, New Zealand. *N.Z. Journal of Geology and Geophysics*, **16** (3): 375-395.
- UI, T. (1983). Volcanic dry avalanche deposits; identification and comparison with nonvolcanic debris stream deposits. *Journal of Volcanology and Geothermal Research*, **18** (1-4): 135-150.
- UI, T., TAKARADA, S. & YOSHIMOTO, M. (2000). Debris avalanches. In *An Encyclopedia of Volcanoes* (Ed H. Sigurdsson), Academic Press, San Diego: 617-626.
- VALENTINE, M.J. & CZARNECKI, J. (1997). Paleomagnetism of Basalts From Ascension Island. *Abstract no. GP51A-18, AGU Spring Meeting 1997*.
- VAN ANDEL, T.H. & HEATH, G.R. (1970). Tectonics of the Mid-Atlantic Ridge 6° – 8° south latitude. *Marine Geophysical Research*, **1**: 5-36.
- VAN ANDEL, T.H., REA, D.K, VON HERZEN, R.P. & HOSKINS, H. (1973). Ascension Fracture Zone, Ascension Island, the Mid-Atlantic Ridge. *Bulletin of the Geological Society of America*, **84**: 1527-1546.
- VAN TASSEL, R. (1952). Dalyite, a new potassium zirconium silicate, from Ascension Island, Atlantic. *Mineralogical Magazine*, **29**: 850-857.
- WALDERHAUG, H.J. (1992). Directional properties of alteration CRM in basic igneous rocks. *Geophysical Journal International*, **111**: 335-347.

- WALDERHAUG, H.J., TORSVIK, T.H. & LØVLIE, R. (1991). Experimental CRM production in a basaltic rock; evidence for stable intermediate palaeomagnetic directions. *Geophysical Journal International*, **105**: 747-756.
- WALKER, G.P.L. (1973b). Explosive volcanic eruptions – a new classification scheme. *Geol. Rundsch.*, **62**: 431-46.
- WALKER, G.P.L. (1980). The Taupo pumice: product of the most powerful known (ultraplinian) eruption? *Journal of Volcanology and Geothermal Research* **8**: 69-94.
- WALKER, G.P.L. (1981b). Plinian eruptions and their products. *Bulletin of Volcanology*, **44**: 223-40.
- WATSON, G.S. (1956). A test for randomness of directions. *Monthly Notices of the Royal Astronomical Society Geophysical Supplements*, **7**: 160-161.
- WEAVER, B. (2001). Ascension Island - information on the history and natural history with literature sources and a photo tour of the island. Website: <http://geowww.gcn.ou.edu/~bweaver/Ascension/ai.htm>.
- WEAVER, B., KAR, A, DAVIDSON, J. & COLUCCI, M. (1996). Geochemical characteristics of volcanic rocks from Ascension Island, South Atlantic Ocean. *Geothermics*, **25**: 449-470.
- WEIS, D. (1983). Pb isotopes in Ascension Island rocks: oceanic origin for the gabbroic to granitic plutonic xenoliths. *Earth and Planetary Science Letters*, **62**: 273-282.
- WEIS, D., DEMAIFFE, D, CAUET, S & JAVOY, M. (1987). Sr, Nd, O and H isotopic ratios in Ascension Island lavas and plutonic inclusions; cogenetic origin. *Earth and Planetary Science Letters*, **82**: 255-268.
- WILSON, C.J.N. (1980). The role of fluidisation in the emplacement of pyroclastic flows: An experimental approach. *Journal of Volcanology and Geothermal Research*, **20**: 55-84.
- WILSON, C.J.N. (1984). The role of fluidisation in the emplacement of pyroclastic flows, 2: experimental results and their interpretation. *Journal of Volcanology and Geothermal Research*, **8**: 231-49.
- WILSON, C.J.N. (1985). The Taupo Eruption, New Zealand: II. The Taupo ignimbrite. *Phil. Trans. R. Soc. Lond., A*. **314**: 229-310.
- WILSON, C.J.N. & HILDRETH, W. (1998). Hybrid fall deposits in the Bishop Tuff, California: A novel pyroclastic depositional mechanism. *Geology*, **26** (1): 7-10.
- WILSON, C.J.N. & WALKER, G.P.L. (1982). Ignimbrite depositional facies: the anatomy of a pyroclastic flow. *J. Geol. Soc. Lond.* **139**: 581-92
- WILSON, C.J.N. & WALKER, G.P.L. (1985). The Taupo Eruption, New Zealand: I. General Aspects. *Phil. Trans. R. Soc. Lond. A*. **314**: 199-228.

- WILSON, C.J.N., HOUGHTON, B.F., PILLANS, B.J. & WEAVER, S.D. (1995). Taupo Volcanic Zone calc-alkaline tephras on the peralkaline Mayor Island volcano, New Zealand: identification and uses as marker horizons. *Journal of Volcanology and Geothermal Research*, **69**: 303-311.
- WILSON, C.J.N., ROGAN, A.M., SMITH, I.E.M., NORTHEY, D.J., NAIRN, I.A. & HOUGHTON, B.F. (1984). Caldera volcanoes of the Taupo Volcanic Zone, New Zealand. *Journal of Geophysical Research*, **89(B10)**: 8463-8484.
- WILSON, L. (1976). Explosive volcanic eruptions – III. Plinian eruption columns. *Geophysical Journal of the Royal Astronomical Society*, **45**: 543-56.
- WILSON, L. (1980A). Relationships between pressure, volatile content and ejecta velocity in three types of volcanic explosion. *Journal of Volcanology and Geothermal Research*, **8**: 297-313.
- WILSON, L. & SPARKS, R.S.J. (1976). Plinian eruptions columns and ignimbrite formation. *Eos, Transactions of the American Geophysical Union*. **57** (4): 347.
- WRIGHT, J.V. (1978). Remanent magnetism of poorly sorted deposits from the Minoan eruption of Santorini. *Bulletin Volcanologique*, **41**: 131-134.
- WRIGHT, J.V. & WALKER, G.P.L (1977). The ignimbrite source problem; significance of a co-ignimbrite lag-fall deposit. *Geology (Boulder)*, **5** (12): 729-732.
- WRIGHT, J.V. & WALKER, G.P.L (1981). Eruption, transport and deposition of ignimbrite; a case study from Mexico. *Journal of Volcanology and Geothermal Research*, **9** (2-3): 113-131.
- YAMAZAKI, T., MUROI, I., KATO, I. & ABE, M. (1973). Minor structures of Rokuya pyroclastic flow deposits, Nijo-san District. *Kasan – Bulletin of the Volcanological Society of Japan*, **18** (2): 105.
- ZIJDERVELD, J.D.A. (1967). Analysis of results. In: Collinson D.W., Creer, K.M. and Runcorn, S.K. (eds). *Methods in Palaeomagnetism*, Elsevier, Amsterdam
- ZLOTNICKI, J., POZZI, J.P., BOUNDON, G. & MOREAU, M.G. (1984). A new method for the determination of the setting temperature of pyroclastic deposits (example of Guadeloupe: French West Indies). *Journal of Volcanology and Geothermal Research*, **21**: 297-312.

Appendix A

SAMPLING SITE DESCRIPTIONS

BILL – Basalt Flow – 572310E 9122225N

Dark grey (weathers black) vesicular basaltic lava flow overlying and cross-cutting pumiceous deposits above thick sequence of (unwelded) ignimbrite. The flow has a rubbly, blocky base and streaked-out vesicles can be seen in some of the larger blocks (flow banding).

BPB – Big Pumice Breccia – 573095E 9122700N

Samples were taken from two units from a thick sequence (over 4.5m) of coarse pumice breccia deposits. The units sampled contain very coarse pumice and lithic blocks (pumices up to 50cm and lithics up to 35cm in length) and a relatively high percentage of fine material. Pumice clasts generally weather to a white-grey colour and many are banded. A large range of lithics is seen, including dark mafic lava, pink crystal-rich lava, black and red scoria and much obsidian, some of which displays green/black banding. The lower unit sampled is slightly less coarse than the upper unit and more lithic-rich, also containing plutonic blocks and clasts of ignimbrite. Both units have a fine-grained, gritty basal layer.

Other units in the sequence contain lenses of pumice clasts that 'pinch and swell' as well as weak stratification, picked out by fine grit layers.

BX1 – explosion breccia on path to White Hill, E of Cricket Valley – 574405E 9121455N

This is a matrix supported trachytic breccia. The deposit consists of cm to m-size trachyte blocks in a yellow-white-grey matrix. Trachyte clasts show varying degrees of weathering, from solid to a white and powdery nature. The unit contains some banded lava (rhyolite?), some obsidian, some small pumiceous clasts as well as blue-grey 'pseudo pumice' (difficult to tell whether this is in fact pumice or weathered trachyte lava). In most places the surface of the deposit is rubbly and unconsolidated and no vertical section could be measured (i.e. the thickness of the unit is unknown). The unit is found on a ridge to the N as well as to the SE & E of Cricket Valley. This deposit overlies the CVP units and is most likely an explosion breccia.

CGB – Coarse Grey Breccia 1 – lithic rich breccia, valley W of LA Flow – 573150E 9122750N

This unit is a coarse, very lithic-rich breccia, at least 4m in thickness. The unit contains some discrete

matrix-rich areas and some irregular layers of coarser and finer material. At the base of the unit is a layer of very coarse lithics containing boulders up to 2m in length. Lithics include orange ignimbrite, red and black scoria, dark pink and dark grey mafic lava, banded green-grey lava and paler, more felsic lava. The unit also contains some small pumice clasts.

CVS1 – Cricket Valley surge deposit 1 – 573265E 9121590N

The unit sampled is a breccia at the top of a sequence of interbedded ash and breccia units - unit 6 of the 'Cricket Valley surge deposits'.

Ash layers are pinky-grey in colour and laminated on a mm scale. Some areas contain mm-size lithics and some areas are deformed by overlying breccia units. Layers are up to 20cm thick and wavy and irregular.

Breccia layers are up to 30cm thick and poorly sorted with little matrix. Clasts are mainly lithics with occasional scoria clasts. The unit is composed of mainly lapilli-size clasts, although some coarser areas exist, containing clasts up to 12cm in length. The unit also contains some ashy bands forming lensoid areas of coarser material between them.

CVS2 – Cricket Valley surge deposit 2 – 573264E 9121535N

This site is ~2m below site CVS1, part of another sequence of interbedded ash and breccia layers (unit 4 of CVS deposits). This sequence grades up into laminated ash beds (unit 5) as coarser interbeds get thinner and less frequent. Here the unit is well-stratified with 5-6cm ash layers and 3-30cm coarser breccia interbeds. Clasts are generally cm-size or less but the unit contains a few fist-size clasts. Beds are wavy and dune like with cross stratification. Some ash layers cut erosively into others.

DAVE – Mountain Road Trachyte – 570940E 9121795N

This is a small (around 6m wide) exposure of white and grey banded trachyte (dyke/sill?). The trachyte is overlain a number chaotic, faulted lithic-rich unit which is mixed up with a brown-orange weathered unit containing flattened fiamme-style pumices.

DRA1 – Devil's Riding School Airfall 1 – 568500E 9120345N

These samples were taken from a thick sequence (8-9m) of stratified, angular trachytic pumice units. These units are banked up on to the trachyte rim of the Devil's Riding School and dip into the centre of the crater. Units dip steeply (around 26°) at the edge of the crater and shallow towards the centre (presumably mantling existing topography). The deposit consists of alternating beds of cm-size pumices with some fist-size clasts, and finer ashy beds with pumices <1cm in size. Bed thickness ranges from 1-40cm and individual layers are generally medium to well-sorted. Pumices tend to be crystal-rich and lithic content varies, with clasts tending to be 1cm or smaller. Two distinctive white ash layers are seen, around 2m from the top of the deposit and several other mm-cm ash layers can be seen throughout the deposit, especially towards the top of individual beds. The top of the unit is coarse-grained with some pumice blocks up to 20cm in length. No overall grading is seen in the unit, although individual beds may show normal or reverse grading.

DRS1 – Devil's Riding School flow deposit – 568450E 9120300N

This unit is an ashy, fine-grained unit with scattered clasts of mm-size pumice, larger (<1cm) scoria and some small lithics, in a fine-grained, orange scoriaceous matrix. Clasts generally occur in trains or lenses, delineating weak stratification, though this is wavy and irregular. The unit contains blackened cylindrical concave structures, which are probably the remains of gas escape structures. This unit is cross cut by a darker, brownish-grey fine grit unit. This is a lithic rich grit that contains lenses of coarser lithics and occasional fist-size clasts. The unit shows chaotic cross-stratification and wavy bedding. The top of the unit

is cut by several thin joints, which are filled with white matrix similar to that seen in the centre of the gas escape pipes in the area. This unit grades up into a mixture of the two units described – matrix-supported but more lithic-rich and gritty. This unit contains matrix-rich lenses containing lithic and scoria clasts, and generally contains more large lithics. This part of the deposit is very obviously cross-stratified.

EB1 – Explosion Breccia – Cricket Valley – 573270E 9121435N

This is a very coarse grained, poorly sorted breccia deposit. The deposit has a pinky-grey basal unit consisting of poorly-sorted, large angular blocks of lava up to 60cm in length in a fine-grained ashy matrix. The upper part of the deposit is grey and more clast rich, containing >1m blocks of white weathered trachyte. The base of the deposit is uneven and in many places blocks have sagged into the underlying deposit. The unit is 4-5m in thickness.

EFB1 – Eastern Felsic complex Breccia – NE Point – 573875E 9124800N

This is a matrix supported lithic-rich brown-grey breccia. The unit is stratified with cross bedding and wavy bedding. Sorting is poor, with clast sizes ranging from mm to up to 60cm. The clasts type is very variable and includes dark mafic to felsic lava, orange crystal-rich lava, pale trachyte, ignimbrite, plutonic rock (acid blocks) and scoria showing varying degrees of weathering. The deposit also contains some pumice but is generally pumice-poor. The deposit can be divided up into a lower, matrix rich, more massive unit, a middle stratified unit containing ash beds and an upper coarser almost clast supported unit. This in turn is overlain by a finer grit-like unit with better sorting. This unit overlies mafic lava and is not laterally continuous but appears to be filling a valley.

EFFB1 – Eastern Felsic Complex Flow Breccia – 573820E 9122490N

This deposit consists of 1.7m of (two) more massive breccia units below EFS1 (see below). These are moderately-poorly sorted with clast sizes ranging between <1cm to 12cm in diameter. The units are lithic rich with angular clasts of obsidian, dark mafic and lighter (trachytic?) lava as well as much grey-blue trachytic ‘pseudo-pumice’ which is concentrated at the base of the units. Finer basal layers can be identified in both units and in places these layers are stratified and contain coarse pumice clasts.

EFP1 – Eastern Felsic Pumice 1 – basal unit, Spire Beach Track – 574760E 9122060N

This is the basal unit to a thick sequence of pyroclastic deposits exposed in the hillside near Spire Beach. The unit is a lithic rich, bedded grey pumice deposit, containing clasts of light and dark grey lava, obsidian, red scoria and weathered red (brick-like) lava. The majority of pumice clasts are cm-size, however dm-size clasts are abundant. Pumices are angular, but only moderately vesicular and the unit is generally fines poor. Alternating layers of finer and coarser grained material, as well as abundant pink ash layers produce the planar stratification seen in the unit. Ash layers are a few cm in thickness and contain mm-size lithics. Some coarsening up packages can be seen within the deposit.

EFS1 – Eastern Felsic Complex Surge – 573820E 9122490N

A series of cross-stratified pumiceous, lithic and obsidian-rich breccia deposits are seen here. Breccia beds are 5-50cm thick and overall get coarser up the sequence with large pumice blocks present in the top unit. Pumices are subrounded to rounded and breccia layers contain little matrix. Some beds are extremely pumice rich containing coarse trains of pumice. Ash interbeds are <1cm-20cm thick consisting of coarse white-grey ash with mm-size lithics and pumices. Some mm to cm-scale stratification can be seen as well as trains of pumice and lithic clasts. Overall, the unit shows spectacular undulatory bedding, cross stratification and dune-like structures that show internal (cross) stratification. Cross stratification tends to be picked out by ashy beds and dune structures have a metre scale wavelength. Some loading from the breccia unit above can

also be picked out. Samples from this site were taken from the bottom 60cm of the deposit which is a more lithic rich unit containing lapilli-size clasts and more planar stratification with ashy layers (though some cross stratification can still be seen). This unit has a ~1cm thick fine grained basal layer.

Extra pumice samples were taken here in the second field season, as well as samples from differing heights within the deposit (to examine any thermal stratification).

EFS2 – Eastern Felsic Surge 2 – overlying Little Ascension Flow – 573540E 9122560N

This unit is part of a thick sequence of ash and pumice deposits found covering the top end of Little Ascension Flow. As at site EFS1, the sequence is capped by thick volcanic breccia unit TV. These deposits are distinctive in that they have very obvious stratification and abundant sedimentary-style structures (including dune-like structures and ripples, undulatory stratification, pumice trains, low angle cross-stratification and bomb sags). In some cases, upper units in the sequence cross cut and erode (concurrent) lower units.

The unit sampled here comprises three packages of medium to fine-grained pumice and lithic rich breccia separated by cm-thick ash layers. These breccias are rich in fine material but are not well-consolidated (they seem to be grain supported). Average grain size is cm-size or less but some larger pumice clasts are present towards the top of the unit. The majority of pumice clasts are white and crystal rich and some banded pumice is found. Lithic type is variable and includes banded, dark grey and pink lava. This unit is 80cm in thickness and displays undulatory planar bedding (i.e. no cross-stratification is seen in this unit).

GEOFF – Little Ascension Flow Trachyte – base of flow near NW end – 573165E 9124500N

These samples are from the distal end of Little Ascension Flow. The lithology is a fine-grained grey lava, which has a white ‘speckled’ texture on fresh surfaces. Some small crystals are identifiable. The lava is massive with some jointing.

GMI1 – Green Mountain Ignimbrite 1 – N flanks of Green Mountain – 572500E 9122385N

Samples were taken from the welded part of a 5m thick ignimbrite deposit which grades upwards from a non-welded pumiceous breccia to a fully welded ignimbrite. The welded part of the deposit (top 4m) is dark orange to pink or brown in colour. Texture is variable and ranges from blocky, lava-like material to that with a well-developed eutaxitic texture. Semi-welded parts of the deposit are poorly sorted, containing large baked pumice clasts (which look like scoria) within a fine-grained pink-orange matrix. Clast size ranges from less than 1cm to 70cm in length. The semi-welded parts of the deposit also contain angular clasts of lava, many of which have altered rims.

GMP1 – Green Mountain Pumice 1 – 572755E 9121730N

This is a bedded, grey trachytic pumice deposit, exposed along the path from the Scout’s Camp on the North flanks of Green Mountain. The deposit is approximately 6m thick (thickness is difficult to ascertain) and contains abundant thin (mm to cm thick) ash layers. Beds range from 40cm to 80cm in thickness. Pumices are angular to subrounded and the unit contains abundant lithics, including clasts of ignimbrite and scoria. Many beds show reverse grading and pumice clasts range from 1cm to ~12cm in length. Pumices tend to be crystal-rich. Undulose bedding is seen in places, as well as some cross-stratification, which causes ash bands to pinch out and ‘disappear’. Some finer-grained areas thicken down-dip and form lenses of material.

GMP2 – Green Mountain Pumice 2 – airfall below GMI1 – 572500E 9122385N

This 4m thick deposit is a weakly bedded trachytic pumice airfall. Average grain size (pumice) is 1-2cm, but many dm-size clasts exist. Pumices range in colour and vesicularity from blue-grey to white clasts which are

generally more vesicular. Several pumices are pink in colour and weathered. Some pumices show banding and a number of clasts contain inclusions of darker lithic rich material (possibly a result of magma mingling). The deposit is lithic rich, containing clasts of dark grey lava, pale grey speckled lava, obsidian and ignimbrite.

I1 – Invalids 1 – Invalids path, Mountain Road – 571135E 9121395N

This is a grey trachytic pumice airfall deposit of at least 8m thickness. The deposit varies vertically and laterally, in terms of grain size, stratification, banded pumice, ash layers and welding. Numerous faults run through the deposit.

At the sampling site, the unit is massive and contains red scoria, banded grey-pink lava (containing clear crystals), obsidian (cm-size), both black and green-grey, some black scoria and some rounded, vesicular yellow pumice/weathered lava. The deposit is moderately to well-sorted and average grain size is cm-size, although clasts range from mm to dm-size. Two (cm-thick) ash layers are seen here and the deposit is faulted. Samples were taken from two fault blocks.

Above the area sampled is an area of blackened, strongly welded pumice (some are flattened, like fiamme) and this grades up through coarse, semi-welded pumice to weathered, white pumice. This top part of the deposit is extremely rich in obsidian and this is often fractured, shattered or altered. In other areas of the deposit (i.e. round invalids path), many pink ash layers are seen running through the deposit (often offset by faults) and a greater proportion of banded pumice is seen.

I2 – Invalids 2 – Mountain Road – 570730E 9122038N

This is a 7m thick unit of bedded grey trachytic pumice. The unit is lithic rich with lithics of dm-size. Pumice clasts are also large (up to 25cm in length) and many are banded. The unit contains few ash layers. Stratification becomes weaker nearer the base of the unit.

This may be part of a much thicker pumice deposit, as another thick fall (10m) lies above this unit. However, the two are separated by a thin (20cm) white pumice and ash unit and the pumice unit above is less lithic rich, shows more structure (normal grading) and many thin ash bands.

I3 – Invalids 3 – upper NASA Road – 569560E 9120400N

This is part of a thick (10m) unit of well-bedded grey pumice. This unit has a prominent (1m thick) white layer composed of ash and rounded pumices (a flow deposit?) and the whole unit has a number of faults running through it. Samples were taken from above and below the white ash layer within this airfall pumice unit. Above the white layer, the deposit is 4.5m thick (at the sampling location). Pumices are angular and moderately to poorly vesicular. The unit is lithic-rich, containing mafic lava (dark grey or pink), black and red scoria and obsidian and clasts are mm to cm-size. Many beds show reverse grading, although overall the deposit fines upwards. Abundant fine ash beds are also present and these increase in number toward the top of the unit, where there are also some more gritty, flow-like units. Directly below the white layer, pumice is more weathered and appears less well-sorted and stratified and the pumice contains matrix-rich lenses. However, these may also be flow layers. Below this region, pumice is well-bedded, angular and clasts of up to 30cm are seen, as well as clasts of ignimbrite. Some fine-grained layers are seen within the deposit, which contain small lithics (cm-size or less). Normal grading is present in some areas as well as some ash-rich layers.

I4 – Invalids 4 – above NRLB2, NASA Road – 1569350E 9120255N

Samples were taken from three units from a steeply dipping, 10m thick grey pumice unit. These units are of

grey trachytic pumice and are separated by two distinct white ash layers a few cm thick. The pumice is lithic-rich and contains some obsidian. Pumices are sub-angular. The lower unit has a fine-grained base, which coarsens up to clasts of a few cm in size, then fines upward again. The middle pumice unit is slightly finer-grained (lapilli-size and smaller) than the other two and shows some stratification. In places, this stratification is slightly undulatory. Ash layers are white, finely (mm scale) stratified and often contain coated grains. The basal contact of this unit is erosional and clasts from the unit below have been ripped up and incorporated into the base of the pumice. Lower units also seem to thicken down-dip.

I5 – Invalids 5 – unit 8b + 10, Pyroclastic Plain – 569248E 9120400N

Samples were taken from two pumice units separated by a thin ash layer. These units are composed of normally graded angular white pumice of cm to mm-size. Lithics are concentrated at the base of the unit and lithic content decreases upwards. Toward the top of the unit, stratification is picked out by finer grained layers of pumice and lithics.

I6 – Invalids 6 – overlying base of SB units – 570420E 9120305N

This is a bedded grey pumice unit that is found draping the slopes south of Middletons ridge. The deposit is at least 10m in thickness and in places is very steeply dipping (up to 39°). Pumices are angular and are up to 49cm in length. The unit is lithic poor and any lithics are typically only a few cm in length. Several fine-grained ashy layers can be seen throughout the unit, delineating bedding and some ash layers are undulatory and cut into lower units. Stratification increases toward the base of the unit, where layers of coarser and finer material, undulose bedding and wavy ash layers, (possible) low-angle cross stratification and some pumice trains are seen. These lower layers are more lithic-rich and some otherwise well-sorted layers contain large blocks.

LA1 – Little Ascension 1 – overlying Little Ascension Flow – 573323E 9123670N

This is a 1.2m thick coarse 'pseudo-pumice' breccia deposit. The unit is grey-white, and poorly sorted, with clast size ranging from mm to dm. Lithics are large and abundant (up to 30cm in length) and the majority of clasts are trachytic in composition, from coherent grey trachyte lava to powdery white weathered trachyte, which grades to pseudo-pumice. Abundant blocks of banded, glassy grey/black lava are also present, as well as some obsidian and the occasional clast of red lava. The unit is unconsolidated overall and lacks a coherent cementing matrix.

LA2 – Little Ascension 2 – overlying Little Ascension Flow – 573323E 9123670N

This 3m thick unit lies stratigraphically below LA1. It is composed of several interbedded pumice and lithic breccia, ash layers and coarser pumice layers. Layers range from a few to 20cm in thickness and some are undulatory. Breccia units are medium to fine-grained (grain size ranging from mm to a few cm) and pumice layers tend to be slightly coarser. Ash layers are white or pale pink and all units are crystal rich. Some of these finer layers have a concentration of pumice clasts at their top. The unit weathers in a distinctive way, forming concentric patterns.

LF1 – Lithic Flow 1 – E of Little White Hill – 575045E 9121625N

From a distance, this unit resembles a trachytic pumice airfall but it is in fact composed of angular fragments of grey lava or pseudo-pumice (trachytic). Grain size is coarse, with some clasts reaching 60cm in length. Much obsidian is present, which ranges from black to green-grey banded and this gives the unit an almost bimodal composition. Some 'true' lithics (weathered lava) are also found though these are scarce. The unit contains much fine material that crumbles to the touch. Some stratification is seen, picked out by coarser and finer layers.

LF2 – Lithic Flow 2 – E of Cricket Valley – 574810E 9121725N

This is a breccia unit rich in yellow-white weathered trachyte and pumice. The unit comprises alternating medium to coarse-grained breccia layers and fine-grained ash-rich layers, which produces stratification. Beds range in thickness from 1cm to 60cm. Breccia units vary in grain size (from cm to dm largest grain size) and pumice content, but all are lithic-rich. These layers typically show fine-coarse-fine grading. This unit contains much flow-banded lava and obsidian. Stratification is undulatory in places and in many places, large clasts have deformed ash layers in units below them. Near the base of the exposure is a 1m thick, very coarse obsidian-rich unit. Below this is a unit of fine-grained (ash-rich) stratified layers.

MRBB1 – Mountain Road Brown Breccia – 570770E 9122040N

This is a chaotic orange-brown pumiceous unit, which is very variable in thickness. The unit is poorly sorted with some boulder-size clasts of dark grey lava and much pumice in a fine grained brown matrix. The unit also contains clasts of ignimbrite, obsidian and plutonic blocks. The unit is erosive and has cut into the underlying bedded pumice deposit to a depth of up to 5m. Large (70cm x 30cm) complete blocks of a bedded pumiceous deposit can be seen within the deposit, that are probably parts of the underlying pumice. Some weak stratification can also be seen but this is not laterally continuous and fans out in areas. A small channel-like structure is seen which is filled with horizontally stratified material. The unit is overlain by a finer grained, thin flow unit, which in turn is overlain by 2-3m of black stratified scoriaceous material. These three units as well as the underlying bedded pumice dip into a bend in the road as if they were deposited in a valley.

MRGB1 – Mountain Road Grey Breccia – 570952E 9121620N

This is a poorly sorted grey pumice deposit, which contains large scoriaceous clasts (up to 40cm in length), as well as trachyte lava and some clasts of ignimbrite (pinkish, crystal rich, streaky texture). Pumice clasts are generally fist-size. The unit contains some fine ashy layers but these are not easily traced. The unit is laterally variable; where sampled, clast size is up to 70cm to 80cm in length and clasts are seen in varying orientations, one elongated clast seen standing almost vertical within the deposit. (This implies that the unit is not an airfall!). A few metres down the section bedding can be seen in the deposit as well as an overall decrease in grain size and better sorting. Some small faults run through this unit.

MRGB2 – Mountain Road Grey Breccia 2 – 570900E 9121788N

This is similar to MRGB1, a coarse, chaotic pumice and lithic breccia deposit. The unit is dark grey, poorly sorted and lithic rich. Average grain size is cm-size although the unit contains a number of large (up to 30cm in length) clasts of blackened, welded pumice. The unit also contains clasts of black, green-grey and banded obsidian, some of which are dm-size. Some weak undulose stratification can be seen, picked out by layers of coarser and finer ash.

MRH1 – Middleton's Ridge Hydromagmatic deposits – 570240E 9121045N

Twelve samples were taken from various (mainly pumiceous) units over ~7m stratigraphic height. The members of the sequence are laterally variable in welding, clasts type and grain size. Most contacts between units are gradational. Samples were taken from units marked *. (Units are described in *descending* stratigraphic height).

Unit -1* (~2m): This is a matrix rich, pinkish-brown medium grained lithic breccia containing little pumice. Clasts are mainly cm-size or smaller. The unit is not stratified and becomes finer grained and more matrix rich towards the top.

Unit -2 (50cm): This is a white-yellow, matrix supported, pumiceous deposit containing abundant dark

lithics. The unit is poorly sorted with a maximum clast size of 4cm. Most pumices are yellow and have degraded. The unit has a streaky texture, which appears eutaxitic in places.

Unit -3 (1m): This is a unit of grey pumice lapilli containing some matrix and lithics. This is possibly a less welded/degraded version of unit -2.

Unit -4* (30cm): This is a pale yellow, weathered matrix supported pumice deposit. Some angular lithics are seen up to 5cm in length. Pumice clasts are closely packed within the deposit and most are flattened and streaky and have degraded to a powdery consistency. The matrix is black in places (possibly lichen!).

Unit -5* (2m): This is a chaotic unit, mainly consisting of pinky stratified ash layers with occasional thick, coarse breccia lenses. The top of the unit is a very poorly sorted breccia with a fine pink matrix and fist-size clasts with altered rims. This cuts down into a matrix layer, which contains lenses of small lithics and flattened, streaked out pumices. Within this layer is a 40cm thick lens of poorly sorted coarse lithics with a sandy-ashy matrix. Flattened pumices and clasts up to 25cm in length are seen within this lens. The lower ~1m* of the unit is more finely stratified with cm and mm thick lithic layers containing bands of fiamme and flattened pumice shards.

Unit -6* (~1m): This unit consists of similar stratified layers (as above) with more fine lithics and grit layers but much less streaked pumice. Fine grit layers show some cross stratification and overall the unit contains less fine matrix.

Unit -7* (~80cm): This is a pinky matrix rich, stratified unit with mm-size lithics and a mainly sandy matrix. Fine grit layers are interbedded with ash bands that show mm scale stratification. Ash bands show what appears to be soft sediment deformation or small scale gas/water escape structures. The top 8-10cm of the unit is fine grained, white and chalk-like.

Unit -8: Cross-cut by the above unit, at the base of the sequence is a yellowy-brown matrix rich unit containing flattened and streaked out pumices and some small (<1cm) blackened clasts. This unit is degraded and has weathered to clay minerals.

MRP1 – Middleton's Pumice 1 – capping Middleton's Ridge – 570570E 9121120N

This is an angular grey pumice deposit at least 9m in thickness. Sorting varies, though the deposit is generally moderately to well-sorted. Pumice clasts are moderately vesicular and typically cm-size, though some 25cm blocks are seen. The deposit is fairly lithic-poor (less lithic-rich than the Invalids type section), but contains some mm to cm-size lithics of brown, pink and grey lava, as well as some obsidian. Weak bedding is seen in some parts of the deposit, though the unit is massive overall. Lithic content increases toward the bottom of the unit and a layer of fine lithics is seen at the base. A thin (<1cm) layer of brown organic (?) material is also seen here.

Below this unit is another pumice lapilli unit that contains boulders of basaltic and trachytic lava. This unit is more matrix-rich and is separated from the unit above by a thin pink ash layer. This lower unit may be part of the major pumice deposit, though poor exposure makes this difficult to ascertain.

MRP2 – Middleton's Ridge Pumice 2 – above orange unit – 570360E 9121080N

This is a unit of crystal-rich pumice lapilli, which ranges in thickness from 1m to 3m. The extent of weathering is variable through the unit, with pumice ranging from fresh and grey (up slope) to white and degraded. Weathering has also caused the outer surfaces of several clasts to become blackened.

MRP3 – Middleton's Ridge Pumice 3 – 'below'/base of MRP1 – 570390E 9121010N

Samples were taken from a small exposure of pumice airfall some metres below the thick airfall capping the ridge. The unit has been faulted making an estimate of thickness difficult, but at least 1.5m of the pumice is exposed here. The unit contains several fine white ash layers. Samples were taken from two different fault blocks.

MRT1 – Middleton's Ridge Trachyte 1 – below MRH1, Middleton's Ridge – 570110E 9120778N

This is an extensive trachyte flow, part of which crops out beneath the hydromagmatic deposits capping Middleton's Ridge. The unit is white to grey in colour and in many places, weathering has degraded the trachyte so it resembles powdery white ash. In some places, a hardened 'skin' can be seen enclosing discrete pockets of altered trachyte. The flow contains abundant distinctive black basaltic inclusions.

MVA1 – Middleton's Valley Airfall 1 – unit 16, Middleton's Valley – 569730E 9120785N

This is a ~2m thick pumice airfall unit. Fresh pumice clasts are grey (trachytic) but the unit is weathered giving it a white coloration overall. Abundant clasts of red scoria and grey lava can be seen and many clasts are coated with white matrix, although this may be a feature of weathering. The unit is crystal-rich.

MVA2 – Middleton's Valley Airfall 2 – unit 8, Middleton's Valley – 569730E 9120785N

This is a unit of white pumice which is ~5m in thickness. Pumices in the deposit are weathered and rounded and commonly contain black specks, and the unit is rich in lithic clasts of grey lava. A number of different layers are seen in the unit including a 3-4cm ash horizon, ~1m from the base. Below this lie a layer where larger (fist-sized) pumice clasts are seen and a discrete finer-grained, lithic-rich layer. Above the ash layer is a layer of fine-grained lithics and ash and a yellow, streaky pumice layer. Above this, the unit is similar to the basal layers. The upper layer appears to cut into layers beneath it, although the whole area is faulted. The top of this unit is more matrix and crystal-rich and grades up into a unit of pumice and scoria, which grades up into scoria unit MVS1.

MVF1 – Middleton's Valley Flow 1 – unit 17, Middleton's Valley – 569730E 9120785N

This is a yellowy-orange matrix-rich breccia, which is at least 1.4m in thickness. The unit is poorly sorted, containing clasts of scoria and red and grey lava that range from centimetre to boulder size in an ashy matrix. Larger clasts are distributed throughout the deposit. The unit is crystal-rich and weathered.

MVF2 – Middleton's Valley Flow 2 – unit 11, Middleton's Valley – 569730E 9120785N

This is a creamy-white matrix-rich breccia containing clasts of black and pink-red scoria and grey and pink lava. Clasts are cm or mm-sized and some clasts have an ashy coating. The matrix is pumiceous, powdery and crystal-rich, containing small black and white shiny crystals. The top of the unit is weathered and brown in colour and is ashy and hard.

MVLB1 – Middleton's Valley Lava Breccia 1 – unit 12, Middleton's Valley – 569730E 9120785N

This 2m thick unit is a weathered white lava breccia. The unit comprises clasts of powdery white trachyte and clasts of vesicular black basaltic material in a white trachytic ash matrix. Some grey, dm-size clasts are also present and some of these are banded. White trachyte clasts are typically cm-size and contain black specks (weathered crystals?). The top of the unit is cream coloured, matrix rich and weathered.

MVS1 – Middleton's Valley Scoria 1 – unit 9, Middleton's Valley – 569730E 9120785N

This is a 1.8m thick unit that contains large streaky clasts of scoria and degraded yellowy pumice. The upper and lower contacts of the unit are gradational and the unit fines both upward and downward, becoming more

pumice rich each way. This unit eventually grades down into pumice unit MVA2. The thickness of the unit is variable.

MVS2 – Middleton's Valley Scoria 2 – unit 4, Middleton's Valley – 569730E 9120785N

This is a coarse weathered scoria and pumice deposit similar to MVS1. The unit is ~4m thick (although thickness is variable) and contains possibly welded (or semi-welded) streaky clasts of scoria up to 30cm in length in a matrix of finer scoria and degraded yellowy pumice. This unit is chaotic and cuts erosively into the unit below. The unit resembles the orange clay-like unit seen in the sequence of deposits on Middletons Ridge.

NEB – North East Breccias – beneath LA Flow, NE Bay – 573810E 9124775N

These are a sequence of ashy pumiceous units with interbeds or lenses of coarse pumiceous breccia. Breccia units are poorly sorted and very coarse, containing abundant pumice clasts up to 40cm and lithics (mostly lava) up to ~90cm in length. These units contain much fine ashy material and both pumice clasts and ashy matrix are crystal-rich. Breccia units also contain some coherent blocks of a previous pumice deposit. These units are. Some stratification is seen in these units, especially in boulder-rich layers and upper units show cross-stratification or wavy bedding. This sequence is erosional and has cut down into the units below

NELL – North East Lava – underlying breccias at Hummock Point – 574380E 9124510N

This is a black to dark grey mafic lava flow found on the beach at Hummock Point. The unit is blocky and craggy and contains abundant vesicles.

NEP – North East Pumice (& scoria) – underlying breccias at Hummock Point – 573800E 9124780N

This is in fact a scoria and pumice unit which has a thickness where exposed of 1.8m. The unit grades downward from black scoria lapilli to a more matrix-rich grey-white pumice deposit, containing cm-sized lithics. The scoriaceous part of the deposit is fine-grained (with clasts <1cm in size) and stratified.

NRA1 – NASA Road Airfall 1 – unit 2 (below ash), unit 4 (above ash) – 569350E 9120255N

These are the lowest (stratigraphically) of the steeply dipping grey pumice units on the NASA Road and are separated by a 10cm white ash layer. Unit 2 is composed of well-sorted, cm-size angular grey trachytic pumice. The unit is relatively lithic poor, with any lithics concentrated mainly at the base. This unit is stratified, with a number of fine-grained (grit-like) layers running through it. Unit 4 is also a lithic-poor grey pumice, but this unit also contains obsidian. Pumices are cm-size but are more rounded than those in the unit 2 and some are banded. The unit has a coarser grained layer at the base. As below, finer-grained layers pick out stratification in the unit, however many of these layers display low-angle cross-stratification, especially toward the top of the unit. In places, trains of pumice are also found. Above unit 4 lies a matrix and crystal-rich unit containing grey pumice, lithics, scoria and obsidian. The contact between this and unit 4 is irregular and indistinct.

NRA2 – NASA Road Airfall 2 – above NRA1 – 569350E 9120255N

This thick (10.2m), stratified grey pumice unit lies above NRA1. Pumices in this unit are more angular than that in NRA1 and grain size ranges from mm to cm-size. The unit contains a greater proportion of red scoria and is more lithic-rich overall. Lithic and matrix content both increase upward through the unit and a buff coloured lithic and matrix-rich layer forms the top 20-30cm of the unit. Finer-grained layers and ash-rich layers also increase in number toward the top of the unit. Some of these finer layers are not continuous and some coarser lenses of pumice are present. Two distinctive white ash layers are present, 3m from the top of the deposit and these contain nodular lapilli-like features.

NRF1 – NASA Road Flow 1 – underlying NRLB1 – 569458E 9120300N

This is a matrix-supported, lithic and pumice breccia deposit. The deposit is poorly sorted and lithics range in type and size, with some as large as 40cm in length. The pale buff-white matrix is fine-grained and most likely composed of degraded pumice. Across the road from this exposure, the same unit is very weathered, brown and composed solely of ashy matrix. Lithics only were sampled here as pumices were too weathered.

NRF2 – NASA Road Flow 2 – lava breccia, unit A – 569458E 9120300N

This is a white, weathered lava breccia unit consisting of clasts of lava (trachyte or weathered mafic lava?) surrounded by a powdery white ashy matrix.

NRF3 – NASA Road Flow 3 – below NRLB2 – 569350E 9120255N

This is a pumiceous, matrix-rich, chaotic brown flow unit. Up-dip, at the sampling site, the unit cuts discordantly through layers below it, although further down-dip the unit is also erosive, but follows the dipping topography. Where weathered, the unit has a blocky undulose texture, but where the unit is fresher, it is possible to identify weathered pumices that are aligned with bedding.

NRGP1 – NASA Road Grey Pumice 1 – 569350E 9120255N

Unit NRGP1 is the basal 2m of one of a sequence of stratified, dipping pumice deposits exposed on the NASA road. This is a coarse, lithic-rich, poorly sorted pumice deposit with clasts ranging from mm to dm-size. The unit is crystal rich (lithics, pumices and matrix) and very lithic rich with lithics up to 20cm in length. This unit displays no stratification, but has a fine-grained layer at its base and fines up to an ashy layer. Pumice samples were taken from the lower 1.5m of the unit in the second field season.

NRLB1 – NASA Road Lava Breccia 1 – 569458E 9120300N

This is a thick (6m), very coarse pumiceous breccia unit. The unit contains large blocks of lava, clasts of obsidian, banded lava, acid blocks and very weathered blue grey trachytic 'pseudo-pumice'. The unit is poorly sorted with quite a lot of matrix and cuts erosively into the underlying breccia deposit.

NRLB2 – NASA Road Lava Breccia 2 – 569350E 9120255N

This is a massive lava breccia unit, 3.2m thick. Although the unit weathers to a brown colour, it is composed of coarse blocks of blue-grey 'pseudo-pumice' – a cross between lava and pumice – up to 26cm in length. The deposit is moderately to poorly sorted and the texture of clasts varies from dense and solid (lava-like), to light and easily broken (more pumice-like). Most clasts are crystal-rich. The top 20-30cm of the unit is paler in colour and more matrix-rich, containing some lithics and smaller clasts. The basal contact of the unit is erosional and the unit thickens down-slope.

NRLB3 – NASA Road Lava Breccia 3 – unit 18, Middleton's Valley – 569730E 9120785N

This is a 4.5m thick lava breccia which is packed full of clasts of grey-blue trachytic pseudo-pumice. The deposit is coarse-grained and clasts are crystal-rich. The deposit is lithic-poor although some small lithics are seen. In some areas, the unit has a <1m thick white basal layer.

NRLB4 – NASA Road Lava Breccia 4 – above I3 – 569560E 9120400N

This is a 1.8m thick, blocky lava breccia deposit composed of blocks of weathered blue-grey trachyte 'pseudo-pumice' in an ashy matrix of the same composition. The unit contains very few 'true' lithics and texture varies laterally from coherent and lava-like, to rubbly and brecciated. The unit has a fine-grained basal layer and has incised the unit below. The top of the unit is pinky-orange and composed of ashy matrix, with few clasts, which are extremely weathered. This part of the unit contains vertical joints.

NRPF1 – NASA Road Pumice Flow 1 – 569280E 9120255N

Samples were taken from two units at this site. The lower unit is a moderately to poorly sorted grey pumice deposit. Pumices are rounded and are packed together in the lower part of the unit. The unit becomes increasingly matrix rich towards the top (with a fine grained buff matrix) and generally more weathered with very rounded pumices. The upper unit is a buff coloured chaotic, pumiceous breccia, which is matrix-supported and lithic rich. The contact between these two units was impossible to distinguish in the field and five samples were therefore taken from each unit. Pumice samples were taken in season two, from both the lower and upper units.

NRS1 – NASA Road Scoria 1 – 569350E 9120255N

This is a 1.5m thick unit of moderately well-sorted scoriaceous lapilli. The deposit is lithic-rich and contains some pumice. Some stratification can be seen up-dip, toward the top of the unit. Down-dip however, the top of the unit has been partly eroded and scoriaceous clasts have been ripped up and incorporated into the deposit above. A thin, erosive flow unit is also found at the base of the unit.

P1 – Pumice 1 – pumiceous unit at site LF2 – 574810E 9121725N

Pumices were taken from one of the pumice and ash-rich layers below the obsidian-rich layer of unit LF2.

PA1 – Pumice Airfall 1 – valley W of Little Ascension Flow – 573150E 9122750N

This is a grey trachytic airfall, which is at least 5m in thickness. The deposit is well-bedded and contains numerous pink ash layers. A spectacular bomb sag is seen in the deposit, which has resulted in the deformation of ash layers below it. As is seen in unit RSP1, pumice clasts are 'plastered' with a hard white coating that remains if clasts are removed from the deposit.

PB – Piggery Breccia – top of Mountain Road – 571445E 9121185N

This is a weathered, coarse grey pumice breccia, which is at least 8m in thickness. Weathering colour ranges from black or grey to red-pink. The deposit is laterally variable and ranges from pumice rich, clast supported areas with weak bedding and few lithics, to more chaotic, rubbly areas containing very large lithics, including vesicular lava and much banded lava. Lava clasts are grey, pink or green in colour and some have a glassy texture. Average clast size of pumices is 2cm although clasts range from lapilli-size to large blocks up to 20cm in length. Some of these larger blocks are fragmented (implying that they may be volcanic bombs?). The unit also contains some scoria clasts or baked pumice clasts and in places contains ashy matrix. A number of small faults run through the unit, offsetting the contact with the overlying unit.

PBS1 – Pumice Based Scoria 1 – Residency Road – 571275E 9121380N

This is a unit of black scoria lapilli at least 5m in thickness. The deposit is massive, although a distinctive 20-25cm thick layer of grey trachytic pumice is seen at the base. Plutonic blocks can be found within the deposit. These are dense, mm to cm-size and generally white (probably granitic in composition). The unit has a number of faults running through it, which have displaced the basal contact by at least 1.5m.

PBS2 – Pumice Based Scoria 2 – Pyroclastic Plain – 569248E 9120400N

This is a unit of black scoria lapilli. Scoria clasts are black or brown and angular and the unit contains some lithic clasts as well as some plutonic (granitic) blocks. The unit varies in thickness but is 1.6m thick where sampled. A distinctive concentration of white-grey pumice is seen in the bottom 10cm of the unit. Two 5cm thick ash layers are seen, 10cm and 40cm from the top of the unit.

PBS3 – Pumice Based Scoria 3 – above NRLB4, NASA Road – 569550E 9121375N

This is a scoria lapilli deposit, which has a layer of pumice at the base, as seen at PBS1 and PBS2. The unit is ~1.8m thick where exposed and scoria clasts are black and generally cm-sized or smaller. The pumices at the base are coarser (cm to dm size) and are highly vesicular. The unit contains some small lithics and abundant white (granitic) plutonic blocks and becomes finer-grained and more stratified towards the top.

PC1 – Peak Cinders 1 – Mountain Road – 571160E 9121339N

This is a bedded lapilli deposit composed of scoria, lithics and ash layers. The deposit is lithic-rich overall but contains a number of discrete lithic-rich layers and lenses. Lithics range from mm to 6cm in size. A normal fault runs through the sampling area, which has moved at least 1m. Samples were taken from both sides of the fault. The base of the deposit (below the area sampled) is much more chaotic and contains numerous undulose layers of ash, lithics and scoria. Many of these layers are discontinuous and pinch out to form lenses. Some layers are composed solely of tightly packed, angular lithics and scoria, which show normal grading.

PF1 – Pumice Flow 1 – below I6 – 570490E 9120275N

Samples were taken from the middle of a poorly sorted, creamy-white pumice deposit which is ~3m in thickness altogether. The unit is lithic-rich and contains mm to dm-sized clasts of lava, ignimbrite and black scoria as well as some plutonic blocks. Average clasts size is 1-2cm but dm-sized boulders are abundant. Some clasts have a blackened, charred appearance, though this may be a product of weathering. Layers of coarser and finer material produce stratification at the base of the unit and some trains of coarser material can be seen. In other locations, this unit is seen to be erosional and contain rounded pumices. The unit also contains bomb sags and has a fine-grained basal layer containing cross-cutting lenses of gritty material.

PPA1 – Pyroclastic Plain Airfall 1 – above basal rhyolite – 569310E 9120415N

This is a thick (8m minimum) grey trachytic pumice unit. Pumice is angular and grain size is 'bimodal' containing populations of both cm-size and mm-size clasts. Some banded pumice is seen. The unit is rich in mm-size lithics but is less lithic-rich overall than the pumice units above (Pyroclastic Plain and NASA road). Lithic types include grey lava, banded pink/grey lava (rhyolite?) and some black, but little red scoria. Coarser, more lithic-rich layers are seen toward the base of the unit. Toward the top, more stratified lithic-rich layers are seen as well as ash-rich layers and some lenses of coarser pumice. The deposit is fines-rich and contains a number of degraded white clasts, which are likely to be weathered pumices.

PPBB1 – Pyroclastic Plain Brown Breccia – 569145E 9120468N

Samples were taken from a ~4m sequence of lapilli breccia and ash layers. Breccia beds are erosional brown scoriaceous lapilli containing pumice and some lithic clasts, and are mainly matrix supported. Ash beds are irregular and lensoid/channel shaped and up to 1m in thickness. Some ash beds contain small lithics. Samples were taken from two breccia interbeds, one thick ash bed and from a thicker breccia bed at the base of the main sequence (which is cross cut by the overlying beds).

PPBF1 – Pyroclastic Plain Brown Flow – roadside near Devils Riding School – 569025E 9120402N

This is a brown, medium to fine-grained pumiceous breccia with abundant lithics and scoria clasts. The unit is laterally variable, some areas being clast supported and some areas being matrix supported. Weak stratification can be seen, picked out by coarser pumice rich beds (which are generally lense-like and not laterally continuous) and finer grained lithic rich beds. The unit contains some flat clasts that are aligned with bedding.

PPF1 – Pyroclastic Plain Flow 1 – below lava breccia (above lower airfall) – 569310E 9120415N

This is a pinky-orange pumiceous flow deposit which grades upward into lava/lava breccia. The unit is ~1.5m at the thickest point although thickness is variable and the base of the unit is irregular. The unit contains clasts of grey-white trachyte lava and pseudo-pumice in an ashy matrix.

PPLB1 – Pyroclastic Plain Lava Breccia 1 – below PBS2 – 569248E 9120400N

This unit varies in texture from coherent lava to rubbly lava breccia. The unit is 2m thick (minimum) and the top 30cm is orange-brown and matrix-rich. This part of the unit contains large (up to 40cm in length) blocks of lava.

PPPF1 – Pyroclastic Plain Pumice Flow – 569100E 9120530N

This is a ~2.5m unit of pumice and lithics with varying amounts of matrix. Pumices are rounded, grey and trachytic and generally cm-size or smaller. The amount of lithics increases towards the base of the unit. The unit is laterally variable; a few m away, the top 75cm of the unit is very matrix rich and is pink in colour with vertical jointing features at the top (heat/soil?). As before the amount of lithics increases towards the bottom of the deposit but here grey pumice clasts have a yellow-white coating (weathering?) and some large (~20cm length) pink pumices can be seen. Some stratification can also be seen here, picked out by finer grained beds. The deposit is gritty and cross-stratified below 75cm from the top of the unit. Pumices were taken from this site in season two.

PPR1 – Pyroclastic Plain Rhyolite – below lower airfall – 569310E 9120415N

This is a rhyolite flow found below the pyroclastic sequence in Pyroclastic Plain. The unit is grey to white in colour and fine-grained and in places shows flow banding.

RF1 – Residency Flow 1 – underlying PBS1 – 571335E 9121400N

This is a 2m thick weathered flow deposit. The deposit is composed of fine, crystal rich, buff coloured ash although weathering gives the impression that it is composed of lapilli. The unit contains a few lithics, 50-60cm from the upper contact as well as some areas of flattened, degraded pumices, which produce some weak stratification. The contact with the overlying unit (PBS1) is uneven and here the unit has a red colour to it.

RL – Red Lion trachyte – above PB, Green Mountain – 571445E 9121185N

This is a complex deposit, which ranges laterally and vertically from a breccia deposit, to a coherent, lava-like deposit. The breccia is composed of grey-green lava (trachyte?) clasts in a pale white-pink ashy matrix. Boulders of banded lava (possibly rhyolite) are also seen, as well as abundant streaky fiamme-like lava clasts, giving some areas of the unit an eutaxitic-like texture. Basal parts of the unit consist of powdery, more unconsolidated material containing streaked out clasts. Within these areas, what looks like flow-fabric can be seen around a number of lava blocks. The unit grades upwards through more 'welded' material, to solid trachytic 'lava-like' material at the top. The unit is at least 20m thick and clasts range from mm-size to large blocks. The unit has a distinctive appearance where weathered, forming pod like areas of powdered white weathered material within a thin, hardened 'rind'. The weathered material sometimes contains individual clasts within it.

RP – Residency Pumice – entrance to Residency Road – 571200E 9121352N

This is a grey trachytic pumice deposit, 2-3m in thickness (minimum). The outcrop sampled is small (15m lateral extent). The deposit is lithic rich, with coarser lithics (lava, scoria and 'spatter') found at the base. Pumice and lithics show normal grading in most areas, although some reverse grading can also be seen

(possibly due to fluctuating energy of the eruption?). Around 1m from the base of the unit is a stratified pink ash layer which contains fine lithics. This ash layer has been deformed, in places, by the layer above.

RSP1 – Red Scoria Pumice 1 – valley W of Little Ascension Flow – 573150E 9122750N

This is a very thick (at least 12m) sequence of pumice units found at the base of a valley. The deposit is composed of pale grey to white pumice with abundant lithics. Clasts are rounded to sub-angular and mainly cm-size, with some dm blocks. Lithics types are variable; red and black scoria, grey-pink banded lava, plutonic blocks (dense, orange, crystal rich), green-grey obsidian and banded pale grey glassy lava are all present. Red scoria is very common. Clasts often have a coating of white hardened ash (matrix?) stuck to them. The number of large lithics and pumices increases upwards through the deposit. Large-scale bedding can be seen in these units. Some bedding can be seen in the deposits defined by layers of coarser and finer material.

S1 – Scoria 1 – underlying I1, Mountain Rd – 570995E 9121505N

This is a fine grained scoriaceous lapilli unit with a minimum thickness of 6m. The colour of the deposit ranges from dark blue-grey to orange where lapilli have weathered (and oxidised). The deposit contains few lithics and is well-sorted, with an average grain size of less than 1cm. Toward the top of the unit, some cm-scale stratification can be seen, however lower down the unit is more massive. Two (reverse) faults run through the exposure (where sampled) which have upthrown the deposit up by at least 3m.

SB1 – Streaky Bacon 1 – above SB2 – 570860E 9120740N

This is an exposure of partly welded (pumiceous) ignimbrite 15m in length and 3m in thickness. The deposit resembles an airfall in places and ranges in colour from yellow to grey. The unit contains angular pumices and is lithic-rich, containing some clasts of (possibly) ignimbrite. The major feature of this deposit is the presence of abundant, large blocks of blackened, semi-welded pumice. These blocks are up to 1m in length and are typically elongated and irregular in shape. These blocks generally lie along bedding in the deposit, which is weak.

SB2 – Streaky Bacon 2 – W of Green Mountain – 570810E 9120630N

This is the welded part of a thick sequence of pumice deposits south of Middletons Ridge. Where the unit is most densely welded, it is lithified and dark orange in colour with a black streaky eutaxitic texture. Where the unit is less welded or weathered, it is blocky and orange or pink coloured and appears to contain scoria, although this may in fact be baked pumice. In less welded areas it is possible to distinguish individual clasts from the pinky ash matrix. At other locations, the unit has the appearance of grey lava.

SB3 – Streaky Bacon 3 – S of Middleton's Ridge – 570490E 9120275N

This is part of a thick sequence of pumiceous deposits (Streaky Bacon formation) exposed in the valleys south of Middletons Ridge. Here ~3.5m of the sequence are exposed and four distinctly coloured units can be identified. SB3 is a massive orange deposit composed of coarse semi-welded pumice. The unit contains some streaky blackened pumice blocks and at the contact with the unit above, a block 1.15m in length is seen. The unit also contains abundant lithics, mainly of mafic lava. SB3 is overlain by a yellow pumice unit, which contains abundant welded blocks. The amount of streaky pumice blocks increases toward the top of this unit. Above this is a similar orange-grey pumice unit and underlying SB3 is a grey lava breccia unit (SB4).

SB4 – Streaky Bacon 4 – below SB3 – 570490E 9120275N

This massive grey unit lies beneath a 4m thick sequence of Streaky Bacon pumice deposits. The deposit is

similar to the semi-welded pumice units above, but is dominantly composed of dm-sized clasts of (what appears to be) grey and grey-pink banded lava. In places, clasts have become stretched out or the surrounding material has 'flowed' around clasts to produce a streaky (eutaxitic?) fabric. This streaky texture is especially prominent close to the contact with the overlying unit. In places, it is difficult to distinguish clasts from the surrounding matrix, which is hardened. It is possible that this is a more welded version of the units above.

SBA1 – Streaky Bacon Airfall 1 – below SB2 – 570810E 9120620N

This is a white-grey airfall deposit that lies below welded ignimbrite unit SB2. The contact with the unit above is not sharp, but the deposit grades from orange welded to semi-welded ignimbrite, down to grey-white blocky airfall. Samples were taken from the lower 3m of this deposit. Here, pumices are cm-size and some are white in colour and weathered. Banded pumices are also common and some fine white ash layers run through the deposit here.

SBA2 – Streaky Bacon Airfall 2 – above SB2, S of Middleton's Ridge – 571140E 9120800N

This is a grey-white coarse blocky pumice deposit located several metres above the welded ignimbrite (SB2) on a spur south of Middletons Ridge. Pumice clasts are up to 20cm long and range in colour from grey to white (more weathered clasts are white). The unit is lithic rich, containing dark grey and pink-red lava as well as obsidian and plutonic blocks. Some areas of the deposit are blackened (presumably from welding) and the unit is very hard (lithified) making it difficult to excavate clasts.

SF1 – Scoria Flow 1 – valley W of Little Ascension Flow – 573150E 9122750N

This is a coarse black scoria deposit, which is lithic-poor, but contains some dm-size lithics of grey and red (altered) lava. The deposit is matrix-poor and contains lenses of finer scoria and lithics. The unit is up to 3m in thickness and erosive and has cut down through upper units in the sequence. A fine-grained layer is seen at the base of the unit.

SP1 – Sandy Plain 1 – "White deposits" – 570910E 9123400N

These samples were taken from one of the upper layers of a large expanse of fine grained, flat-lying white deposits. These are well-bedded ashy deposits, 1cm to 70cm in thickness, which contain some interbeds of fine lithic grit. Most layers are homogeneous, but certain layers contain discontinuous trains of cm-size (or smaller) pumice clasts and in some cases, lithic clasts are concentrated at the top of the layer. Lithic content increases, overall, toward the top of the deposit, where a number of lithic-rich layers are found. Some layers within the deposit cross-cut lower layers and contain sedimentary-style structures. Some of the finely stratified upper layers display soft-sediment deformation or small-scale cross stratification and many of these upper layers pinch out or thicken laterally. In some areas, these deposits are overlain by a very coarse, poorly sorted breccia. In a number of cases, boulder-size clasts from this unit can be found embedded (to a depth of up to 1m) in the top of the white deposits. Where this coarse breccia is not found capping the deposits, upper layers display fine (mm-scale) stratification, giving the top of the unit a platy, sheet-like texture. Some of the stratigraphically lower layers within these deposits have a pink tint. Samples for this site were taken from a lithic-rich layer 1-2m from the (finely stratified) top of the deposits. Lithic types within this layer include mafic and felsic lava as well as ignimbrite. Little pumice is found.

TBA – Turtle's Back Airfall – S of Turtle's Back – 571395E 9123475N

This is a well-sorted grey pumice airfall that is 1.8m thick where exposed. Pumices are angular and up to 4cm in size and the unit also contains some lithics, which are generally <1cm in length. The main body of the unit is massive, but there are some stratified layers of finer pumice and ash at the top of the unit.

Interbedded with these stratified ashy layers is a layer containing coarser (cm-sized) lithics that has a concentration of pumice clasts at its top.

TBF1 – Turtle's Back Flow 1 – valleys N of Green Mountain – 571335E 9122945N

This is a pumiceous flow deposit ~ 80cm in thickness. The unit is matrix-supported but contains some cm-size (and some larger) lithics. The lower half of the unit is almost entirely composed of rounded pumice, though matrix content increases upwards. The upper 20cm of the unit is made up of brown-grey ash and sand with sparse mm-size lithics. This part of the deposit displays some undulatory bedding in places.

TBLB1 – Turtle's Back Lower Breccia – 571195E 9123395N

This is a buff-orange matrix supported pumiceous breccia. The unit is poorly sorted and lithic and scoria rich with distinct pumice rich bands. Clasts are up to 35cm in length. The upper 1m of the unit is clast rich whilst the lower part is mainly matrix with some weak cross stratification and some coarser lithic rich lenses. Where sampled the unit is more obviously stratified with much channel like cross stratification.

TBUB1 – Turtle's Back Upper Breccia – 571265E 9123525N

This is a matrix supported grey-buff coloured breccia with a slightly coarser matrix than that seen in unit TBLB1. The unit is poorly sorted and pumice and lithic rich, also containing some scoria, some clasts of a previous pumiceous deposit (white weathered pumice) and clasts of dark mafic lava. Lithics range from <1cm-20cm in length. The unit varies in thickness and is dominantly pumiceous in thicker areas. The unit is overlain by black scoriaceous lapilli and in places, the breccia has been 'squeezed' up into the overlying unit. These structures are probably gas or water escape structures. Four pumices were taken from this unit on the second visit.

THB1 – Travellers Hill Breccia – 568750E 9121445N

This is a roadside exposure of a brown matrix supported breccia. The unit is medium-poorly sorted with mm to 15cm-size clasts in a sandy matrix. Clasts of dark grey (mafic), light grey (silicic) and banded lava are seen as well as some scoria and some obsidian. Clasts are sub-angular to sub-rounded. The unit has a sharp top but an irregular shape, varying in thickness from 65cm to 145cm and cutting erosively into underlying breccia layers.

TV1 – Trachyte Volcanic Breccia – 573540E 9122560N

This is a poorly-sorted, rubbly white breccia. The deposit is mainly made up of trachyte blocks ranging from cm-size to 1.5m in length. Fresher clasts of trachyte are a pale blue-grey colour, but many clasts have weathered to a powdery white consistency and have altered rims. Some pink-brown mafic lava clasts are also seen. Clasts are set in a fine-grained white matrix. The deposit contains some obsidian and has a concentration of darker clasts at the base. This unit is variable in thickness and tends to thicken into dips.

There is a fine-grained layer beneath this unit (possibly a basal layer?). This layer is ~20cm thick and is a brownish stratified ash with some pumices, lithics and obsidian. Some dune-like structures can be seen in this unit.

UVA1 – Upper Valley Airfall 1 – valley W of Upper Valley Crater – 572527E 9122875N

This is an angular grey trachytic pumice airfall. The unit is lithic-rich, containing much banded lava. Pumices are generally cm-size, with some are dm-size. Many pumices are pink (alteration?) and some have fine-grained breccia in-fills. The unit is finer toward the top, above which lies a brown matrix-rich layer. Obsidian is not seen in the unit.

UVA2 – Upper Valley Airfall 2 – valley W of Upper Valley Crater – 572000E 9123280N

This is a bedded grey pumice airfall deposit that is ~3.5m in thickness. Pumices are angular and reach 23cm in length and some banded pumice is seen. The unit is lithic-rich (though not as lithic-rich as UVA3), containing mainly dark grey (mafic?) lava with some banded lava (trachyte?) and very little red scoria. A number of stratified ash beds overlie this unit.

UVA3 – Upper Valley Airfall 3 – unit 3, valley W of Upper Valley Crater – 572000E 9123250N

This is a bedded pumice airfall, with a minimum thickness of 5m. Pumice. The unit is lithic rich and contains abundant red scoria as well as black scoria, mafic lava, plutonic blocks and green-grey crystal-rich lava. Obsidian does not appear to be present. Pumice clasts are angular, grey-white in colour, and typically cm-size, though a number of dm-size clasts are seen. A yellow tinged layer can be seen toward the bottom of the exposure.

UVB1 – Upper Valley Crater Breccia – valley W of Upper Valley Crater – 572005E 9123195N

This is a coarse breccia deposit found in the bottom of a gully. The deposit consists of a medium-fine grained basal unit which is matrix supported (grey-brown fine grained matrix). It is poorly sorted with sub-angular to sub-rounded mainly lithic clasts of mafic and felsic lava, ignimbrite but little pumice. Clasts range from <1cm to up to 50cm blocks. Overlying this is a very coarse breccia unit, which is very poorly-sorted and contains blocks up to 1m in diameter. Large blocks are rounded. Coarser areas are more clast supported but overall the unit is matrix supported. The unit is at least 2m thick overall.

Appendix B

EXPERIMENTAL TECHNIQUES AND EQUIPMENT

Over 750 samples were taken for palaeomagnetic analysis on Ascension Island and over 40 samples for geochemical analysis. Palaeomagnetic analysis involved partial thermal demagnetisation, remanence measurement and bulk and temperature-dependent susceptibility measurement (high-T χ) of samples in the laboratory at Oxford. Geochemical analysis involved the determination of major and trace elemental compositions using x-ray fractionation (XRF) at the Open University, Milton Keynes.

B.1 PALAEOMAGNETIC ANALYSIS

B.1.1 Sampling technique

The typically unconsolidated nature of the pyroclastic rocks on Ascension (and at Ruapehu) precluded the need to drill samples for palaeomagnetic analysis. Instead, discreet clasts or blocks were taken from each sampling site (see McClelland & Druitt, 1989 for a more detailed description of this sampling technique). Before sampling, each site was located and recorded on a map and a lithological description made. Samples were then oriented by marking strike and dip on to a flat surface of the clast, or onto a 1cm² perspex plate, attached to the clast using epoxy resin. Where appropriate, the stratigraphic height of the clast within the unit was recorded, along with the overall unit thickness at that point (to allow for effects of thermal overprinting by stratigraphically higher units). Clasts were then removed and stored in sample bags. Where the aim of the sampling was to provide an emplacement temperature, between eight and fourteen samples were taken. Where possible, both lithic and pumice clasts were sampled. Where the site was sampled for magnetostratigraphic purposes, between four and eight samples

the site was sampled for magnetostratigraphic purposes, between four and eight samples were taken, generally of juvenile material (pumice or scoria). The number and size of clasts taken from each site was dependent on the grain size and freshness of the deposit. Clasts ranged from a few mm to around 15cm in size.

B.1.2 Sample preparation

Once in the laboratory, samples were set in plaster, with the perspex plate (or flat surface) set horizontal. Orientation marks (dip lines) were transferred from the plate to the rest of the exposed surface of the sample and cores of either 1 inch or $\frac{3}{4}$ inch diameter were then drilled, depending on the size of the sample. This was carried out using a bench drill at the Institute of Hydrology, Wallingford. Where possible, more than one core was taken to allow measurements to be repeated. Cores were trimmed to one-inch length (using a double-bladed saw) to remove any weathered outer surfaces. Orientation marks were then painted on to each core in white ink. The figure below shows the orientation conventions used for measurement in the laboratory at Oxford.

B.1.3 Equipment

Two different furnaces were used for thermal demagnetisation in the laboratory at Oxford. Samples were typically heated in increments of 50°C, to a maximum temperature of 650°C, or until the intensity of the sample was less than 5% of its original value. In some cases, where samples were analysed for magnetostratigraphic purposes, temperature steps were as large as 100° C (in these cases analysis was carried out to yield polarity data only). Remanence was measured after each heating step, on one of 3 magnetometers (depending on sample strength and size). Bulk susceptibility was also measured after each step on either the Molspin or Kappabridge equipment. This was carried out in order to ascertain whether alteration had occurred in samples (as a result of heating). Alteration was inferred to have occurred if the value of susceptibility changed by more than 10%. Between measurements, samples were kept in μ -metal boxes (which have an internal field of < 50 nT), to prevent acquisition of secondary magnetisation arising from magnetising fields in the laboratory. The area around the mouth of each furnace, as well as around the Cryogenic and Molspin magnetometers, was surrounded by Helmholtz coils, which reduce the magnetic field in these areas (where samples could otherwise pick up a secondary magnetisation).

B.1.3.1 Furnaces

The majority of thermal demagnetisation was carried out using the Shaw MMTD Furnace (*Magnetic Measurements Thermal Demagnetiser*). This is a horizontal furnace (constructed by Magnetic Measurements Ltd), which has a residual field of <10 nT (internal field strength was checked regularly using a fluxgate magnetometer). The furnace is able to

accommodate 18 samples (1 inch cores or smaller), which are slid into the centre of the furnace on a tray. The desired heating rates and hold times (the length of time samples are held at a particular temperature, e.g. peak temperature) are programmed into the furnace and the subsequent heating and cooling cycle is fully automated. Complications are encountered when using this furnace, however, due to the existence of an internal thermal gradient. This means that at high temperatures, actual temperature may exceed the set temperature in certain parts of the furnace. Calibration of the furnace was therefore carried out (by Patrick Erwin & Brian Daniels) and this allowed an accurate temperature estimate to be made for each sample position within the furnace at a particular temperature.

Thermal demagnetisation was also carried out using the *Vertical Thermal Demagnetiser*. This furnace has a residual field of <5 nT and was constructed by the Department of Earth Sciences at Leeds University. The furnace is able to hold up to 30 samples (depending on diameter), which are arranged on four shelves. A thermocouple is positioned on each shelf (three within dummy samples and one exposed), and this allows accurate temperature measurements to be made for each shelf, throughout the heating cycle. Temperature increase is recorded on a chart, connected to the furnace. This allows the user to determine when thermal equilibrium has been reached at peak temperature. A number of parameters may be set for a particular heating cycle, including heating rate, the rate of change of temperature as set temperature is approached and external power limit. Although this furnace allows more accurate temperature measurements to be made, it was not functioning for much of the duration of the experimental work and hence the majority of demagnetisation was carried out using the MMTD.

B.1.3.2 Magnetometers

Strongly magnetic samples (i.e. those over around 100 mA/m in intensity) were typically measured on either the *Molspin* or *Geofisica Buno JR5A spinner magnetometer*. In this type of magnetometer, a magnetized sample is rotated within a coil or fluxgate system. Rotation of the sample generates an oscillating voltage proportional to the strength of the magnetic moment perpendicular to the rotation axis. The phase of the signal produced relates to the direction of magnetism, according to a reference direction on the sample holder. The total vector component of magnetism is determined by measuring the sample in 6 orientations (in each of which, any 2 of the X, Y or Z directions are perpendicular to the spin axis). This yields two values each for $\pm X$, $\pm Y$ and $\pm Z$ and produces an averaged value of NRM. In the case of the *Molspin* magnetometer, the sample is oriented manually before each spin. With the *JR5A*, the entire measurement process is computer controlled.

Weaker samples were measured on the *Cryogenic* or SQUID (Super Conducting Quantum Interface Device) magnetometer, constructed by Cryogenic Consultants Ltd (CCL). Effectively, this magnetometer works on the principle that the introduction of a

magnetized sample into the magnetometer chamber generates an electric current, which unbalances the system. The amount by which the system has to compensate to re-balance the system is proportional to the magnetic intensity of the sample. The cryogenic magnetometer contains two superconducting rings (SQUIDs), which are cooled by an inner reservoir of liquid helium and outer collar of liquid nitrogen. The presence of two SQUIDs allows both the axial and radial components of magnetism to be measured at the same time. The SQUIDs are connected to a superconducting pick-up coil system, into which the sample is introduced. Introduction of a magnetized sample into the SQUID system alters the magnetic field along the ring axis such that a circulating current is generated which is sufficient to suppress the superconducting property of the ring. A positive feedback system is then set up, as the ring becomes resistive, causing the current to decrease, and eventually the superconducting state is regained. The change in current that is needed to allow superconductivity to be regained is a measure of the intensity of the sample. SQUIDs are able to measure exceedingly small changes in current and thus are much more sensitive than the spinner magnetometers. The Oxford CCL magnetometer is able to measure samples of approximately 10^{-3} mA/m or less. Each sample is measured in eight orientations (achieved by manual rotation of the sample holder).

For each of the magnetometers described here, the direction and intensity of remanence of the sample is calculated automatically by computer. The way in which these data can be represented is discussed in Appendix C. Further details of both spinner and cryogenic magnetometers can be found in a number of texts on palaeomagnetism, for example Collinson, 1983.

B.1.3.3 Bulk susceptibility

Bulk susceptibility was measured for each sample, after each magnetic measurement using either the *Molspin*, or the *Geofisica Buno KLY-2 Kappabridge* bulk susceptibility equipment. These essentially comprise a long coil (a transformer), which is supplied with a voltage from a generator. The output from this transformer consists of two voltages of equal but opposite phase, which are carried by two connected measuring coils - a pick-up coil and a similarly designed balancing coil. These coils are both connected (at the non-transformer end) to an output point. Introduction of the sample into the pick-up coil unbalances the system by an amount proportional to the bulk susceptibility of the sample. The signal of unbalance is then processed at the output point (and a compensating signal is sent back to maintain the balance of the bridge circuit). As with the magnetometers, values for bulk susceptibility values were calculated automatically.

B.1.3.4 Temperature-dependent susceptibility (high-T χ)

The temperature dependence of low-field susceptibility was measured for a number of

samples to provide information on their magnetic mineralogies. The CS-2 furnace apparatus was used in conjunction with the KLY-2 *Kappabridge* for this purpose. In this procedure, approximately 0.25 cm³ of powdered sample is placed in a glass sample tube (this amount fills the bottom ~ 2cm of the sample tube, where temperature and magnetic field conditions should be homogeneous). A Pt-PtRh thermocouple is put into the tube, in the centre of the powdered sample (to ensure contact with the maximum volume of sample) and this thermocouple connected to a reference thermocouple held at 0°C. The sample tube is then inserted into the furnace and the desired parameters are set (e.g. maximum and minimum temperature, heating and cooling rate and sample volume) using the attached computer. The subsequent heating and measurement process is fully automated, with the furnace being automatically moved into (and out of) the KLY-2 pick-up unit for each measurement. Data is stored on the computer (in tabular form) and a graph of temperature versus susceptibility is automatically produced. At periodic intervals, a 'dummy' run is carried out using an empty sample tube to allow background measurements to be made. Corrected values for susceptibility can then be produced by applying these background measurements to the recorded data, using the 'CUREVAL' program. Re-calibration is necessary if the thermocouple is changed, and this is carried out using calibration beads (of nickel and magnetite) with known Curie temperatures.

B.2 GEOCHEMICAL ANALYSIS

Whole rock major and trace element analyses were carried out by Peter Webb and John Watson at the Open University. Data from these analyses are shown in Appendix E.

B.2.1 Sampling technique

Over 40 individual units on Ascension Island were sampled for geochemical analysis. Material was preferentially sampled in the form of discrete clasts or blocks and placed in sample bags. Care was taken to sample the freshest material possible, and to avoid areas where obvious alteration or disruption (i.e. faulting) had taken place.

B.2.2 Sample preparation

The outer surfaces of each block sample were removed (using a rock saw) and any weathered material discarded. Each sample was then washed thoroughly in distilled water to remove any traces of water or material picked up during sawing (which could contaminate samples), and dried overnight. Samples were crushed to a fine powder using a ball-mill and placed in sample bags. Subsequent preparation was carried out at the Open University. Firstly, powdered samples were dried, overnight, at 110° C to remove moisture (which is influenced by recent storage conditions and hence is an undesirable variable). For trace element analysis, 35mm diameter pellets were made by

mixing approximately 10g of powdered sample with 0.7-1.0 ml of methyl cellulose binder and pressing in a mould (at 7-9 ton in⁻²) to a thickness of 3.5 mm. Pellets were dried overnight in an oven at 110° C. For major element analysis, glass discs of 36mm diameter were made from a mixture of powdered sample and lithium tetraborate flux. Exact quantities of each (1 part powder to 5 parts flux) were fused together, by heating to 1100° C for 15-20 minutes. Swirling the melt regularly ensured that it was mixed thoroughly and that gas bubbles were removed. The melt was then poured into a brass mould and pressed into a disc. Care was taken not to touch the discs after formation as this can have the effect of increasing the apparent sodium content of the sample by as much as 0.5% Na₂O absolute. Lastly, loss on ignition was determined for each sample used for major element analysis. This involved igniting a given amount of powder at 1000° C for 1 hour and recording the percentage weight loss. This is essential for major element analysis as it accounts for the main volatile constituents (e.g. H₂O, CO₂) that cannot be measured directly by XRF (and are lost on fusion).

B.2.3 Equipment

Major and trace element analyses were carried out using an ARL 8420+ dual goniometer wavelength dispersive X-ray fluorescence (XRF) spectrometer. The spectrometer is equipped with a 3kW Rh anode end-window X-ray tube and uses AX06 (multiplayer), PET (penta-erythritol), Ge111, LiF200 and LiF220 analysing crystals.

Elemental intensities were corrected for background and known peak overlap interferences and major and trace element analyses were corrected using analytical packages at the O.U. The XRF was calibrated using reference materials with a wide range of silicate compositions and major and trace element data quality were assessed using monitor samples.

Major element oxide totals may be affected by a number of factors including contamination of glass beads, insufficient mixing of rock powder and flux, or excessive heating, however all totals fell within the range 99–100.8% and were consequently considered acceptable. A detailed account of the errors associated with XRF analysis may be found in Potts (1987).

Appendix C

REPRESENTATION OF PALAEOMAGNETIC DATA AND STATISTICAL ANALYSIS

C.1 Representation of data

The initial remanence of a sample (NRM) can be defined by a vector whose length is proportional to the intensity of the magnetisation. During progressive thermal demagnetisation (PTD), the remanence vector (i.e. the intensity and direction of magnetisation) changes, describing a path in three-dimensional space, from the initial NRM value (the end-point of the vector path), via a series of points determined by the PTD steps, to the point at which the sample is fully demagnetised (the origin of the *z*-plot). Such data are typically viewed on orthogonal vector component plots or *Zijderveld plots* (Zijderveld, 1969), which combine the 3-D declination and inclination information (projected onto the horizontal and vertical planes respectively) into one single 2-D diagram (Figure C.1).

Vector directions can also be viewed on a stereoplot. For single-component samples, no change in direction is observed with demagnetisation (only in intensity) and hence directions after each PTD step plot in the same position. However, in multi-component samples, a path between the low temperature component direction and the high-temperature component is described on the stereoplot during demagnetisation. Stereoplots can also be used to display directional data for multiple clasts from the same sampling site.

Data from PTD can also be displayed in the form of unblocking temperature spectra, which show percentage intensity versus temperature. The temperature by which the sample is fully demagnetised (maximum unblocking temperature) provides an

approximation of the Curie temperature for the sample's magnetic minerals.

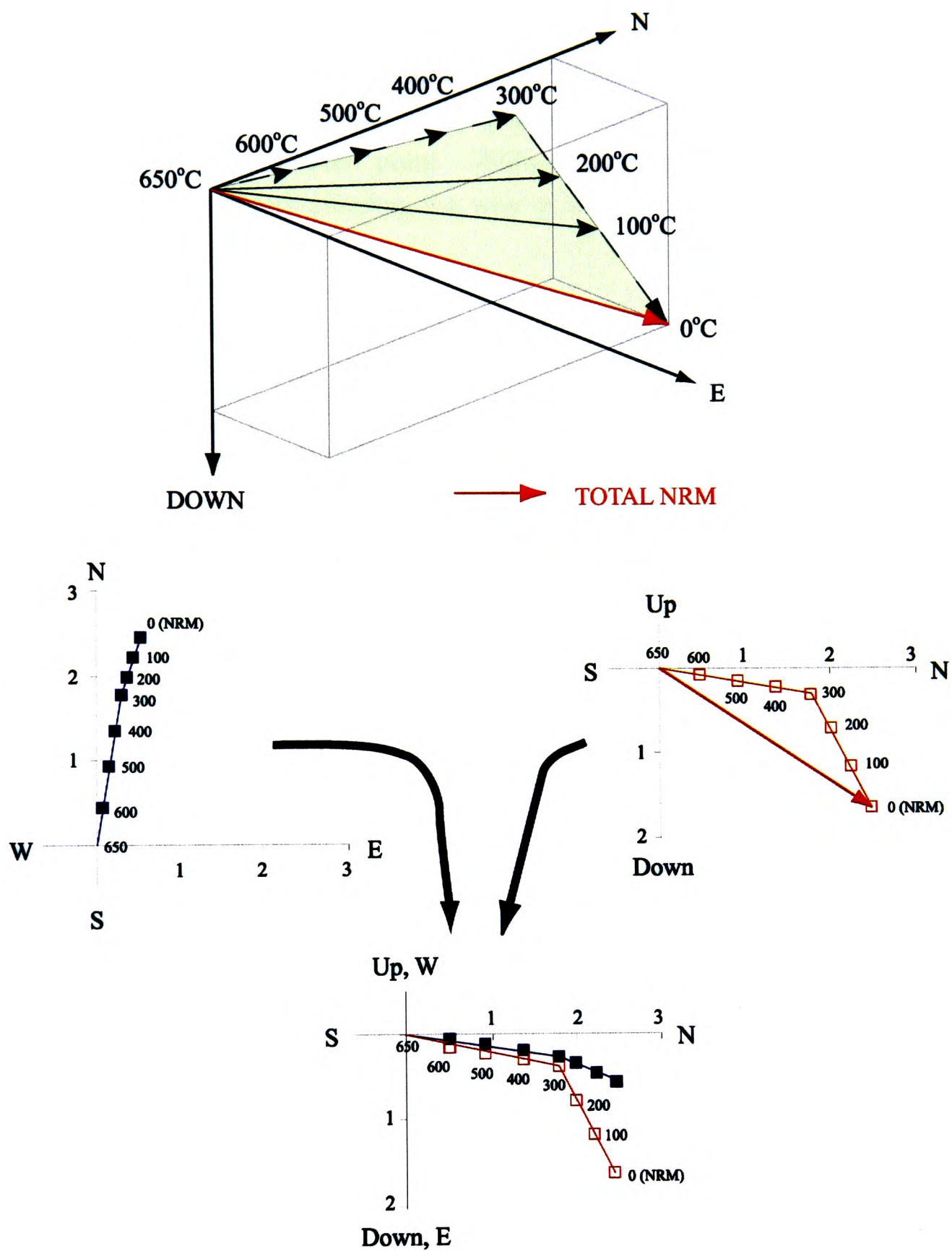


Figure C.1: Schematic diagram showing the way in which 3D vector demagnetisation data are displayed on a 2D Zijderveld diagram (after Butler, 1992). Here a two-component remanence (e.g. TRM + pTRM) is being demagnetised, with the low-T component (pTRM) demagnetised between 0°C (NRM) and 300°C and the high-T component (TRM) between 300°C and 650°C (by which temperature the sample is completely demagnetised). The direction and intensity (length) of the NRM vector shifts with each demagnetisation step until the low-T component is removed. As the high-T component is then removed, intensity continues to decrease (but direction remains the same) until the sample is fully demagnetised. This path of demagnetisation can be tracked by recording the end point of the NRM vector after each demagnetisation step on the N-E-S-W and up-N-down-S planes (b and c). These plots are then combined to form a Zijderveld plot (d).

C.2 Statistical analysis

In this study, palaeomagnetic data were analysed using the Super IAPD program of Torsvik et al. For each sample, the principal components of magnetism were determined in Super IAPD using the principal component analysis (PCA) routine of Kirschvink (1980), or the LINEFIND algorithm of Kent et al. (1983), which identifies and fits a line through sequences of co-linear and co-planar points in a sequence of 3D data, assigning a weight (its error variance) to each point. Within the program, the treatment of error variances, and the parameters affecting the way in which lines and planes are fit by the algorithm may be adjusted.

In many cases, the start and end points of lines were set manually using PCA, to account for instances where components display curved trajectories or data is excessively noisy, and for the tendency of the LINEFIND program to fit longer lines (where a long and a short line intersect, points on the shorter line may be allocated to the longer line, if they are close enough to be considered co-linear with points of the long line).

C.2.1 Fisher statistics

The mean direction (declination and inclination) for a particular population of samples, N (e.g. low-temperature components for samples from the same unit), can be calculated by vector addition (Butler, 1992). *Fisher statistics* (Fisher, 1953) can be used to provide: a) a measure of the amount of scatter of the directions around the mean direction and b) a confidence limit for the calculated mean direction (i.e. a measure of the precision with which the mean direction has been estimated), according to the *Fisher distribution*. The Fisher distribution is a probability density function (derived by Fisher, 1953) that considers magnetic vectors as points on a sphere, and gives the probability per unit angular area of finding a direction within an angular area surrounding the true mean (Butler, 1992). The amount of scatter of a population of directions around the mean direction is given by *precision parameter*, κ . The best estimate of this value, k , can be calculated by:

$$k = \frac{N-1}{N-R}$$

where R is the resultant vector (from vector addition). The confidence limit for the mean direction is expressed as an angular radius from the mean direction and at the 95% confidence level, α_{95} , is given as:

$$\alpha_{95} = \cos^{-1} \left\{ 1 - \frac{N-R}{R} \left[\left(20^{\frac{1}{N-1}} \right) - 1 \right] \right\}$$

C.2.2 Tests of randomness of magnetic directions

Directions of low-temperature components from hot deposits are expected to be closely grouped and to approximate the expected geocentric axial dipole mean direction for the sampling locality. It is therefore necessary to be able to test the randomness of such a population of directions. Rayleigh (1919) and Watson (1956) have derived tests to ascertain whether a population of directions, N , can be considered as random or non-random. These *significance tests* provide for each value of N , values of R (the resultant vector) that will be exceeded on the hypothesis of randomness, with a specified probability (Watson, 1956). If the observed value of R exceeds the specified value, R_0 , the null-hypothesis of randomness is rejected, whereas if R is less than R_0 , the null-hypothesis is not disproved. Rayleigh (1919) provides an approximation for the significance test whereby the null-hypothesis of randomness is not disproved (i.e. that population of directions can be regarded as random) if the value of $3R^2/N$ for that population exceeds 7.81. Watson (1956) provides a table of exact values of R_0 for values of N from 5 to 20, at 1% and 5% significance points and states that for values of N between 20 and 100, Rayleigh's approximation (1919) is 0.04 above the true value. However, in this study, values of N typically lie between 3 and 15 and hence Rayleigh's approximation (1919) is valid.

Appendix D

PALAEOMAGNETIC DATA

This appendix contains palaeomagnetic data for each unit sampled on Ascension Island for palaeomagnetic analysis.

Table D.1 (overleaf) shows Fisher statistics and mean directions for the principal components of magnetism determined for each unit, using LINEFIND (Kent et. al, 1983) or PCA (Kirschvink, 1980) within the Super-IAPD 99 program by Torsvik et al.

Table D.2 lists average emplacement temperatures (T_e s) for those sites for which T_e could be calculated. The average emplacement temperature is best approximated to the lowest value of clast T_e within the deposit (McClelland & Druitt, 1989).

Table D.1: Mean directions and Fisherian statistics for the principal components of magnetism calculated for each site sampled on Ascension for palaeomagnetic analysis. D = declination, I = inclination, N = number of clasts, R = the vector resultant of N vectors, k = the best estimate of the precision parameter, κ , α_{95} = the 95% confidence limit, and $3R^2/N$ is a measure of grouping whereby directions of a population of N samples are considered to be non-random ('grouped') if the value of $3R^2/N$ for that population is greater than 7.81.

BILL	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	47.3	-2.9	5	4.82	22.42	16.5	13.94
high-T	16.3	-13.0	5	4.94	67.84	9.4	14.64

BPB	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	339.2	-41.4	14	13.11	14.63	10.8	36.83
high-T	330.7	-38.6	11	3.45	1.32	76.4	3.25

BX1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ¹	353.0	-24.0	5	4.77	17.55	18.8	13.65
low-T ²	11.5	-41.6	10	4.37	1.60	60.5	5.73
med-T	75.2	-56.5	10	2.41	1.19	104.0	1.74
high-T	342.1	-29.2	5	2.48	1.58	97.9	3.69

CGB1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ¹	359.1	-21.3	6	5.21	6.29	29.0	13.57
low-T ²	1.2	-18.5	7	4.25	2.18	54.6	7.74
low-T ^j	9.5	-49.7	3	2.91	22.04	26.9	8.47
high-T	273.9	46.7	7	0.70	0.95	180.0	0.21

CVS1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ¹	357.5	-21.1	5	4.70	13.18	21.9	13.25
low-T ²	67.5	1.7	9	2.51	1.23	100.1	2.10

CVS2	D	I	N	R	k	α_{95}	$3R^2/N$
VRM	336.5	-13.0	3	2.94	35.25	21.1	8.64
low-T	323.3	-3.5	7	6.38	9.67	20.4	17.44
high-T	342.9	63.0	7	2.01	1.20	127.4	1.73

DAVE	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	17.5	-11.1	5	4.95	82.68	8.5	14.70

DRA1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	348.8	-22.2	8	7.30	9.98	18.4	19.98

DRS1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	346.4	25.9	10	3.14	1.31	81.9	2.96
med-T	245.5	58.3	3	1.84	1.72	180.0	3.39
high-T	269.6	63.9	8	1.57	1.09	180.0	0.92

EB1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	8.3	-9.1	12	7.81	2.62	33.7	15.25
high-T	322.2	-0.8	8	1.10	1.65	180.0	0.45

EFB1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	9.9	-0.1	14	4.68	1.40	61.0	4.69
high-T	332.2	-33.9	11	4.94	1.65	55.1	6.66

EFFB1	D	I	N	R	k	α_{95}	$3R^2/N$
VRM	355.3	-3.5	6	5.79	23.54	14.1	16.76
low-T	3.4	-26.9	10	9.90	91.93	5.1	29.40
high-T	92.4	-6.1	3	2.00	2.00	137.0	4.00

EFP1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	91.9	-53.4	8	4.37	1.93	56.2	7.16
low-T ^j	16.7	-37.8	4	3.83	17.92	22.3	11.00
high-T	90.0	47.8	5	1.39	1.11	180.0	1.16

EFS1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	344.4	-23.0	18	17.50	33.68	6.0	51.04
high-T	196.4	-61.6	13	3.21	1.23	82.2	2.38

EFS2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	1.7	-21.1	10	9.18	10.95	15.3	25.28
high-T	21.2	24.4	4	1.61	1.26	180.0	1.94

GEOFF	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	338.5	-31.3	4	3.99	225.60	6.1	11.94

GMI1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	6.1	-13.7	5	4.97	156.15	6.1	14.82

GMP1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	16.3	-18.8	4	3.76	12.60	26.9	10.60
low-T ^{L+j}	8.8	-17.5	8	7.43	12.33	16.4	20.70
high-T	155.0	-55.5	3	1.00	1.00	180.0	1.00

GMP2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	10.9	-25.1	3	2.98	99.58	12.4	8.88

I1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	0.9	-24.0	6	5.75	20.24	15.3	16.53

I2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	335.3	-19.5	3	2.82	10.91	39.3	7.95

I3	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	347.5	-21.6	2	1.99	175.34	19.0	5.94

I4	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	359.6	-24.0	6	5.18	6.11	29.5	13.42
high-T	7.9	-15.4	4	3.73	11.25	28.7	10.43

I5	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	345.2	-19.6	8	7.70	23.29	11.7	22.23

I6	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	14.5	-32.5	4	3.82	16.55	23.3	10.94

LA1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	349.7	-23.8	8	7.87	52.60	7.7	23.23
high-T	24.7	-16.7	4	2.05	1.54	128.6	3.15

LA2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	358.7	-13.6	7	6.78	27.12	11.8	19.70
high-T	319.2	-8.1	6	3.38	1.91	68.6	5.71

LF1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	9.4	-24.0	8	7.96	180.39	4.1	23.76
high-T	16.0	-23.9	6	5.58	11.98	20.2	15.57

LF2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	3.5	-28.0	10	9.21	11.41	14.9	25.45
high-T	321.2	-5.1	6	2.19	1.31	115.6	2.40

MRBB1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	313.5	-44.6	9	2.78	1.29	90.8	2.58
high-T	135.2	-4.3	8	4.44	1.97	55.2	7.39

MRGB1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	161.8	11.8	10	7.97	4.44	25.9	19.06
high-T	241.3	-47.6	7	1.25	1.04	180.0	0.67

MRGB2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	190.5	10.4	7	6.87	45.60	9.0	20.23
low-T ^{L+J}	189.4	8.3	10	9.75	35.61	8.2	28.52
high-T	36.8	-26.6	7	1.17	1.03	180.0	0.59

MRH1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	47.9	-28.7	12	3.28	1.26	80.4	2.69
high-T	127.0	-48.8	10	2.12	1.14	117.9	1.35

MRP1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	358.0	-15.6	4	3.80	15.37	24.2	10.83

MRP2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	29.9	-35.5	3	2.70	6.66	52.1	7.29

MRP3	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	7.8	-15.5	2	1.80	4.96	180.0	4.86

MRT1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	183.0	22.3	4	3.79	14.06	25.4	10.77

MVA1	D	I	N	R	k	α_{95}	$3R^2/N$
NO COMPONENTS RESOLVABLE							

MVA2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	215.1	-33.0	4	1.03	1.01	180.0	0.80
low T ^J	0.9	-11.0	3	2.95	38.09	20.3	8.70
high-T ^J	180.7	43.0	3	2.88	16.24	31.6	8.29

MVF1	D	I	N	R	k	α_{95}	$3R^2/N$
VRM	351.2	-1.9	3	2.48	3.82	74.5	6.15
low-T ¹	198.1	47.3	3	2.94	33.30	21.7	8.64
low-T ²	191.7	12.3	5	3.53	2.72	57.7	7.48

MVF2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	165.4	-4.9	4	2.48	1.98	92.7	4.61

MVLBI	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	180.0	23.6	7	6.92	76.27	7.0	20.52

MVS1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	175.5	27.7	3	2.82	11.23	38.7	7.95
low-T ^{L+J}	183.7	31.0	7	6.75	24.41	12.5	19.53

MVS2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	190.2	6.4	5	4.97	127.09	6.8	14.82

NEB	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	340.5	-41.4	8	7.95	129.91	4.9	23.70
high-T	338.8	-47.2	4	2.09	1.57	124.1	3.28

NELL	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^C	299.8	-61.7	8	5.30	2.59	43.3	10.53
high-T ^T	344.8	-21.2	8	7.96	158.91	4.4	23.76

NEP	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	331.0	-6.7	3	2.94	31.60	22.3	8.64
low-T ^{L+J}	340.6	-18.7	7	6.63	16.34	15.4	18.84
high-T	339.1	-14.0	4	1.66	1.28	180.0	2.07

NRA1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	349.7	-22.8	4	3.98	177.63	6.9	11.88

NRA2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	353.0	-29.3	3	2.93	26.68	24.4	8.58

NRF1	D	I	N	R	k	α_{95}	$3R^2/N$
CRM	312.9	-2.1	4	3.83	17.38	22.7	11.00
low-T	174.5	42.9	4	3.78	13.61	25.8	10.72
high-T	141.2	30.8	3	0.67	0.86	180.0	0.45

NRF2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	184.5	28.3	5	4.98	196.40	5.5	14.88

NRF3	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	359.9	-16.4	4	3.88	25.39	18.6	11.29
med-T	33.1	-11.3	4	2.89	2.71	69.8	6.26
high-T	88.4	-8.9	3	1.89	1.80	180.0	3.57

PBS2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	7.9	-22.8	5	4.71	13.78	21.4	13.31
low-T ^{L+J}	357.9	-22.2	11	10.44	17.78	11.1	29.73
high-T	326.9	6.0	4	2.80	2.50	74.5	5.88

| | | | | | | | |

NRGP1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	286.9	16.9	9	2.19	1.17	114.5	1.60
low-T ^{L+J}	292.4	-10.8	14	3.64	1.26	74.8	2.84
high-T ^L	138.6	-34.2	6	0.33	0.88	180.0	0.05
high-T ^{L+J}	199.4	-42.1	8	0.26	0.90	180.0	0.03

PBS3	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	350.4	-15.1	4	3.92	36.68	15.4	11.52
low-T ^{L+J}	358.0	-19.4	8	7.64	19.46	12.9	21.89
high-T	29.7	-58.7	4	1.25	1.09	180.0	1.17

| | | | | | | | |

NRLB1	D	I	N	R	k	α_{95}	$3R^2/N$
VRM	350.6	-18.9	8	6.44	4.49	29.5	15.55
low-T	174.2	20.1	9	8.83	48.23	7.5	25.99

PC1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	7.9	0.0	7	5.21	3.35	39.0	11.63
low-T ^{L+J}	8.0	-3.8	9	7.03	4.06	29.2	16.47
high-T	159.0	34.1	6	1.47	1.10	180.0	1.08

| | | | | | | | |

NRLB2	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	5.3	-23.5	7	6.97	239.84	3.9	20.82

PF1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	359.2	-14.3	4	3.91	31.70	16.6	11.47
low-T ^{L+J}	351.9	-23.1	8	7.67	21.34	12.3	22.06
high-T	94.2	-38.4	4	1.57	1.23	180.0	1.85

| | | | | | | | |

NRLB3	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	166.6	21.3	8	7.86	49.94	7.9	23.17

PPA1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	318.3	-35.4	2	1.86	7.00	117.5	5.19

| | | | | | | | |

NRLB4	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	2.1	-25.0	4	3.98	120.60	8.4	11.88

PPBB1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	347.9	-6.2	9	7.59	5.67	23.7	19.20
high-T	315.1	-38.2	7	1.01	1.00	180.0	0.44

| | | | | | | | |

NRPF1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	12.0	-9.4	9	8.08	8.74	18.5	21.76
low-T ^J	339.4	-25.3	4	3.94	52.26	12.8	11.64
high-T	112.8	24.3	9	3.43	1.41	76.8	3.92

PPBF1	D	I	N	R	k	α_{95}	$3R^2/N$
VRM	11.9	-11.3	4	3.69	9.63	31.2	10.21
low-T	89.6	23.4	6	4.22	2.80	49.3	8.90
high-T	171.7	53.6	2	1.45	1.81	180.0	3.15

| | | | | | | | |

NRS1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^L	341.2	-32.0	4	3.53	6.37	39.6	9.35
low-T ^{L+J}	344.3	-30.7	6	5.45	9.04	23.6	14.85
high-T	82.7	-50.5	4	1.78	1.35	180.0	2.38

PPF1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T ^{CT}	355.7	-16.5	5	4.98	223.22	5.1	14.88
high-T	357.5	-27.1	6	5.89	44.54	10.1	17.35

| | | | | | | | |

P1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	354.3	-28.4	3	2.66	5.93	55.9	7.08

PPLB1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	10.1	-20.5	4	3.94	47.20	13.5	11.64

| | | | | | | | |

PA1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	338.8	-27.4	5	4.84	25.12	15.6	14.06

PPPF1	D	I	N	R	k	α_{95}	$3R^2/N$
VRM	11.9	-11.3	4	3.69	9.63	31.2	10.21
low-T	89.6	23.4	6	4.22	2.80	49.3	8.90

| | | | | | | | |

PB	D	I	N	R	k	α_{95}	$3R^2/N$
VRM	30.6	1.0	9	7.75	6.42	22.0	20.02
low-T	360.0	-22.0	10	9.93	121.94	4.4	29.58

PPR	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	160.1	-2.7	5	4.95	84.60	8.4	14.70

| | | | | | | | |

PBS1	D	I	N	R	k	α_{95}	$3R^2/N$
low T ^L	3.0	-20.8	5	3.99	3.97	44.0	9.55
low-T ^J	356.7	-11.5	3	3.00	408.96	6.1	9.00
low T ^{L+J}	0.3	-16.8	8	6.96	6.70	23.1	18.17
high-T	41.9	16.5	5	2.37	1.52	103.5	3.37

RF1	D	I	N	R	k	α_{95}	$3R^2/N$
low-T	354.0	-7.5	5	4.63	10.68	24.5	12.86
high-T	223.5	8.7	5	1.42	1.12	180.0	1.21

RL	D	I	N	R	k	α95	3R ² /N
low-T	8.6	-11.2	4	3.69	9.78	31.0	10.21

RP	D	I	N	R	k	α95	3R ² /N
low-T ^L	34.8	2.4	11	3.97	1.42	67.6	4.30
low-T ^{L+J}	21.6	-2.4	15	7.43	1.85	40.8	11.04
high-T	3.1	56.4	10	3.09	1.30	83.4	2.86

RSP1	D	I	N	R	k	α95	3R ² /N
low-T ^L	354.8	-56.4	8	2.49	1.27	100.5	2.33
low-T ^J	2.2	-28.3	4	3.96	73.46	10.8	11.76

S1	D	I	N	R	k	α95	3R ² /N
low-T ¹	183.6	-20.8	3	2.82	11.36	38.4	7.95
low-T ²	172.0	-8.2	4	2.13	1.60	120.8	3.40

SB1	D	I	N	R	k	α95	3R ² /N
VRM	336.6	-14.6	8	7.39	11.40	17.1	20.48
low-T	337.3	-4.2	11	10.31	14.53	12.4	28.99
high-T	342.8	-2.9	6	5.89	46.79	9.9	17.35

SB2	D	I	N	R	k	α95	3R ² /N
low-T ^C	325.7	-11.2	4	2.71	2.33	79.3	5.51
high-T ^T	336.3	8.0	4	3.92	36.24	15.5	11.52

SB3	D	I	N	R	k	α95	3R ² /N
low-T	350.9	-12.0	8	7.80	35.32	9.4	22.82
high-T	343.5	6.2	7	6.84	36.52	10.1	20.05

SB4	D	I	N	R	k	α95	3R ² /N
low-T	348.9	-9.9	7	6.95	120.22	5.5	20.70

SBA1	D	I	N	R	k	α95	3R ² /N
low-T	358.8	-23.2	4	3.76	12.38	27.2	10.60
high-T	41.4	-20.4	3	2.18	2.43	108.4	4.75

SBA2	D	I	N	R	k	α95	3R ² /N
low-T ¹	0.7	-19.1	3	2.96	47.46	18.1	8.76
low-T ²	343.0	-25.0	4	3.29	4.21	51.1	8.12

SF1	D	I	N	R	k	α95	3R ² /N
low-T	355.2	-28.3	6	5.97	183.70	5.0	17.82
high-T	6.3	-26.7	3	2.99	162.07	9.7	8.94

SP1	D	I	N	R	k	α95	3R ² /N
low-T	86.8	-71.3	13	4.68	1.44	60.2	5.05
high-T	59.4	-31.4	6	1.88	1.21	142.9	1.77

TBA	D	I	N	R	k	α95	3R ² /N
low-T	12.5	-26.7	4	2.95	2.87	66.9	6.53

TBF1	D	I	N	R	k	α95	3R ² /N
low-T	278.9	-0.9	4	2.01	1.51	134.0	3.03
high-T	210.4	43.8	5	1.93	1.30	140.8	2.23

TBLB1	D	I	N	R	k	α95	3R ² /N
low-T	17.1	6.3	13	3.14	1.22	83.8	2.28
high-T	33.2	16.3	9	2.99	1.33	85.0	2.98

TBUB1	D	I	N	R	k	α95	3R ² /N
low-T ^L	68.8	-7.5	12	2.26	1.13	110.6	1.28
low-T ^J	329.3	-36.5	4	3.81	15.81	23.8	10.89

THB1	D	I	N	R	k	α95	3R ² /N
low-T	237.9	1.4	10	2.51	1.20	100.2	1.89
high-T	59.1	3.5	4	1.59	1.24	180.0	1.90

TV1	D	I	N	R	k	α95	3R ² /N
low-T	342.6	-22.7	9	8.92	103.62	5.1	26.52

UVA1	D	I	N	R	k	α95	3R ² /N
low-T	5.6	-15.9	5	4.97	144.71	6.4	14.82
high-T	358.7	-32.6	2	1.41	1.69	180.0	2.98

UVA2	D	I	N	R	k	α95	3R ² /N
low-T	354.6	-18.3	4	3.85	19.76	21.2	11.12
high-T	22.6	8.4	2	1.98	46.20	37.6	5.88

UVA3	D	I	N	R	k	α95	3R ² /N
low-T	10.7	-23.1	4	3.80	14.69	24.8	10.83

UVB1	D	I	N	R	k	α95	3R ² /N
low-T	14.4	-13.9	11	2.88	1.23	89.2	2.26
high-T	230.7	-37.0	3	1.84	1.73	180.0	3.39

^L = lithic clasts, ^J = juvenile clasts, ^{L+J} = lithic + juvenile clasts

¹ = type 1 clasts, ² = all clasts, ^C = CRM, ^T = TRM

Table D.2: Average emplacement temperatures for units sampled for palaeomagnetic analysis on Ascension Island. Average emplacement temperatures typically represent the lowest clast T_e for the unit. 0°C here represents ambient temperature. Values in brackets represent relict T_e s (i.e. the T_e of the source deposit). ^U and ^L represent upper and lower units sampled at site BPB1. ^C=temperature to which CRM overprints persist. ¹= T_e from hot (type 1) clasts. ²=secondary (pTRM) overprint temperature. [†]unit has two possible values for T_e . ^{††}an accurate T_e could not be calculated due to clast alteration, however clasts typically have a one-component remanence and may therefore have been emplaced above T_e .

unit	average T_e , °C	unit	average T_e , °C
BILL	>580	NRF2	>580
BPB1 (average)	204	NRF3	243 (404)
BPB1 (separate)	204 ^U , 356 ^L	NRGP1	0 (295)
BX1	0, 218 ¹ (427)	NRLB1	>580
CGB1	0/217 [†]	NRLB2	>580
CVS1	0, 161 [†]	NRLB3	>580
CVS2	0, 164 [†]	NRLB4	>580
DAVE	>580	NRPF1	186
DRS1	0 (264, 349)	NRS1	350
EB1	0/185 [†]	PB	>580
EFB1	0 (313)	PBS1	418
EFFB1	313	PBS2	322
EFP1	0 (211)	PBS3	273
EFS1	311	PC1	325
EFS2	287	PF1	199
GEOFF	>580	PPBB1	0, 160 [†]
GMI	>580	PPBF1	0
GMP1	210	PPF1	>580, 227 ²
LA1	293	PPLB1	>580
LA2	291	PPPF1	0, 211 [†]
LF1	417	PPR	>580
LF2 (P)	453	RF1	200 (300)
MRBB1	0 (161)	RL	>580
MRGB1	265	RP1	0/190
MRGB2	350	RSP1	0 (326)
MRH1	0 (214)	SB1	450, 216 ²
MRT	>580	SB2	>580
MVA2	0, 211 ^C	SB3	>580, 229 ²
MVF1	>580	SB4	>580
MVF2	>580 ? ^{††}	SF1	>580
MVLB1	>580	SP1	0 (264)
MVS1	>580	TBF1	0 (292)
NEB1	438	TBLB1	0 (240)
NEP1	175	TBUB1	0 (239)
NELL	>580	THB1	0 (269)
NRF1	487	UVB1	0

Appendix E

GEOCHEMICAL DATA

This appendix contains whole rock major and trace element X-ray fluorescence data for units sampled on Ascension Island for geochemical analysis. Major element totals originally fell between 99.19% and 100.32% but have been recalculated to 100%. Loss on ignition accounts for the main constituents of the sample (e.g. H₂O, CO₂) that cannot be measured directly by XRF. Trace element data were chondrite-normalised before plotting, using the normalisation values of Sun and McDonough (1989) and McDonough Sun (1995).

A measure of instrumental precision is provided by errors for trace element data which are calculated from pre-existing graphs showing the maximum 2 sigma error (95% probability) expected at any concentration level (graphs provided by Peter Webb at the Open University).

The quality of data produced by the instrument was checked using a number of monitor samples which were analysed routinely during the run allowing results obtained to be compared with the ranges of results expected. Actual and expected values for monitor samples are shown in Tables E2 and E3.

Table E.1: Major and trace element analyses. LOI = loss on ignition. Major element values are in wt% and trace element values are in ppm. The approximate detection limits for trace elements are shown. The detection limit for major elements is generally <0.1wt%. Errors shown for trace element data are a measure of instrument precision and are calculated from graphs of maximum 2 sigma error expected at any concentration level.

	loc. 12	loc. 26	loc. 27	loc. 28	loc. 71	loc. 74	DRA	GMI1	II
	63.55	63.11	63.97	63.64	61.68	49.53	65.74	59.98	64.33
SiO ₂	0.33	0.34	0.32	0.32	0.61	2.53	0.26	0.90	0.32
TiO ₂	14.14	13.60	13.41	13.49	15.76	15.34	13.69	17.63	13.48
Al ₂ O ₃	5.52	5.52	5.53	5.62	4.56	12.10	4.63	7.09	5.59
Fe ₂ O ₃	0.23	0.23	0.23	0.24	0.16	0.18	0.17	0.15	0.24
MnO	0.11	0.21	0.16	0.13	0.61	5.89	0.10	0.81	0.08
MgO	0.52	0.83	0.52	0.54	1.68	8.62	0.55	1.74	0.55
CaO	3.83	5.31	5.11	4.84	5.57	2.84	4.19	6.17	4.56
Na ₂ O	4.71	5.13	5.19	5.21	4.15	0.93	5.36	2.81	5.21
K ₂ O	0.51	0.04	0.04	0.04	0.16	0.38	0.02	0.07	0.03
P ₂ O ₅	6.53	5.65	5.54	5.93	5.05	1.67	5.29	2.66	5.60
LOI	100	100	100	100	100	100	100	100	100
Total									
Rb	113	119	132	135	88	20	125	51	145
Sr	8	10	4	5	138	393	4	228	5
Y	98	92	103	114	57	34	99	49	103
Zr	1126	1022	1169	1187	727	209	986	698	1163
Nb	180	170	192	192	104	33	169	108	189
Ba	44	43	35	33	780	238	114	824	32
Pb	9	8	8	9	6	1	7	5	7
Th	19	16	20	19	13	0	18	12	18
U	6	4	6	5	5	0	5	4	6
Sc	6	6	3	4	6	31	1	18	3
V	1	4	1	5	5	280	3	51	2
Cr	4	6	4	5	3	38	4	13	5
Co	1	18	2	4	7	44	3	10	1
Ni	3	5	5	7	4	42	2	9	3
Cu	5	124	21	22	29	68	23	10	13
Zn	198	201	227	228	115	114	201	137	229
Ga	31	30	32	34	25	20	30	28	33
Mo	10	11	14	11	9	1	12	6	13
As	2	6	2	7	5	7	6	6	3
S	86	160	149	82	55	492	101	174	62

Table E.1 continued: Major and trace element analyses.

	TBUS		UVA1		UVA2		UVA3	
SiO ₂	52.97	61.61	61.40	58.94				
TiO ₂	2.18	0.45	0.39	0.23				
Al ₂ O ₃	15.66	16.16	15.80	13.88				
Fe ₂ O ₃	10.84	4.62	4.36	3.26				
MnO	0.28	0.17	0.16	0.13				
MgO	3.16	0.52	0.54	0.79				
CaO	6.64	1.81	1.67	0.98				
Na ₂ O	4.44	5.83	6.26	8.70				
K ₂ O	1.72	3.79	4.06	4.39				
P ₂ O ₅	0.83	0.12	0.08	0.03				
LOI	1.28	4.93	5.27	8.67				
Total	100	100	100	100				
approx detect limit (gen <0.1 wt% for major)								
Rb	34	84	85	85	1.5	1.5	85	1.5
Sr	512	169	159	48	1.9	1.9	48	1.4
Y	63	69	63	68	1.7	1.7	68	1.7
Zr	371	731	725	779	4.5	4.5	779	4.7
Nb	72	114	111	107	1.9	1.9	107	1.8
Ba	462	880	861	681	23.5	23.0	681	19.0
Pb	3	6	6	6	2.5	2.5	6	2.5
Th	4	11	12	10	2.3	2.3	10	2.3
U	3	4	4	3	1.5	1.5	3	1.5
Sc	25	7	8	6	3.7	3.8	6	3.5
V	99	7	0	3	4.1	-	3	4.0
Cr	12	6	6	6	2.2	2.2	6	2.2
Co	19	12	5	3	-	-	3	-
Ni	4	5	3	6	2.0	2.0	6	2.1
Cu	45	93	63	27	2.4	2.3	27	2.1
Zn	154	132	127	124	2.9	2.9	124	2.9
Ga	23	27	25	24	2.2	2.2	24	2.2
Mo	2	8	7	8	-	-	8	-
As	3	5	0	4	-	-	4	-
S	4276	130	182	177	-	-	177	-

Table E.2: Major element analyses for monitor samples. LOI = loss on ignition. Values are in wt%. Analyses were carried out over two days (10-11 December).

	WS-E (1) 10 Dec	WS-E (2) 10 Dec	WS-E expected 10 Dec	WS-E (1) 11 Dec	WS-E (2) 11 Dec	WS-E expected 11 Dec	OUG94 (1) 10 Dec	OUG94 (2) 10 Dec	OUG94 expected 10 Dec	OUG94 (1) 11 Dec	OUG94 (2) 11 Dec	OUG94 expected 11 Dec
SiO ₂	51.04	51.07	51.05	51.11	51.08	51.05	69.73	69.82	69.93	69.79	69.84	69.93
TiO ₂	2.42	2.42	2.42	2.40	2.41	2.42	0.32	0.31	0.31	0.31	0.31	0.31
Al ₂ O ₃	13.91	13.93	13.87	13.92	13.93	13.87	14.67	14.66	14.66	14.69	14.71	14.66
Fe ₂ O ₃	13.22	13.19	13.24	13.20	13.22	13.24	3.02	3.00	3.05	3.01	3.01	3.05
MnO	0.17	0.17	0.17	0.17	0.17	0.17	0.08	0.07	0.07	0.08	0.08	0.07
MgO	5.63	5.61	5.59	5.60	5.60	5.59	1.04	1.03	1.04	1.04	1.03	1.04
CaO	9.04	9.00	9.01	9.02	9.03	9.01	1.37	1.36	1.34	1.36	1.35	1.34
Na ₂ O	2.43	2.46	2.49	2.42	2.41	2.49	4.68	4.66	4.50	4.61	4.59	4.50
K ₂ O	1.00	1.00	1.01	1.00	1.00	1.01	2.97	2.96	2.96	2.97	2.95	2.96
P ₂ O ₅	0.31	0.30	0.30	0.31	0.31	0.30	0.17	0.17	0.16	0.17	0.17	0.16
LOI	0.85	0.85	0.86	0.85	0.85	0.86	1.97	1.97	1.97	1.97	1.97	1.97
Total	100	100	100	100	100	100	100	100	100	100	100	100

Table E.3: Trace element analyses for monitor samples. Values are in ppm.

	BHVO-1 (1)	BHVO-1 (2)	WS-E expected	WS-E (1)	WS-E (2)	WS-E expected	OUG94 (1)	OUG94 (2)	OUG94 expected	OUG94 (1)	OUG94 (2)	OUG94 expected
Rb	9	9	11	74	75	74	5	4	5	22	21	20
Sr	403	404	403	335	333	336	149	149	145	201	200	194
Y	29	29	28	26	26	24	20	19	18	23	23	24
Zr	177	177	179	189	189	185	40	41	41	95	94	94
Nb	19	19	19	10	10	10	3	2	3	8	7	8
Ba	150	151	139	1392	1368	1370	113	113	114	184	182	182
Pb	4	2	3	17	18	20	7	7	6	7	8	9
Th	3	2	1	6	5	5	0	1	0	3	3	2
U	1	3	0	1	1	2	1	0	0	2	0	1
Sc	33	34	32	7	8	9	30	31	31	35	41	35
V	316	315	317	51	47	54	150	143	148	267	266	262
Cr	288	287	289	5	6	3	274	277	285	96	96	93
Co	47	49	45	14	12	7	62	63	55	48	48	44
Ni	122	120	121	6	4	6	249	252	247	71	70	70
Cu	141	138	136	28	28	29	96	99	96	107	107	103
Zn	113	113	105	64	64	61	71	71	66	82	85	77
Ga	21	22	21	16	17	17	15	14	15	21	20	20
Mo	0	0	1	2	1	3	0	0	1	0	0	1
As	0	0	0	4	2	4	0	0	0	1	1	1
S	158	157	102	91	88	30	437	431	392	192	203	79