Sandstone Weathering, Electrical Resistivity Tomography, and the Deterioration of San Rock Art in the Golden Gate Highlands National Park, South Africa



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Submitted: Hilary Term 2011

This DPhil thesis is submitted to the School of Geography and the Environment, University of Oxford

Word count: 70,045

SANDSTONE WEATHERING, ELECTRICAL RESISTIVITY TOMOGRAPHY, AND THE DETERIORATION OF SAN ROCK ART IN THE GOLDEN GATE HIGHLANDS NATIONAL PARK, SOUTH AFRICA

Lisa Mol, St Cross College

Submitted for the degree of Doctor of Philosophy, Hilary Term 2011

Abstract

Electrical Resistivity Tomography (ERT) is a novel technique which can be used to build up a 2D pseudo-section of resistivity distribution of a porous material. Here, it is used to visualise internal moisture regimes by measuring the resistivity distribution of transects within sandstone, inferring that high resistivity equals low moisture content and vice versa. This method was used to perform two intermediate complexity laboratory tests; the first one to determine high-resolution, multi-scale drying patterns of sandstone, the second to determine capillary ingress of moisture within a sandstone block and the influence of temperature on moisture distribution. It was found that moisture behaviour showed far more complex patterns than previously acknowledged. A new model is therefore proposed which describes the influence of increased near-surface temperatures on capillary rise. This series of tests bridge the gap between field observations and mathematical models, as well as confirm the validity of ERT as a geomorphological tool.

This research was continued by investigating the role of internal moisture in sandstone weathering using the Golden Gate Highlands National Park (GGHNP), South Africa as a case study. The ERT data was correlated with Equotip (rock surface hardness) and Protimeter (rock surface saturation) measurements. Seven sites were investigated, which showed that there is a non-linear correlation between rock surface hardness and internal moisture patterns. In addition, annual change measurements confirmed that the fluctuating patterns of internal moisture can be correlated to strengthening or weakening of the rock surface. This research therefore proposes two new conceptual weathering models. The first correlates 'optimal moisture content' to rock surface strength. The second correlates the development of shelters and changing weathering patterns to the non-linear interaction between case hardening and internal moisture. This new approach to sandstone weathering can be incorporated into conservation methods, as rock surface loss is one of the main causes of the San Rock Art deterioration observed in the GGHNP.

Acknowledgements

Starting a PhD is remarkably similar to going for a walk in the desert; you've read the travel guides, mapped your route, determined your destination and acquired your passport (or MSc). However, on arrival, you find that the landscape doesn't quite correlate with the map, the path isn't clearly marked and the transport links you thought would be present aren't quite in place. At the same time, you find fascinating nuggets of knowledge, unexpected peoples and landscapes and amazing little detours along your route you never thought would be there. Every step you take brings new possibilities, angles and factors on your path.

It seems that 3,5 years later my walk has come to an end. It has been a fascinating, exciting, and challenging journey. I could not have completed this journey without the people I have met along the way. I owe a great debt of gratitude towards a number of people who have walked with me, suggested routes and explained the wonders of the desert. At the School of Geography I particularly would like to thank Prof Andrew Goudie, Prof David Thomas, Dr Giles Wiggs, Dr Troy Sternberg and Jennifer Booth for their help, encouragement, feedback and support. I would like to thank all the members of the OxRBL, especially Dr Mona Edwards and Dr Hong Zhang for the invaluable support and patience.

This research could not have been completed without spending a few weeks in the Golden Gate Highlands National Park, South Africa. I therefore would like to thank all the people who made this possible; Dr Matt Telfer, Dr Stefan Grab, and Sandra and John Taljaard, Sam, Moses and Josef at the Gladstone Offices. Furthermore, I would like to thank the British Society for Geomorphology for their Conference Support Grant, the School of Geography and the Environment for their Postgraduate Conference Grant, the Quaternary Research Association for the Bill Bishop Award, the Dudley Stamp Memorial Fund with the Royal Geographical Society/IBG for the Dudley Stamp Memorial Award, the Oppenheimer Fund, the Fell Fund and St Cross College, Oxford for their financial support. In addition, I would like to thank the Prins Bernard Cultuurfonds for the scholarship they so generously awarded me, which made completion of this DPhil possible.

I look back fondly at my time as a DPhil student in Oxford, not in the least thanks to my friends who have been patient, supportive, my lifeline to sanity and the best company anyone could wish for. In particular I would like to mention Dr Mark Larsen, James Golden, Margreet Luth, Dr Tony Craig, Rebecca Davies, Katie Mackay, Abby Loebenberg, Ellen Royrvik, Jamie Anderson and Erika Nitsch (thank you for the Sheffield adventures!).

But above all there are four people who have been instrumental in the completion of this thesis. First of all, my parents, who I would like to thank for their unwavering and unconditional love and support. Their belief in me has kept me going through the good and the bad times. I also owe a great debt of gratitude to my supervisor, Prof Heather Viles, who provided the model of geographical curiosity, a critical eye when sorely needed and above all patience and support throughout the years. There is one more person in particular who has been there every step along the way, helping me find my way and giving support, patience, understanding, kindness and above all love. Mark Williams, I could not have done this without you.

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CHAPTER 1: INTRODUCTION; RATIONALE AND INTENT

Sandstone is well-known for its relatively fragile nature, its susceptibility to weathering processes and its versatility as a building stone. Moreover, its high weathering rates make it a very interesting subject of study for geomorphologists as it allows for monitoring of surface weathering in the field and laboratory simulations within the span of a research project (Pentecost, 1991; Sancho *et al*, 2003; Wells *et al*, 2008). Over the past decades sandstone weathering research has made huge progress (Turkington and Paradise, 2005), creating overlap between biological studies (Chen *et al,* 2000; Viles, 1995), geophysical studies (Olson, 1999; Schrott and Sass, 2008; Nuzzo and Quarta, 2010) and geomorphology. Whilst the role of internal moisture has long been acknowledged as a contributing factor to surface weathering until now it has been poorly understood in terms of defining the influence of subsurface moisture accumulation and surface weakening especially in a temporal scale context of changing moisture regimes. Whilst a number of laboratory studies have investigated the movement of moisture through porous media (Hawkins and McConnell, 1992; Roels and Carmeliet, 2006; Franzen and Mirwald, 2009) and field studies have often connected internal moisture with surface weathering (de'Gennaro *et al*, 2000; Carter and Viles, 2003; Sumner and Loubser, 2008) very few studies examine the distribution of moisture, its changing nature and its influence on surface weathering in as much detail as Electrical Resistivity Tomography (ERT) can provide (see chapter 3 for more information). ERT has been adapted to suit geological needs over the past 15 years. It has now been adapted to suit meso-scale rock surfaces, such as are found in the built environment and natural rock formations such as cliffs and rock shelters, proving 2D transects of resistivity distribution into the rock face. This study is placed in the gap between low resolution field studies and high resolution laboratory studies, as well as using ERT in a field situation to measure changes in moisture behaviour on both a spatial and temporal scale. The aim is to further our understanding of cavernous weathering by looking at the interaction between internal moisture and surface weathering at high spatial resolution scale that has only recently become possible.

Clarens sandstone in particular is an excellent subject for weathering studies. Its erodible nature in combination with the basalt capping found in the Golden Gate Highlands National Park (GGHNP) allows for the formation of mushroom rocks, shelters and caves. A number of studies have been conducted on this particular sandstone because it is home to the largest collection of Rock Art south of the Sahara, which is outstanding both in quality and diversity of subject (UNESCO World Heritage List). In addition, it is part of the uKhahlamba / Drakensberg Mountains, listed by UNESCO as a World Heritage Site in 2000 because of its exceptional natural beauty, rich biotic habitats and geologic interest.

The San Rock Art is present in several areas of the GGHNP as well, showing a variety of depictions of eland, hunters and Therianthropes (man-animals) and worshippers. There are a number of different sites within the GGHNP and the neighbouring Qwa-Qwa Reserve, varying in size and age, which are noticeably deteriorating. Flaking and crumbling are commonly found problems on many Rock Art sites, but the positioning of the paintings is determined by religious beliefs which exacerbates the problem; cracks and fissures are believed to be gateways to the Spirit World and paintings often overlap with these to aid communication with the Ancestors and deities such as the Rain Animal or the Eland which is believed to have supernatural potency (Vinnicombe, 1976). However, this also means that often these paintings are placed on the vulnerable areas of the rock surface where moisture seepage, crumbling and flaking often take place. The San tradition of creating and renewing these paintings dates back far much as 60,000 years, but a number of clashes with both the Zulu and the white settlers drove them away from the Drakensbergen area, and by approximately 1870 they had all but disappeared (Moses, guide at GGHNP, April 2009; Meiklejohn *et al*, 2009). As a consequence, previously renewed and maintained Rock Art sites are now stagnant and at risk of rapid deterioration. Some of the shelters are extraordinarily well monitored, such as the Game Pass Shelter, but there are an estimated 15,000 Rock Art sites in southern Africa, most of which are undocumented (Meiklejohn, 1997; Meiklejohn *et al*, 2009). This therefore adds another

dimension to this research project, as increasing our knowledge of moisture behaviour within the rock can aid our understanding of the deterioration of the canvas of the painting, i.e. the rock face, which is especially important considering the challenges we face of a changing environment and a changing climate.

The order in which this project was established does not follow a fieldsite – particular study site – methodology – results order. Instead, the Oxford Rock Breakdown Laboratory (OxRBL) acquired a new piece of Electric Resistivity Tomography (ERT) equipment called a Geotom (Geolog2000) in January 2007, which had showed potential as a new geomorphological tool (Sass, 2005; Sass and Viles, 2006) but required further testing in other environments and on other lithologies. A full understanding of exactly how the results should be interpreted in this context required both laboratory studies and field studies. A pilot study was therefore undertaken, together with Prof Heather Viles and Dr Stefan Grab, in the GGHNP in April 2008 to take preliminary measurements and flag up the areas where the method needed to be either adjusted or further investigated in the laboratory. The results of this study were published in *Geomorphology* in 2010 (see **chapter 5**).

Further fieldwork was undertaken in the GGHNP in April 2009 to conduct a more extensive field survey of an array of shelters. The shelters initially surveyed in 2008 were re-measured and the results were compared to assess how much internal moisture regimes change on an annual basis and how that affects rock surface strength. Temperature loggers left on site between 2008 and 2009 provide a very detailed database of the near-surface temperatures that affected the rock surface of both shelters in the course of the year. The results are discussed in **chapter 6**, and have been submitted as a paper to *Catena*. In addition, a further 5 sites were surveyed using ERT, rock surface hardness (Equotip) and saturation (Protimeter), infiltration and weathering survey techniques. In addition, 3 Rock Art sites were surveyed using the Equotip and Protimeter as ERT was deemed to be potentially too invasive for the both structurally and ethically very sensitive paintings. The results of this particular field season are discussed in **chapter 7**, which has been accepted for publication in

Earth Surface Processes and Landforms. However, the data gathered on the Rock Art sites has not been used for publication as the issues of conservation and intrusion on culturally important ground are too sensitive in this case and could provoke negative responses. They are, however, incorporated the Rock Art deterioration into the findings, as is evident in **chapter 7**.

In the ensuing year a discrepancy between mathematical models of moisture behaviour and field studies was found; the field observations did not correspond well with the theoretical models described in the literature. A semi-controlled intermediate complexity laboratory experiment was therefore undertaken. The test focussed on understanding the influence of increasing temperatures on the drying behaviour of a porous stone when a groundwater source is available. This test was designed to further our understanding of capillary behaviour of moisture and how this would change when the stone surface is exposed to increased heat, such as would be found in the field on a hot sunny day. The results of this study have been submitted to *Environmental Earth Sciences* (see **chapter 8**).

1.1 Thesis aims

The overall aim of the thesis is to determine the influence of internal moisture on sandstone weathering. However, this is a rather large subject to tackle, so this research is focussed on understanding moisture behaviour in Clarens sandstone shelters in the GGHNP, thereby contributing to understanding of cavernous weathering of sandstone in semi-arid environments. In addition, the question whether or not surface weathering caused by subsurface moisture is a significant detrimental factor to the San Rock Art found in the GGHNP is examined. To this end the following aims and research questions have been identified:

1. To further our understanding of internal moisture behaviour within sandstones and how this affects sandstone weathering (**chapters 5 and 6)**.
    a. How does the distribution of moisture translate into surface weathering?
    b. How does the distribution and intensity of moisture change on an annual time scale?
    c. How does the distribution of moisture vary spatially within the park?
2. To understand the influence of internal moisture on sandstone weathering in the development of cavernous weathering features (**chapter 7**).
    a. Does the combination of ERT and Equotip provide any additional information on core softening and case hardening, the two most commonly described processes in cavernous weathering studies?
    b. Can we, by substituting spatial variability in shelter development for development over time, infer which role internal moisture plays in cavernous weathering?
    c. To what extent are aspect and temperature important in shelter development and what are the feedback processes?
    d. How does this new insight into cavernous weathering affect our understanding of the deterioration of San rock art?
3. To determine if ERT is a valid method for understanding these processes (**chapter 8**)
    a. Can ERT aid with examination of links between external microclimate and internal moisture contents?
    b. To which extent are semi-controlled intermediate complexity methods useful for understanding the influence of temperature fluctuations on internal moisture behaviour?
    c. How successful is ERT as a geomorphological tool?

1.2 Choice of techniques

Rather than first selecting a field site, this research is based on the rationale that ERT as a recently adopted geomorphological technique showed a tremendous potential for weathering investigations. The overall technique selection was based on a non-destructive approach which could be used in protected areas such as the GGHNP and the walls of the Oxford Colleges. The main technique (ERT) was therefore selected before the field site selection. In order to further our understanding of ERT results and interpretation, pilot studies were undertaken in Oxford and Wytham in the period of January to October 2007, thus before the official start of the DPhil. Based on the encouraging results of these small-scale studies this particular technique was carried further into the DPhil research. To complement the ERT findings, rock surface hardness (Equotip) as an indicator of weathering (as previously used by Hack *et al*, 1993; Aoki and Matsukura, 2007) and rock near-surface saturation (Protimeter) were used, as these are also non-destructive techniques. In addition temperature regimes in the GGHNP shelters were monitored where possible using iButtons, and Karsten tubes and conductivity measurements to investigate the nature of Clarens sandstone. These are all commercially available methods commonly used in field and have been used in a number of studies (Barbel, 1992; Nwaubani *et al*, 2000; Török, 2003).

1.3 Choice of field locations

The GGHNP was selected as a main study site once it became apparent that the specific sandstone weathering in this area is exceptional both in terms of outstanding natural beauty (as confirmed by its UNESCO World Heritage Listing as part of the Drakensberg area) and rate of weathering. The exposed rock surfaces all show signs of moisture within the rock, as streaks of algae and bacterial colonies mark the outlets of water, which are especially apparent in areas of cavernous weathering.

It was therefore decided that this would be both an ideal test site for ERT and an excellent opportunity to expand our knowledge on cavernous weathering in sandstone.

Within the GGHNP there is a plethora of shelters in many shapes and sizes. However, the final site selection was often determined simply by access possibilities. Many sites are high up on very steep slopes, too steep to safely navigate with the equipment as they are strewn with boulders and covered with high grasses, making finding safe footing difficult. The selection of sites was therefore in the first instance based on which sites would be accessible, and secondly if these represented the range of shelters found in the GGHNP. Seven sites were found to qualify on both accounts, and where therefore surveyed using ERT, Protimeter and Equotip.

1.4 Thesis structure

1.4.1 Part 1: Background

This first section of the thesis discusses the larger body of literature within which this research is set. It consists of two parts; the first (**chapter 2**) highlights recent and current research in sandstone weathering. This chapter discusses recent and current advances in weathering research, with specific reference of heritage deterioration. The second part (**chapter 3**) discusses the development of ERT from a medical tool through to geomorphology and also assesses its potential use within geoarchaeological research. This paper was written in collaboration with Paul Preston, an archaeology graduate student, and published in *Archaeometry* (2010).

1.4.2 Part 2: Field studies

This part of the thesis comprises the three previously mentioned fieldwork papers, which report on the pilot study, annual change and the main field season. They discuss the results of the GGHNP measurements and the contribution this research has made towards our understanding of

cavernous weathering. **Chapter 5** specifically reports the results of the April 2008 pilot study, which showed that there is a correlation between subsurface moisture accumulation and rock surface hardness. The same sites surveyed in 2008 were revisited in 2009. This dual dataset has been used to compare internal moisture regimes and to assess how changes observed are reflected in changes in rock surface hardness, as described in **chapter 6**. The final chapter in this series, **chapter 7**, looks at the influence of internal moisture on surface weathering across space, which has been substituted for development over time, to further our understanding of the cavernous weathering of sandstone and how internal moisture is dynamic and adapts to and influences changes in factors such as exposure and surface crust formation.

1.4.3 Part 3: Laboratory study

This part of the thesis discusses the study which investigated the effect of elevated near-surface temperatures on moisture behaviour in sandstone, specifically focussing on the influence of capillary ingress of moisture and its changing distribution under changing environmental circumstances. The results of this experiment are discussed in **chapter 8**.

1.4.4 Part 4: Synthesis and conclusions

The final part of the thesis, **chapter 9**, is a discussion of the findings across the range of papers and how they aid in advancing our understanding of cavernous weathering of sandstone. This draws together the conclusions drawn across the five papers of the main body of the thesis and reflects back on the aims and objectives of the research, as described in this introduction (section 1.1).

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CHAPTER 2: WEATHERING OF SANDSTONE; CURRENT RESEARCH CONTEXT

While in comparison with other earth surface processes weathering is often slow and hard to discern, it is undoubtedly a key influence on landscape development (Viles, 2011). Weathering studies used to be primarily the domain of soil scientists, geomorphologists and geochemists. However, in recent decades a large number of other disciplines have also taken an interest in understanding these processes. These include archaeologists, architects, engineers and conservators who are interested in the weathering of stone (the term often given to natural rock used in buildings) (Pope, 2000a). A large number of laboratory as well as field studies have been undertaken to further our understanding of stone weathering. This work builds on pioneering fieldwork such as Blackwelder's observations of exfoliation (1925) and Goldich's analysis of chemical changes during weathering of rocks (1938). Winkler (1966) identified a number of important agents of weathering in stone, effectively linking chemical decay and the role of biological activity in weathering rates, followed by his 1987 work on weathering rates which identified the complex interaction of different weathering processes. Particularly in the past decade, weathering research has gained momentum within geomorphological studies. As Whalley and Turkington (2001, p.1) state: "To imagine geomorphology without the sub-discipline of weathering is like imagining a chess game having swept all the pieces off the board. Weathering research is integral to much geomorphological work, but is rarely viewed as forming a major research area in its own right." According to Pope (2002, p.409) "there have been significant advances in weathering science in the past ten or fifteen years, particularly in the realm of molecular scale mechanisms and processes and in the modeling of weathering systems over geographic areas." Weathering is a key research area and pedagogic topic in the earth sciences because it is the interface at which the crust interacts with the atmosphere, biosphere and hydrosphere (McLennan, 1993). It affects landscapes, on scales ranging from micro

(mm to cm) to macro (10s of meters)(Carter and Viles, 2005), through a number of processes. Within this field there are many approaches such as lichenological research (Winchester and Chaujar, 2002), weathering features analysis, geochemical research (e.g. Pellegrino and Prestininzi, 2007; López *et al*, 2005) and visual classification (e.g. Warke *et al,* 2003). Each of these fields has developed different methods to analyse the processes and consequences of the different factors in stone weathering.

2.1 Subdivisions within weathering research

In general there are three strands within weathering research that can be distinguished in terms of aims and approaches:

1. Microscale weathering process understanding; deterioration of minerals and mineral structure
2. Weathering feature development
3. The influence of rock characteristics on the nature and role of weathering

The first subdivision, microscale weathering process understanding, focuses on the investigation of mineral deterioration both at the surface and subsurface level. This discipline comprises physical (such as porosity changes due to pore widening or collapse), chemical (such as mineral alteration due to chemical alterations such as salt weathering) and biological (due to microorganism activity, such as bacteria and lichen) weathering. There are two perspectives on microscale weathering, the physical weathering studies appear to focus on the physical properties and the ensuing alteration due to processes such as freeze-thaw (Saad *et al*, 2010; Seto, 2006; Tan *et al*, 2011; Yavus *et al*, 2006; Zhang *et al*, 2004). Biological weathering research examines the external factors, such as lichen, which is then correlated to the properties of the stone and the weathering effects established on the surface (see for example Bjelland and Thorseth, 2002; Lee and Parsons, 1999; Mottershead

and Lucas, 2000; Stretch and Viles, 2002). Chemical weathering, such as salt weathering, can adopt either of these approaches whether looking at the rock properties to understand salt movement (Benavente *et al*, 2001; Yu and Oguchi, 2010) or investigating the type of salt and its consequential influence on surface weathering (Robinson and Williams, 2000; Williams and Robinson, 2001; Steiger and Asmussen, 2008) or, most commonly, a combination thereof (Rothers *et al*, 2007; Smith *et al,* 2008a; Yu and Oguchi, 2009).

We have gained some understanding of weathering processes on a mineral matrix scale over the past years. Although Turkington and Paradise (2005) claim that "problems in interpretation of single causative weathering processes have arisen due to significant gaps in the understanding of processes that may produce microscale features, or suites of features" (p.235) there are a number of studies in place which have explored the importance of microscale, in this case physical, weathering. Work by Siitari-Kauppi *et al* (1997), for example, shows that weathering can create micrometric-scale pore apertures, visible as fissures and cracks, resulting in high effective porosities and diffusivities and an increased heterogeneity of the material due to the development of flow paths in tonalite, an igneous stone. This has also been recorded as an important weathering control in sandstone as in conjunction with mineralogy and grain size, the configuration of pore space is an important intrinsic property that controls rock strength. As such, rock strength decreases with an increase in porosity (McKinley and McCabe, 2010). A decrease in rock strength can be correlated with increased weathering rates (Aoki and Matsukura, 2007; Gokceoglu *et al*, 2008, Dagdelenler *et al*, 2011), and the appearance of associated weathering features on the rock surface (Török, 2003).

This seamlessly merges into the second approach identified; weathering features development investigations. A large array of weathering features have been identified, such as alveolar weathering, also referred to as honeycomb weathering, (Aoki and Matsukura, 2007a; Smith *et al,* 2008b; Mustoe, 2010; Siedel, 2010) and tafoni development (Hall and Andre, 2006; Aoki and Matsukura, 2007b; Strini *et al,* 2008; Achyuthan *et al,* 2010; Brandmeier *et al*, 2011), flaking (Mol

and Viles, 2010; Siedel *et al,* 2010) and cracking (Chan *et al*, 2008; Matsuoka and Murton, 2008; Liu *et al,* 2010; Nara *et al*, 2011), to name but a few. Numerous investigations have focussed their efforts on understanding the initial formation and development of these features. These range from large scale formations such as the karstic landforms of Auyan-tepui, Venezuela (Piccini and Mecchia, 2009) and the Carnarvon Range, Australia (Wray, 2009) to smaller scale features such as the deterioration of individual building stones (Fobe *et al*, 1993; Friolo *et al*, 2003; Smith *et al*, 2010). This is reflected in Wray's (1997) statement that "the smaller surface weathering forms are usually found developed upon the larger structurally controlled landforms. It has been emphasised long ago that the smaller weathering forms are just as important in the landscape as the largest elements, as the small landforms often provide the key to understanding large ones" (p.140). However, one of the greatest difficulties encountered within this approach to weathering research is the extrapolation from one scale to another; often it is not possible to infer the landscape-wide weathering processes operating from small-scale case studies in the same way that it is very difficult, and often statistically unviable, to directly contribute landscape forming processes from individual small-scale processes (Viles, 2001). The 'holy grail' of this type of research is finding the overarching mechanisms that can be applied on every scale and in every environment. Unfortunately it is the combination of environmental factors and parent material characteristics that determines the type and rate of weathering, creating non-linear and spatially varied weathering of a rock surface (Philips, 2001).

The third approach to weathering research, the influence of rock characteristics on the nature and role of weathering, investigates the problem set out above; increasing our understanding of the importance of parent material and environmental factors. Philips (2001) noted that one of the restrictions of assessing the influence of the parent material is that weathering processes alter the material while the unweathered parent material is often inaccessible. However, mineralogical analysis of the investigated stone can aid the understanding of the susceptibility of the stone to particular weathering processes, such as pore structure (Benavente *et al*, 2004), chemical

composition (e.g. cation and anion analysis; Islam *et al*, 2002; Ceryan *et al*, 2008) and mineral (especially clay) strength and deterioration (Hall and André, 2003; McCabe *et al*, 2010). Marquez *et al* (2010) remarked that 'concerning mechanical properties, it has been observed with considerable unanimity amongst researchers that rock material becomes more porous, soft, friable and weakened as the grain to grain bonding disrupts and micro fractures and new minerals are formed' (p. 2).

No matter which approach is taken, the overarching questions asked in weathering research are: 1. What processes affect the rock surface? 2. How does this change the rock surface? 3. What is the rate of material removal from the surface? The deterioration of a rock surface can lead to a general retreat of the rock face whether through gradual removal of material (Lim *et al*, 2010) or more catastrophic collapse such as the collapse of an overhang or building structure. Often, these two factors work in tandem where slow removal of surface material can lead to increased fragility of the overall stone structure, such as found in cavernous weathering, which can be followed by the catastrophic collapse. However, the process of material removal is not necessarily directly related to contemporary environmental conditions as "sandstone weathering comprises several different stages, not all of which are associated with debris release and surface retreat, and over time the duration of each of these stages can be extremely variable. Further complexity regarding the weathering and breakdown of sandstone arises from the fact that debris release may not necessarily be coincident with a specific weathering event but occurs sometime later in response to the cumulative effects of weathering, with a resultant decrease in material strength and eventual breaching of some critical intrinsic strength/stress threshold. The corollary of this is the recognition that some sandstone weathering phenomena may owe their initiation and subsequent development to environmental conditions that differ from those of the present day and hence to weathering processes that may have been more effective in the past." (Warke *et al*, 2006, p.715).

2.2 Weathering: primary processes

There are a number of processes that play a significant role in rock. Table 2.1 shows an overview of the most common weathering processes and key research published on each process.

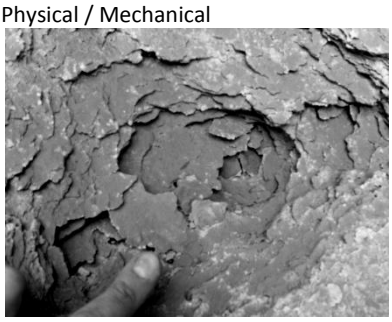
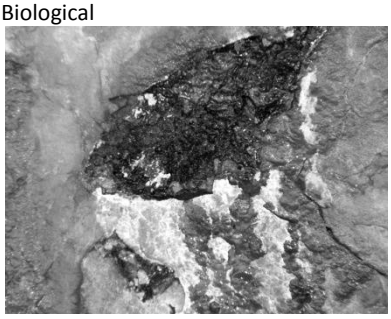
Weathering Process	Sub-type	Research examples (further reading)
Physical / Mechanical 	Thermal expansion Contraction and expansion of rock masses by temperature fluctuations Frost weathering Shattering of minerals by continual fluctuations of temperatures around zero ºC Salt weathering (haloclasty) Disintegration of rocks by saline solution seep into cracks and joints Insolation weathering Solar energy induced stress on rock surface Hydration weathering Wetting and drying of rock leading to expansion and contraction	Siegesmund *et al* (2002 Hall and Hall (1991) McGreevy and Whalley (1985) Matsuoka (2001) Goudie and Viles (1997) Robinson and Williams (2000) Singh (1988) McCabe *et al* (2006) Day (1994) Hall and Hall (1996)
Chemical 	Solution (chemical denudation) Decomposition of minerals by solution in water Hydrolysis Replacement of metal cations (most commonly K^+, Na^+, Ca^+ and Mg^+) in a mineral lattice by H^+ ions and the combining of these released cations with hydroxyl OH- ions, causing disintegration of the mineral structure of the rock	Welch and Ullman (1996) Sherlock *et al* (1995) Pope *et al* (1995) Matsuoka (1995)
Biological 	Lichen and mosses These perform a dual role by creating a protective cover but also a damaging micro-environment through altered chemistry, temperature and intrusion in the actual rock face Bacteria, algae and fungi Geochemical agents in the upper lithosphere, mobilizing mineral constituents with inorganic or organic acids or ligands they excrete, as well as promote rock wethering by reodx attack of mineral constituents such as Fe or Mn	Winchester (2004) Carter and Viles (2005) Ehrlich (1998) Hoffland *et al* (2004)

Table 2.1: Overview of rock weathering processes and examples of research

These processes will be present in virtually every geographical location, however the intensity of each individual process will vary according to environmental circumstances. This includes factors

such as exposure to sun, rain and degree of temperature fluctuations as well as exposure to pollution, as well as the variability and complexities of the parent material (Phillips, 2001). Pope *et al* (1995) propose that the processes responsible for spatial variations within weathering patterns operate principally at the weathering boundary-layer, i.e. the rock-atmosphere-hydrosphere-biosphere interface, a notion that is contested by Phillips (2001) who states that the weathering of the surface is to some degree determined by inherited weaknesses of the parent material rather than determined at the moment of exposure to external weathering processes. In addition, as Warke (2007) points out, weathering studies have often sought to explain features in terms of a prevailing set of environmental conditions, which is are not necessarily the conditions under which the weathering processes were activated. However, it is clear that, if weathering features are present, the rock surface has been exposed to a range of weathering environments and processes on both a temporal and spatial scale, especially if the particular rock has travelled e.g. down a slope.

Physical weathering factors, as summarized in table 2.1, comprise a range of processes that can roughly be divided up into three categories; thermal weathering, salt weathering and wetting/drying induced weathering. Thermal weathering is prevalent especially in environments that experience large temperature fluctuations such as arctic and desert environments, but is also heavily dependent on the thermal properties of the rock (McGreevy, 1985). This type of weathering can be a rapid-onset, such as found in thermal shock, or slow-onset, such as thermal stress fatigue, process (Hall, 1999; Hall and André, 2001). Surface and near-surface temperature variations are important because they affect precisely the zone in which many weathering mechanisms, responsible for physical breakdown, are concentrated (Warke *et al*, 1996). In cold environments freeze-thaw weathering is an additional processes which takes place when moisture present in the rock alternates between fluid and solid state, thereby varying the pressure within cracks and spaces resulting in weakening of the rock. However, the rate and spatial variability of freeze-thaw weathering depends on pre-existing weaknesses within the rock (Nicholson and Nicholson, 2000)

and thermal gradients within the rock surface (Hall, 2004). The principles of pre-existing weaknesses and thermal gradients within a rock have also been applied in temperate and warm environments; Hœrlé (2006) reported thermal fatigue through reversal of thermal gradients on a diurnal cycle in South Africa. In the context of this research he makes a number of very important observations. First of all, at his field site within the Drakensbergen area, where the GGHNP is also located, the Clarens sandstone does not record a thermal gradient steep enough to cause thermal shock, but the continuous diurnal variations in temperatures recorded could contribute to long-term thermal fatigue. Secondly, his measurements were recorded in the winter period, while "summers in the Drakensberg are warm and wet, and moisture-dependent mechanisms may then become predominant" (p.388).

The second process mentioned within the physical weathering processes groups is salt weathering. Goudie and Viles (1997) showed that salt weathering is prevalent in a wide geographical variety of arid areas. The destructive nature of soluble salts in combination with high evaporation rates causes high levels of salt to be mobilized within the rock surface and subsurface, creating a hostile environment in which rock weathering is rapid and often catastrophic. Experimental studies have suggested that, of the three mechanical mechanisms of salt weathering, crystal growth is the most significant in causing rock breakdown (Turkington and Paradise, 2005) where crystal growth exerts pressure against the pore walls, leading to a (millimetre-scale) structural breakdown of the rock. Benavente *et al* (2007) found that the rate at which salt can weather a rock surface is predominantly dependent on rock strength, with a minor contribution of water transport and pore structure parameters. Although this has been disputed by for example Smith and McGreevy (1988) who found a direct correlation between moisture movement, as connected to wetting and drying cycles, and salt accumulation.

The role of moisture in weathering is not only constricted to salt transport but also contributes to physical weathering through processes such as wetting/drying cycles. Well *et al* (2005) showed that

wet/dry cycling actively promotes changes to the pore structure of the rock. This can influence the nature and degree of other weathering processes operating synergistically with wetting and drying (Hall and Hall, 1996). In addition, Sass and Viles (2006) found that more weathered surfaces took up moisture, such as precipitation, more rapidly than non-weathered surfaces and also dried out quicker, leading to more intense wetting and drying cycles and creating a positive feedback mechanism. The influence of wetting and drying cycles can be exacerbated further if coupled with greater temperature fluctuations (Wells *et al*, 2005). The influence of moisture, and in particular internal moisture, will be discussed in more detail in section 2.4.

In addition to its role in physical weathering, moisture can exacerbate chemical weathering processes. Both hydrolysis and oxidation, two of the most common forms of chemical weathering, rely to some extend on the presence of moisture. The formation of solutional landforms, such as karst, through chemical weathering has been reported not only in limestone but also sandstone which is held to be almost insoluble (Wray, 1997). Chigira and Oyama (2000) found that 'mineralogy, geochemistry and physical and mechanical properties of (...) mudstones and sandstones in Japan showed that chemical weathering of sedimentary rocks is characterized by sequential reaction between percolating groundwater and rock-forming minerals (p.267). The interaction between moisture, oxygen and rock minerals can result in the chemical alteration not only of the grains (Islam *et al,* 2002), but more specifically the bonds between them. In some cases this can strengthen the rock through cementation of sand grains [within the sandstone] by iron oxide or hydroxide (Chigira and Oyama, 2000) or weaken the structural strength as reported by Qi *et al* (2009) who found that in limestone samples from the Three Gorges area (China), the chemical weathering changed the compositions of the limestone rocks, dramatically reducing the $CaCO_3$ content, which lowered the uniaxial compressive strength. It is therefore difficult to draw an overall conclusion regarding the influence of chemical weathering on rock as it is so heavily dependent on the material properties of

the rock. In addition, it often interacts with other processes such as salt weathering or drying and wetting cycles.

The final category mentioned in table 2.1 is biological weathering. Colonization of the surface by microorganisms can contribute further to the deterioration of the surface or cementation and subsequent case hardening (Herrera and Videla, 2009; Wessels *et al*, 1995). There are three distinct groups of living organisms that are associated with surface weathering; bacteria, archaea (which, although evolutionarily different, are often grouped together with bacteria) and eukarya (which include funghi, lichen and algae) (Viles, 1995). The presence of algae and fungi on stone surfaces is controlled by the deposition of micro-organisms, the stone structure and thus availability of water, nutrients and niches. Biological material may enhance chemical decay processes by increasing water uptake and gas diffusion, increasing the rate of deposition of acidic aerosols and facilitating ion exchange (Turkington *et al*, 2003). These organisms can cause chemical and mineral modifications in the uppermost layers of rocks, as well as changes in aesthetic appearance (Gómez-Alarcón *et al,* 1994). In the wider literature the impact of lichen on weathering is a prominent research focus. It is now widely accepted that lichens can play an important role in both the processes of physical and chemical weathering of rocks and minerals. These plants can influence weathering rates of the rock surface through the penetration of hyphae, the pressure exerted by contraption and expansion of the colony and the root system by microclimatic wetting and drying as well as freezing and thawing, and the introduction of organic and inorganic salts originating from lichen activity (Chen *et al*, 2000).

2.3 Sandstone weathering

In particular, sandstone weathering has become an often-researched field (Turkington and Paradise, 2005). The term "sandstone" denotes a large class of sedimentary rocks with different mineral compositions, diagenetic process and ages or degree of diagenesis. This diversity in rock-forming

origins results in a great variety of rock properties, including the strength, deformability, permeability and resistance to weathering (Lin *et al*, 2005). Sandstones are produced through the cementation or lithification of sand grains through processes of pressure melting and recrystallisation, compaction and consolidation of incorporated clay minerals, and/or by the precipitation of authigenic minerals from water migration through pores (Grab *et al*, 2011). It has been shown that petrographic parameters affect the physical and mechanical behavior of sandstone (Jeng *et al*, 2004), which in turn determine the weathering type and rate of the sandstone surface. The composition of the sandstone depends on the primary chemical composition of the source rock area, as sedimentary rocks while the textural characteristics are the products of weathering, transportation and sedimentary processes (Tijani *et al*, 2010). It is therefore difficult to give a description of 'sandstone characteristics' beyond generally found characteristics such as high quartz content, sometimes feldspar elements and a low clay content which acts as cement (Baraka-Lokmane, 2002). However, several studies (e.g. Netoff and Shroba, 2001; Young *et al,* 2003; Tijani *et al,* 2010) have remarked that in comparison to other stone types such as granite this is a relatively friable stone, and particularly susceptible to rapid weathering processes such as flaking and crumbling. Fitzner *et al*'s work (2003) in Luxor, Egypt, showed a wide range of weathering features within a relatively small area. Similarly, Sancho *et al* (2003) show that sandstone, in this case in the Ebro basin (Spain), exhibits particularly rapid weathering rates. In addition, sandstone weathering comprises several different stages, not all of which are associated with debris release and surface retreat, and over time the duration of each of these stages can be extremely variable (Warke *et al*, 2006). The initial weakening of the stone is not necessarily visible on the surface, such as subsurface weathering processes associated with salt and moisture accumulation and deterioration of the cohesion between individual grains.

A number of additional studies reflect the wide range of processes that have been earmarked as often occurring on sandstone surfaces; these include, but are not limited to, weathering induced by

temperature fluctuations (Warke and Smith, 1998; Smith *et al*, 2005; McCabe *et al*, 2010), dissolution (Colón *et al*, 2004; Aubrecht *et al*, 2011), formation of weathering rinds and cementation of the surface (Tratebas, 2004; Gordon and Dorn, 2005; Zerboni, 2008; Poursoltani and Gibling, 2011). Examples of some common sandstone material removal mechanisms, resulting from the aforementioned processes, are exfoliation and erosion (Friolo *et al*, 2003) where the loosened material is removed by wind, precipitation or physical contact with for example humans and animals.

Sandstone is a widely occurring stone type. Because of its relatively soft nature is has been a popular building stone and can be found in many places such as Angkor Wat, Cambodia (Hosono *et al*, 2006; Siedel *et al*, 2008), Petra, Jordan (Paradise, 2002; Heinrichs, 2008) and El Djem, Tunisia (Younes *et al*, 2011), and natural formations such as found in Arches National Park, Utah (Antonellini *et al*, 1994; NPS, 2011). However, sandstone's relatively low resistance to weathering processes, as previously discussed, has also posed problems. Regular replacement of building blocks and ornamental features in monuments can be needed due to the rapid deterioration of the stonework, especially in areas that experience high groundwater levels or extreme temperatures (such as found in desert environments).

This type of stone occupies a prominent position within this thesis as the rock faces visible, and investigated in this study, in the GGHNP consist predominantly of Clarens Sandstone. This type of stone has been described by Visser (1984) as being composed of fine-grained aeolian sandstone, deposited during the late Triassic when aridity reached its maximum. The stone is a well sorted clay-bound sandstone with 0.2–0.4 mm wide oval shaped mineral grains consisting mainly of silicate. Feldspars and micas make up less than 5% of the mineral content (Büdel *et al*, 2004). Its previous name of 'Cave Sandstone' refers to the most common form of weathering feature – shelters and caves. These shelters form the primary sites for the research presented in this thesis.

2.4 The role of internal moisture in weathering processes and rates

Even though progress has been made in the understanding of the weathering of sandstone, relatively little is known about the internal behaviour of moisture. Internal moisture constitutes any moisture found within a rock or rock face that has been transported there through infiltration, capillary rise or sources from within a rock face such as flow along bedding planes (see figure 2.1).

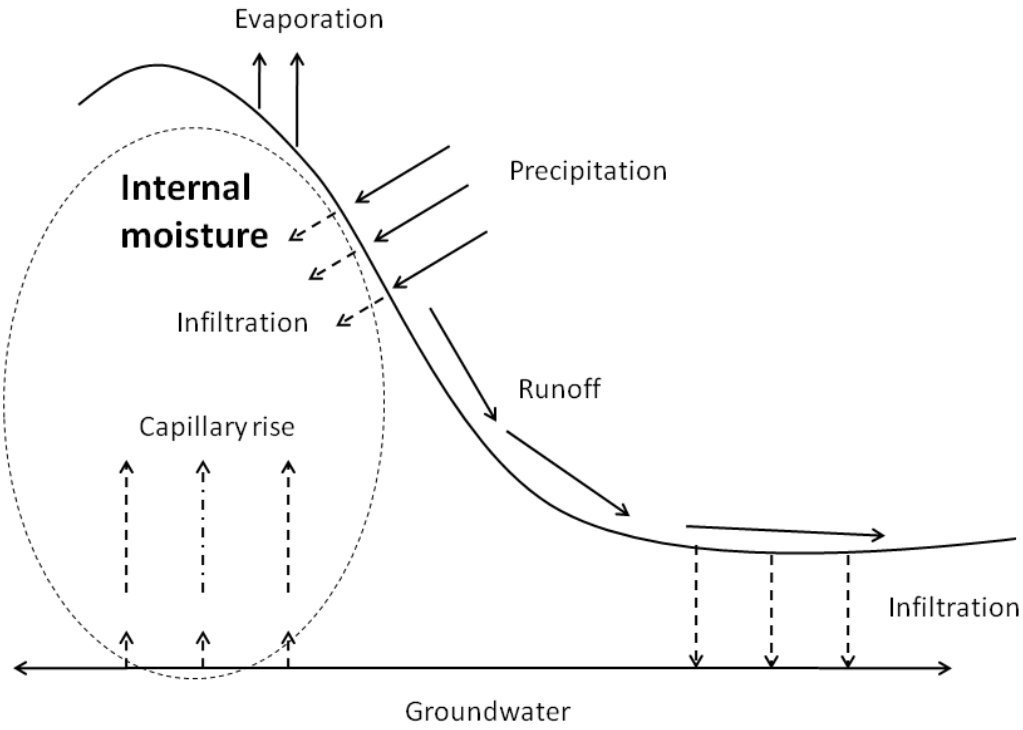


Figure 2.1: Internal moisture and its various sources

Internal moisture is commonly found in both natural rock and building stone and is maintained by capillary rise of groundwater as well as sources within rock outcrops such as infiltrated precipitation travelling along bedding planes. Hall and Hoff (2002, p.1) state that porous materials, such as sandstone, are almost invariably permeable and moisture, in the form of water vapour and liquid water, can penetrate into the pores and permeate through them and can then move freely under the action of capillary forces. This moisture is a critical trigger and accelerator of many weathering processes. Griggs (1936) found temperature fluctuation to be insignificant until the introduction of

moisture, which drastically accelerated the rate of weathering. This notion of the relative importance of moisture within stone has been build upon by a large number of studies, such as Matsukura and Takahashi (2000) who found that rock moisture content is a major control of not only salt weathering but also frost shattering. Similarly, Hosono *et al* (2006) reported that at Angkor monument, Cambodia, capillary rise of moisture through sandstone was the primary movement mechanism for soluble salts. These salts crystallize by evaporation of the penetrating water and exfoliation subsequently occurs due to the crystallization pressure of the salts. Further research has shown that indeed salt weathering is a particularly destructive force, causing accelerated flaking and exfoliation of the surface (Goudie and Viles, 1997; Kuchitsu *et al,* 2000; Mottershead *et* al, 2003; Smith *et al*, 2005; Hosono *et al,* 2006). However, the mobilization of salt first through solution and then transport to the stone surface requires the presence of moisture within the stone as well as the driving factors to facilitate the movement of moisture such as capillary movement and evaporation. Hall *et al* (2011) discussed the concept that capillary rise within a porous stone and subsequent evaporation is strongly influenced by external temperature changes. This amplifies the link between moisture and temperature made by Griggs (1936) and shows that the interaction between moisture and temperature can be significant.

To add complexity to the role of moisture in weathering, it can play a dual role within weathering processes. It can be an agent of stone weakening, such as the facilitation of salt transport and the fluctuation of pore pressure through the increase or decrease of moisture content (Hawkins and McConnell, 1992) but also facilitate the cementation of the stone surface, resulting in case hardening. Viles and Goudie (2004) show that rock-dwelling organisms, which are often sustained by the presence of moisture in the subsurface, may play a role in the development of case-hardened surfaces. In addition, Campbell (1999) proposes that the transport of mineral that form case hardening to the surface of the stone is driven by moisture. This process begins beneath the surface with raw materials being transported to the surface by capillary flow. While this hardened crust may

protect the rock surface from the most direct influences of external processes such as precipitation and can act as a cement to hold the stone surface structure together, it is also associated with sub-surface structural weakening (McAlister *et al*, 2003).

2.5 Cavernous weathering

However, despite the aforementioned agreements on the function of moisture within a porous stone, there are a number of issues that have not been answered conclusively. Of particular interest in this thesis is the contested role of moisture in cavernous weathering formation and progression.

Cavernous weathering can be found in a wide variety of environments, and manifest itself in a number of forms such as shelters, caverns, alveoli and tafoni. Turkington (1998) suggests that lithology and structure of the rock are important controls on the development of cavernous structures such as tafoni. However, the development of these cavernous features has been attributed to a large number of factors over the past 100 years. Primary processes suggested as being responsible for the formation of caverns have ranged from wind regimes (Futterer, 1897; Bartrum, 1936; Hall, 1989; Gillies *et al*, 2009) to fluctuations in moisture availability and relative humidity (Pope *et al*, 1995; Mellor *et al*, 1997).

In recent years salt weathering has dominated in the literature (Mustoe, 1982; McGreevy and Whalley, 1985; Young, 1987; Mottershead and Pye, 1994; Cooke *et al*, 1993 p.26; McBride and Picard, 2004; Strini *et al*, 2008; Mustoe, 2010), even though no consensus appears to have been reached over its precise role in cavernous weathering. In addition, case hardening – the formation of a layer of a few centimetres thick of increased hardness and resilience to weathering (Conca, 1985, p.3; McAlister *et al*, 2003) - is quoted as an important factor in cavernous weathering (Conca and Rossman, 1982) even though its precise role within cavern formation is not agreed upon. As Turkington and Phillips (2004) state, one of the predominant issues within cavernous weathering

research is the tendency to relate it to one single formative process, whereas in many cases cavern development can be only satisfactorily explained by invoking the operation of a range of weathering mechanisms. In particular, the role of internal moisture appears to be unclear. Sancho and Benito (1990) state that the surface and internal circulation of water will have a noticeable effect on phenomena such as wetting and drying and thermal weathering as well as salt weathering. Mellor *et al* (1997) clarify this role by linking evaporation to upward movement of soluble ions by capillary action which draws them towards the outer roof surfaces of the tafoni and precipitates them in the form of near-surface cement. However, this process may be limited to the outer roof surfaces, as in the cavern area the weathering has been suggested to be more rapid due to the absence of such protective cover, resulting in core softening – the weakening of the rock face within the cavernous feature leading to increased weathering and removal of material (Conca and Rossman; 1985; Mellor *et al*, 1997) - where material is loosened by flaking and granular disintegration. Dragovich (1967) observes that flaking is most commonly found within cavernous structures.

Hydration of some minerals points to the importance of moisture, which in the absence of extreme temperature variations, can evenly penetrate relatively unfractured rock and cause swelling of altered minerals. Fracture planes eventually develop along the boundary of innermost moisture penetration. Most non-caverned rock surfaces experience wide variations in temperature and moisture conditions, causing randomly oriented fissures to develop concurrently with a reduction in rock cohesion. On these surfaces, weathering proceeds principally by granular disintegration. However, this concept of cavernous weathering may be too simplistic as differential wind regimes within the cavern may also contribute to the formation of these features as increased wind speeds can increase evaporation rates, thereby exacerbating salt efflorescence on the surface of the cavern wall resulting in higher porosity and weathering rates (Rodriguez-Navarro *et al,* 1999).

Differential wind regimes and evaporation rates may lead to an uneven distribution of moisture and associated salt efflorescence. Matsukura and Tanaka (2000) researched the development of tafoni in

granite tors and found that the inner rock wall and ceiling of the tafoni showed reduced hardness and higher moisture content compared to the other visor of the tafoni, which was in agreement with the elevated salt contents they found at the ceiling and inner rock wall. Bradley *et al* (1978) found that the crystallization of salts in these areas of high moisture content was largely responsible for the formation of tafoni, but state, contrary to Rodriguez-Navarro *et al* (1999), that thermal changes or wetting-and-drying are not major contributors to tafoni formation.

To add further complexity, Lamb *et al* (2006) state that the origin of cavernous weathering and in particular alcove formation remains unclear given that the ability of seepage to erode bedrock is not yet comprehensively understood, and also because the other process mechanisms might have contributed to such cavernous weathering. As yet seepage weathering and erosion in rock have not been quantified, nor have mechanistic rate laws been proposed in the absence of an understanding of seepage erosion mechanisms. As Turkington (2004, p 666) states: "A problem that has beset studies of tafoni weathering has been the tendency to relate it to one single formative process, whereas in many cases cavern development can only be satisfactorily explained by invoking the operation of a range of weathering mechanisms"

2.6 Weathering research; issues in methodology development

In recent years the techniques and equipment available to researchers have consistently become more sophisticated. Research, both in the laboratory and in the field, has greatly improved our understanding of weathering processes. A large number of investigation methods have been newly developed, often adapted from other disciplines and modified for application on stone monuments. However, optimisation of diagnostical procedures and well-targeted evaluation of scientific findings for preservation purposes remains an important research task (Fitzner and Heinrichs, 2002). In addition, numerous studies have flagged up the issues of scale in weathering studies. One of the

reasons scale is seen as problematic is because explanations that appear to operate effectively at one scale, seem inappropriate at another (Inkpen, 2011). The greatest problems facing geomorphologists in weathering research are not only scale itself but also scale-linkage (Hall and Thorn, 2011). Therefore, as Viles (2005) proposes, as a precursor to investigating what is the preferred scale of analysis of weathering systems and which scales of processes and phenomena should be considered, it is useful to attempt to describe at which scales different processes and phenomena occur. In the case of internal moisture – the interaction between temperature, petrology and chemical processes, as discussed previously, add complexity on both a temporal and spatial scale.

Even though there are methods available for accurately measuring surface saturation of stone and rock (for example water absorption capacity, Mottershead; 2000 and Protimeter readings, Akiner *et al*; 1992), Matsukura and Takahashi (2000) state that there is a serious lack of monitoring data on rock moisture content under natural conditions. Only recently have methods become available to accurately measure and monitor the movement of internal moisture. The foremost of these methods is ERT (Electric Resistivity Tomography, as used by Oliver Sass. His work has advanced the usage of this method significantly in recent years (See: Sass, 2003; 2005; 2006, 2008, and Sass and Viles, 2006). This method is the primary tool in this research, and its background and development are discussed in detail in chapter 3.

2.7 Using weathering research to understand rock art deterioration

Rock art is a particularly vulnerable type of heritage. It is often painted or carved onto friable rock, such as sandstone, and the sheer number of rock art sites makes monitoring and protecting all of them an almost impossible task. There are a few famous examples of rock art from around the world, such as the Game Pass Shelter in KwaZulu-Natal, South Africa (Meiklejohn *et al,* 2009), the

caves of Lascaux, France (Malaurent *et al*, 2007; Bastian and Alabouvette, 2009), and the aboriginal rock paintings in the Jenolan Caves, Australia (Dragovich and Grose, 1990) which are well-documented and preserved but none the less still at risk of rapid deterioration. These, however, represent only the tip of the ice berg as in 1997 15,000 rock art sites in southern Africa were recorded but it is estimated there could be well in excess of 50,000 sites (Deacon, 2002).

Many of these sites are under threat from a number of factors. Exposure to precipitation and thermal fluctuations has caused fading of the pigments, leaving sometimes only faint outlines of the original painting. In the Albarracín Cultural Park in Spain, for example, some paintings have deteriorated to such an extent that they are barely identifiable (Benito *et al*, 1993). Similarly, abrasion of rock surfaces has caused wide-spread deterioration of rock carvings, especially ones carved into friable rock such as sandstone (Pope, 2000b). In arid environments the problems are exacerbated by the extreme thermal fluctuations, abrasion by sand picked up by air currents effectively sanding down the rock surface and, where applicable, intense rainstorms during limited annual periods.

A general lack of understanding of rock weathering mechanisms is considered to be the major reason for the inadequacy of previous research into rock art conservation and preservation in southern Africa (Meiklejohn *et al*, 2009). There appears to be a lack of consensus on the principle deterioration processes that affect rock art. This becomes evident when assessing the range of approaches that have been used to assess rock art deterioration and damage. Narrowed down to San rock art, the rock art present on the Clarens sandstone in the GGHNP, there are a number of studies; for example, work was carried out by Hall *et al* (2007; 2010) which investigated the influence of pigment reactions to thermal fluctuations and assumed that the variations in the upper millimetres of the sandstone are driving factors behind rock art deterioration. In contrast, Hœrlé (2006) found that the temperature regimes within the actual rock surface could be the cause of thermal stress fatigue, leading to rock surface, and therefore rock art, deterioration. In later

research, Hœrlé *et al* (2007) express the usefulness of GPR to assess the presence of cracks and fissures within the rock mass hosting the rock art and propose that it should be routinely used as a tool for assessing rock art deterioration mechanisms, placing the cause of the rock art deterioration further into the rock. Meiklejohn *et al* (2009) found that rock moisture regimes and to a lesser extent, rock thermal regimes exert the most damaging influence on San paintings, but focus on the area between the pigments and the rock surface rather than examining the rock near-surface. Prinsloo (2007) proposes a different moisture source that is increasing deterioration rates of the rock art, namely rock hyraces urine. This small selection of studies is an indication of the variety of approaches that are currently in use in the study of rock art deterioration. It also gives some indication of the lack of agreement over the dominance of weathering processes. Within this literary setting, the study presented in this thesis aims to contribute to our understanding of the influence of internal moisture on sandstone surface weathering, specifically within cavernous weathering, which can lead to the deterioration of the rock art hosted on the sandstone.

2.8 Concluding remarks

This literature review discussed the topics and issues that are connected to this research, namely: 1.Weathering studies, 2. Weathering processes, 3. Sandstone weathering, 4. The role of internal moisture in weathering processes, 5. Cavernous weathering, 6. Methodological issues and 7. Using weathering research to understand rock art deterioration. These topics represent the central issues in the development and execution of this research. The primary focus lies on sandstone weathering and the role of internal moisture in the formation of cavernous weathering. By extension, the deterioration of San rock art, as connected to surface weathering, is discussed. This literature review has highlighted the diversity of approaches and theories within weathering research and a number of debates regarding the complex nature of rock weathering. These have been taken into

consideration in the planning and execution of the research and the consecutive interpretation of the data.

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CHAPTER 3: ELECTRICAL RESISTIVITY TOMOGRAPHY: A LITERATURE REVIEW

This chapter was originally published in Archaeometry and discusses the usage of ERT within Archaeology. Despite its geomorphological content it is published in an Archaeological journal to inform archaeologists of the usage of these geomorphological techniques in archaeological investigations. The main aim of this publication is to discuss the general development of the method, showing both the various adaptations of ERT as it has been adopted by different disciplines and the underlying principles of software and hardware. I have used a number of case studies that are applicable to both geomorphologists and archaeologists alike which show the interdisciplinary nature of the technique, namely the historical wall within Hertford College, Oxford and the San rock art in the Golden Gate Highlands National Park, South Africa.

This paper argues that the internal processes, such as internal moisture regimes, are instrumental in the weathering of stone surfaces, whether these are natural as found in rock outcrops for example, or man-made such as hewn building stone and stone artefacts. It shows that an understanding of internal moisture, through advanced understanding of ERT, can be instrumental in our understanding of weathering of the surface and subsequent conservation strategies.

This paper was written to inform archaeologists of one of the latest geomorphological approaches in stone weathering research and how geomorphological research can contribute to understanding the deterioration of heritage. In addition, in the context of this thesis, the paper discusses the development and theoretical background to ERT and how its adaptation by a number of disciplines has contributed to its current form.

Submitted: 06/08/2009, accepted: 16/11/2009

Published in: Archaeometry (2010) 52 (6) 1079 - 1095

THE WRITING'S IN THE WALL: A REVIEW OF NEW PRELIMINARY APPLICATIONS OF ELECTRICAL RESISTIVITY TOMOGRAPHY WITHIN ARCHAEOLOGY

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Abstract

Natural processes are known to cause significant damage to archaeological monuments. In fact, the key to understanding the decay of building materials is the internal movement of water through the mineral matrix, which influences the distribution of chemical, physical and biological deterioration processes. Electrical resistivity tomography (ERT) was traditionally used as a surveying tool within archaeology, but a new high-resolution technique that accurately traces the movement of moisture in building materials could provide a vital tool for understanding the decay of many archaeological monuments. This paper considers current progress, the shift of ERT from soil to rock research and the impact that this development could have on future conservation, using Hertford College (Oxford) and Neolithic rock art (Golden Gate Reserve, South Africa) as case studies.

3.1 Introduction

Stone decay is a very widespread phenomenon, especially in archaeological and historical objects with higher porosity, such as sandstone, limestone and mortars. Many buildings and archaeological

remains are affected by it on a daily basis, whether it is through long-term microscale deterioration (Hall and André 2003; Viles 2005) or short-term catastrophic decline (Viles and Smith 2006). However, there are still numerous unknown factors within stone decay research (Hall *et al.* 2007; Summer and Loubser 2008). For instance, it is not yet known exactly how internal moisture distribution affects the failure of the mineral matrix in the upper layers of the stone. This process not only affects the building material but also causes flaking of rock art, frescos and buildings. The loss of this valuable and irreplaceable heritage could be greatly reduced through adequate monitoring. This would allow such sites to be preserved for future generations. Preliminary results from a new high-resolution application of electrical resistivity tomography (ERT) may provide ways of monitoring the moisture in heritage sites and thereby facilitate proactive remedial action.

This paper focuses on the application of this new technique within archaeology, and seeks to consider and assess the advances of ERT, and investigate how this new development within tomography opens up possibilities for archaeological research. It will also reflect on how the implications of this technique could potentially be applied to aid conservation of archaeological sites.

ERT is a non-destructive method that can be used to measure *in situ* the moisture content of stone. Originally, ERT was used predominantly as a geophysical technique for surveying large-scale features in the landscape. However, recent advances enable the researcher to measure on a meso-scale, using an electrode spacing of under 5 cm. These high-resolution results are very suitable for identifying moisture patterns within a restricted surface, such as a wall or rock face. The importance of internal moisture as a weathering agent has been discussed before (see Matsukura and Takahashi 1999; Vásárhelyi and Ván 2006), and ERT has been successfully applied as a method for furthering the understanding of the effect of moisture regime dynamics on the weathering of stone (Sass 2005, 2007; Sass and Viles 2006). In this paper, we shall consider two main case studies to demonstrate

the potential of this new technique. Case study one is based on fieldwork conducted on building materials in Oxford, UK. This work has shown that both groundwater and precipitation are often connected to spatially restricted disintegration of stone surfaces. This was a relatively unknown factor, even though it is commonly accepted as being of great influence, as there was hardly any data to prove the exact movement of moisture through building material.

The second describes the rapid decay of the rock surfaces in a rock shelter (Golden Gate Reserve, Drakensbergen, South Africa), which threatens Neolithic rock art. The rock art of the Drakensberg is the largest and most concentrated group of rock paintings in sub-Saharan Africa and is outstanding both in quality and diversity of subject. The San people lived in the mountainous Drakensberg area for more than four millennia, leaving behind them a corpus of outstanding rock art that provides an insight into their way of life and their beliefs (UNESCO 2000). However, these paintings are under severe threat of decay both through human interference as well as natural weathering processes. This decay is thought to be a direct consequence of the high levels of moisture in the rock surface, which can be attributed to its exposed position and the variable and harsh local environmental conditions (Mol and Viles 2010). At this site, the new ERT technique has been applied and preliminary results suggest that monitoring could assist conservation.

3.2 ERT development: a summary

Tomography is now applied in many fields, such as medical research (e.g., the monitoring of bone fatigue; see Leng *et al.* 2008), archaeology (Noel and Xu 1991), soil sciences (Daily *et al.* 1992) and Earth sciences (the identification of solid earth material composition as conducted by Friedel *et al.* 1996; Sass *et al.* 2007). Outside of archaeology in geophysical sciences, for example, ERT was adopted after Dines and Lytle (1979) suggested its use. Subsequently, it appears that the rest of the academic world followed suit as a result of Dines and Little's work. However, both electrical

resistivity tomography (ERT) and electrical impedance tomography (EIT) have been used in archaeology since the 1920s, predominantly as a prospection and survey technique, with what Gaffney (2008) described as a 'nadir' in the 1970s and a boom thereafter, particularly in the 1990s. As in other disciplines, especially the geophysical sciences, the method has gone through major changes since the late 1970s, with more and more applications being found (Dyakowski and Jaworski 2003).

ERT has, until recently, been used in archaeology as a solely ground-based geophysical survey technique that is relatively inexpensive and has allowed archaeologists to investigate archaeological sites and deposits with minimal disturbance. It has enabled archaeologists to noninvasively 'read' what is below the surface, either as a two-dimensional plan or, more recently, as a three-dimensional profile or a section of the stratigraphy. Using Ohm's Law, the resistivity of a material is derived using current and voltage values as measured by the electrodes. Differences in the amount of resistance are in response to the differing conductive properties of the sample body. This is determined by the amount of interstitial water and various salts held within. For example, buried walls offer high resistance, whereas the moister ditches or pits offer low resistance. The technique has been shown to be particularly successful in single-phase sites and is good for identifying silted ditches and pits in chalk and gravel, as well as masonry in clay (Clark 1996; Gater and Gaffney 2003). According to Gater and Gaffney (2003), ERT appears to have largely replaced magnetic methods, as it is thought to identify more or less the same features and it can be used in areas close to power lines and in the vicinity of metal. However, these advances have only been facilitated through the development of various 'add-ons' to the standard archaeological prospection equipment. For example, the employment of two- and three-dimensional non-linear algorithms for processing and interpreting the ERT data has allowed the results to be viewed in three dimensions and over a larger area (see Papadopoulos *et al.* 2006; Tsokas *et al.* 2008). Thus, in general, the ERT methodologies used today do represent an advance of the classical resistivity mapping, and together with specific

modifications can achieve many of the objectives that were previously solely measured by magnetic methods.

In terms of comparable tools for geophysical investigations, Leucci *et al.* (2007) have conducted a very comprehensive study comparing ERT to better known methods such as groundpenetrating radar (GPR); and although they preferred the GPR method for the particular site, they acknowledge that ERT identified irregularities within the samples and correlated well with the GPR.

It appears that resistivity studies may have been attempted much earlier in archaeological studies than the 1970s. Hans Lundberg, working in Williamsburg, Virginia (USA), developed various magnetically based techniques in around 1921 but was unable to complete his work. In 1938 it was Lundberg's assistant, Mark Malamphy, who completed the work to identify a possible stone vault beneath and adjacent to the parish church, using an 'equipotential survey' (Bevan 2000; Gater and Gaffney 2003), with parallel lines of grounded electrodes. Audio signals were used to trace changes in voltage, and used to map resistivity changes in the earth (Bevan 2000). This survey, by description, sounds remarkably like a precursor of ERT.

The first survey to have an impact on archaeological studies was in 1946, by Richard Atkinson at Dorchester on Thames, using a modified Megger earth tester and five probes based on the Wenner array. His results plots confirmed the presence of pits and ditches (Clark 1996; Gater and Gaffney 2003). Atkinson's success seemed to encourage archaeologists in Europe to use resistance techniques as a prospection tool to establish the most efficient place to excavate. During the 1960s and 1970s, attempts were made to simplify resistance survey. Changes in data collection using the Wenner array involved using a rigid frame, such as the square array with a resistance meter attached, so that an individual could carry it (Gater and Gaffney 2003).

Aspinall and Lynam (1970) developed the Bradphys resistance meter at around this time, and the innovative 'twin-probe' configuration after the pioneering work of Schwarz (1961). The twin-probe configuration can be regarded as a Wenner array effectively split into two, thus providing two current potential pairs—one mobile and one static. Around the same time, software was also refined and the first successful attempts to couple the instruments with the new generation of PCs were made (Kelly *et al.* 1984).

Geoscan Research's development of reliable, rugged, waterproof and lightweight instruments has taken the development of ERT as a field method further. One impact of the Geoscan devices was that, unlike the preceding Bradphys instruments, they could take readings without a need for back-off or balancing controls. Thus it became possible to record data more quickly, because there was little delay in the measurement of resistance value. Moreover, the watertight housing and larger battery allowed all-weather, and larger-scale, surveying to be undertaken. However, resistance values still had to be noted down, but eventually Geoscan developed a system that logged the data on a microchip. This automatic logging allowed surveys to become one-person operations (Heron and Gaffney 1987; Gater and Gaffney 2003).

During the late 1980s and 1990s, larger-scale surveys were undertaken. This was partly as a consequence of increased levels of construction leading to a greater need for environmental and archaeological assessment as part of the town planning process. Economic pressure strengthened the appreciation of geophysics as part of the mainstream archaeological methodology (Spoerry 1992; Gater and Gaffney 2003). This is because in the United Kingdom, for example, *Planning policy guidance 16* (Department of the Environment 1990) is said to underpin the use of geophysics, as it states that anything that is asked of a developer has to be 'reasonable and practical'. 'Reasonable' is usually interpreted as economical, and given that non-invasive work is cheaper than excavation, geophysical work is always an attractive option. This 'attractive option' stimulated by PPG 16

undoubtedly has been a significant impetus for the more widespread use of geophysical prospecting, including ERT techniques. Another, perhaps more universal, reason for the increase in use of geophysical techniques and ERT specifically is the suggestion by Gaffney (2008) that there is a reluctance among archaeologists to dig on conservation or ethical grounds. ERT and other geophysical techniques are ideal in this respect, as they provide some data in a non-destructive way.

It is evident from the discussion thus far that resistance techniques have, to date, been predominantly used as a prospecting or survey tool. However, elsewhere—for example, in conservation, medicine and now the work of a expanding group of researchers, including the aforementioned Sass and Viles, Tsokas, Leucci and Cataldo, amongst others—it has been shown that there are many other possibilities for the application of ERT other than solely prospection within archaeology. For example, a novel non-destructive technique using flat-based electrodes and bentonite mud (instead of metal stakes) has been used on the exterior south wall of the Acropolis, Athens, to view the cross-wall three-dimensional volume (Gaffney 2008 cites [Tsokas *et al.* 2006b]; Tsokas *et al.* 2006a). Areas of increased moisture were revealed in the prospected volumes, and the thickness of the wall was assessed at particular locations. Tsokas *et al.* (2006a) showed that these types of surveys are feasible and can produce informative results and elucidating images to archaeologists and restoration scientists. Gaffney states this novel approach is likely to be of use on historical buildings and sensitive archaeological structures. In this manner, the new technique to be discussed here has a similar potential.

Correspondingly, this approach enables the investigation of the inner core of solid material, with the actual end result depending on the interpretation of the resistivity results (Kemna *et al.* 2002). If, for example, the object being tested is known to be of one solid material, the resistivity can be used for moisture assessment (Jim Yeh *et al.* 2002). However, if the uniformity of the material is unknown, it can be used to detect differences in material (Chambers *et al.* 2006). This can be both a negative and

a positive for the researcher, as it can lead to inaccurate interpretations when the uniformity of the material is unknown, but within archaeology this actually opens up new possibilities of detecting voids and distinct changes in materials that would have been difficult to trace at a high resolution with other instrumentation (see, e.g., Tsokas *et al.* 2008).

3.3 Technical information on the new ERT technique

ERT is a method that calculates the subsurface distribution of the volumetric resistance from a large number of measurements (current and potential) made from electrodes attached to the sample body. Each data point is the result of the potential resistance reading between two electrodes and placed within a 2D profile. The most likely resistance distribution within a profile is then calculated using Archie's Law (Tronicke *et al.* 2001; Morelli *et al.* 2007). The particular combinations of electrodes are arranged according to the sampling scheme (i.e., Wenner), with the spacing between the two selected electrodes becoming greater according to depth. A single resistivity measurement contains the quotient of the current, which comes from two selected electrodes placed in the ground, and the voltage, which is given off by two other electrodes (Friedel 2000). A sinusoidal current source is applied to a pair of electrodes, at a frequency of some tens of kilohertz, and measures the resulting potential between other pairs of electrodes (York 2005). The sum of all these individual readings is then collated into the interface as is shown in the GeoTom raw data (see figure 1).

The trial data in figure 3.1 shows that in this case there was a problem with one electrode, as marked in the figure, which probably had poor adhesion. However, these problems show up in real time in the software's graphical output, enabling quick identification of the problem and the possibility of re-measuring after checking the electrode. If the problem persists and, for example, an electrode cable is broken and cannot be repaired in the field, the false data point(s) can be deleted

permanently. Since a standard 50-electrode, 16-layer 2D measurement consists of 392 individual data points, it is statistically viable to simply cut these out and calculate the most likely value through an inversion algorithm. These algorithms are loosely based on a '*K* nearest neighbour' system, as introduced by Fix and Hodges (1951), which assumes that a value can be calculated from the data points that surround it, weighted by the distance between unknown data and known data point. This complete array of data points is then converted into a pseudosection through an inversion algorithm.

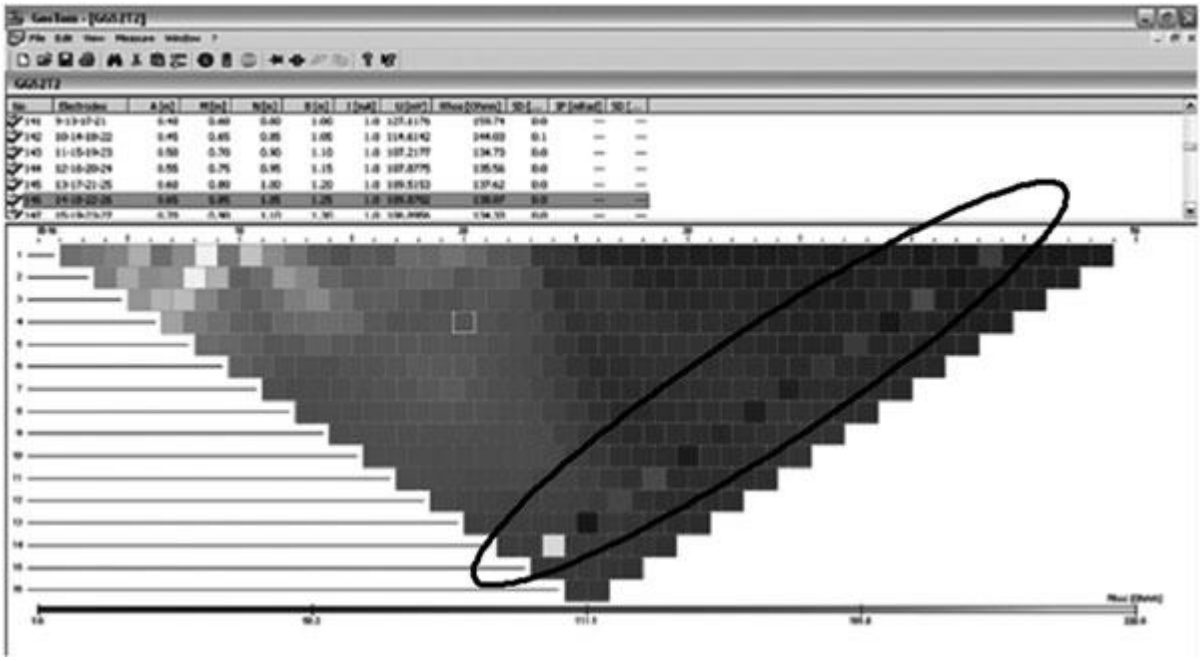

Figure 3.1: A pseudo-section of the GeoTom raw data, showing the Wenner triangular set-up and the faulty electrode (circled). Lower resistivity can be seen on the left side of the section (light tones), whereas the right side shows higher resistivity (dark tones).

A pseudo-section is a representation of apparent resistivity variations in the subsurface. A pseudo-section is not only a function of subsurface resistivity distribution but also a function of the geometry of the electrodes. Therefore, to obtain more accurate resistivity distribution of subsurface, an inversion process is applied. To achieve this, an algorithm mainly based on matrix algebra is

carried out in an iterative manner using apparent resistivity pseudo-sections as input. The result of this calculation gives the true resistivity distribution in the subsurface. (Drahor 2006)

Within the RES2Dinv program, which is used for this research, a forward modelling subroutine is used to calculate the apparent resistivity values, and a non-linear least-squares optimization technique is used for the inversion routine (deGroot-Hedlin and Constable 1990; Loke and Barker 1996). The inversion routine used by the program is based on the smoothness-constrained least-squares method (deGroot-Hedlin and Constable 1990; Sasaki 1992). The RES2Dinv smoothness-constrained least-squares method is based on the following equation:

$$(\mathbf{J}^T\mathbf{J} + \lambda\mathbf{F})\,\mathbf{d} = \mathbf{J}^T\mathbf{g}, \text{ where } \mathbf{F} = \mathbf{f_x}\,\mathbf{f_x}^T + \mathbf{f_z}\,\mathbf{f_z}^T,$$

in which **fX** is the horizontal flatness filter, **fZ** is the vertical flatness filter, **J** is a matrix of partial derivatives, l is a damping factor, **d** is the model perturbation factor and **g** is the discrepancy factor (source: RES2Dinv software technical report, included with software).

To attach the electrodes to a sample body, there are several options, including medical electrodes or screw-holders. The relative destructivity of a method needs to be taken into account when working on archaeological sites—for instance, screw-holders would leave marks as they need to be attached into the surface through drill-holes, whereas medical electrodes may leave a light bleach mark (due to the chemicals in the conductive gel—these are further discussed in the methodology section) but would not damage the actual mineral matrix. Tests on several buildings around Oxford, such as the old city wall in Hertford College (approximate location: Ordinance Survey Great Britain grid reference SP51580642) confirm these observations.

3.4 Current usage of ERT within stone decay research: a case study from Hertford College, Oxford

ERT has already been tested on different geological materials (see Schrott and Sass 2008), and the results showed that it is a very good method of tracking moisture behaviour within a sample body. However, thus far no universal calibration curve exists for easy conversion from relative to absolute values. This does not diminish the usefulness of ERT as a method for conservation purposes, but it does raise questions when comparing data from different sites and stone types. Despite these initial problems with the interpretation of ERT measurements, several field studies have already been carried out (see, e.g., Sass and Viles 2006), with very encouraging results.

One of the case studies used here was conducted by Mol and Preston in September 2008 on the old city wall, which is now within Hertford College, Oxford. Fieldwork was undertaken to illustrate the use of ERT on historic surfaces. It was undertaken in September deliberately because of the elevated moisture levels hypothesized to be in the walls, due to high precipitation. The results illustrate the hydrological transport systems within the wall very well. This wall is also of particular interest as it is exposed on one side but sheltered by a building on the other side (which appears to be a relatively recent addition to the quadrangle). It consists of irregular shaped locally sourced, most likely Headington stone, blocks that are heavily weathered. Headington freestone (the 'soft' stone that was used for walls and carvings, as opposed to the Headington 'hardstone', which was predominantly used for plinths) is a Middle Jurassic calcareous and fossiliferous limestone (Watson 1911). This type of stone was heavily used in the 17th- and 18th-centuries building surge of the university, but also during medieval times, before being abandoned due to its extraordinarily high weathering rates (Arkell 1947; Viles 1996). The exact date of the wall's erection is not known, but it is assumed to have medieval origins, along with parts of the city walls within the grounds of New

College. Exposure has created thick black carbonate weathering crusts, which occur frequently widely across Oxford, and a very fragile surface where exposed (see figure 3.2).



Figure 3.2: ERT measurement transects on Hertford College city wall: the white lines are the rows of ECG electrodes used to attach the GeoTom electrodes to the wall

Viles (1993) reports that *The formation of black, gypsum-rich crusts which then blister and exfoliate is the most important decay feature found in Oxford (...) the severity of blackening and blistering is only partly correlated with heavy traffic as many of the decay features are residual forms produced when coal burning was common.*

Even though a vast amount of the Headington freestone has been replaced (for a good overview of Oxford building stone decay and replacement, see Viles 1996), this part of the wall has seemingly survived the frenzy of replacement and rebuilding that took place during the 17th and 18th, as well as disastrous repair work in the 19th and 20th, centuries. There is, however, evidence of stages of modification and repair, including remnants of metal braces (probably 19th-century), concrete infilling and a layer of baked roof tiles, as well as a layer of brick and concrete on top of the wall (modern). It is very possible that this wall has been spared by humans and time because it is sheltered by 18th-century and modern buildings, as well as simply standing in a place where there is not enough space for another building and 'not being in the way enough' to warrant the effort of destruction.

3.4.1 The methodology of the Hertford College case study

The two rows of medical electrodes (transects) can be seen in figure 3.2. Each transect measures 1.96 m, using 50 electrodes at an interval of 4 cm. This interval was set to cover the span of the wall, without compromising the resolution. The Wenner array showed the best results, a very low error and a profile that appears representative of the wall, after the Schlumberger and dipole–dipole arrays had been used as well. This is possibly because the Wenner array appears to be less sensitive to abrupt changes within a sample body and is therefore very suitable for a wall consisting of stones, mortar and an array of modifications and repairs. Two pseudo-sections were taken for each transect, to assess the validity and repeatability of the measurements. ECG electrode stickers were used to attach the electrodes to the wall. These are disposable, widely available and economical. They have also demonstrated excellent adherence to most surfaces, and the Ag-based gel pad offers the conductive surface needed to guide the current into the sample body.

Alongside each transect, Protimeter readings were also taken to correlate surface moisture to the internal processes and test the accuracy of the Protimeter. The Protimeter measures surface and

near-surface saturation, using a simple resistivity measurement between two points. Previous tests have been conducted with the Protimeter (see, e.g., Gomez-Heras *et al.* 2008) and it is considered a very good support tool for moisture investigations (Forsén and Tarvainen 2000).

3.4.2 The results of the Hertford College study

The second transect (seen on the right in figure 3.2) proved to be of particular interest. The results for this transect in Figure 3 clearly show the drying patterns of the wall and the influence of the shelter behind it, as the white and light grey areas show low resistivity (wet), while the dark grey and black areas indicate high values (dry). Of course, the heterogeneity of the sample poses a problem for the correct interpretation of the results, but in light of the correlations between field observations and patterns found within the pseudo-section and the absence of metal clamps in the vicinity of the measurements, we determined that this measurement provides a good representation of the sample.

The Protimeter readings taken at each electrode can be seen on the right of figure 3.3. The dark bars of the histogram indicate a measurement taken on stone, whereas the light bars show measurements taken on mortar between stones. The ERT measurements show two distinctly wetter areas, at the top and the bottom of the wall. This is the direct result of moisture sealing at the top of the wall by the concrete capping (see Viles and Wood, 2007) and capillary rise of groundwater at the foot of the wall. The area towards the back of the wall is also wetter, most probably because of the shading of this side of the wall by the building behind it. In contrast, the front is exposed to sunlight and, accordingly, shows markedly drier areas. While all this makes sense in theory, it is necessary to quantify this for each individual site, as problematic areas cannot always be identified by the naked eye or even by surface saturation instrumentation.

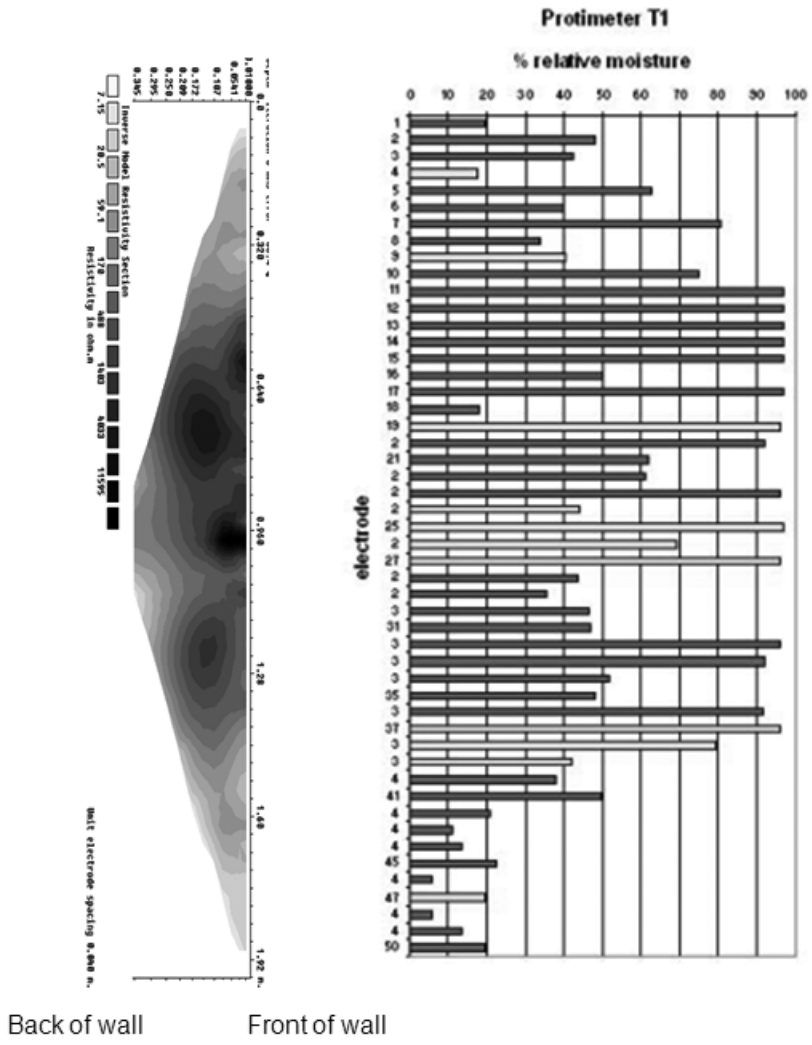

Figure 3.3: A comparison of ERT results of Hertford College city wall and Protimeter measurements. Dark tones indicate high resistivity, light tones low resistivity. Protimeter results are differentiated by (a) taken on stone (dark bars) and (b) taken on mortar (light bars).

It is remarkable that the Protimeter shows an inverse trend compared to the GeoTom: where the GeoTom indicated low levels of moisture, the Protimeter measured very high levels of surface saturation. A reasonable explanation of this discrepancy in measurement is that those areas capable of drying out quickly, such as the areas where the black weathering crust has crumbled and where water has an easy outlet, show a very wet surface but are in fact very dry at subsurface and deeper levels. This shows that weathering crusts and biomechanical weathering have a protective as well as

a destructive internal and external function. In this case, crusts prevent the outlet of water, but also function as an adhesive for the fragile surface of the stone. Even though this is a reasonable assumption to make, very little research has been conducted on this two-way process, and future investigations are needed to understand the function of weathering crusts as a sealant.

The Protimeter also shows very little or no difference between the measurements taken at the stone surface and the mortar, as indicated by the white (mortar) and grey (stone surface) bars in figure 3. The GeoTom, however, does identify these irregularities within the sample body, as shown by the high resistance in the centre of the wall surface. In terms of ERT assessment as a method for understanding decay in archaeological and historical surfaces, Schrott and Sass (2008) praise ERT for its versatility in spacing and configuration, and point out that because of its adaptability it has no issues with topography, which is extremely useful when, for example, measuring a curved rock wall or an ornate historic building. However, the majority of archaeological investigations using ERT have applied it as a method for investigating the structure of the soil and the possibility of artefacts being present (Leucci *et al.* 2006; Negri and Leucci 2006; Cardarelli and Di Filippo 2009).

3.5 San Rock Art deterioration and ERT research

As well as the field study conducted in Hertford College, the ERT equipment has been used in the Golden Gate Reserve, South Africa, where the Neolithic rock art of the San people is severely under threat from flaking, blistering and fading of the rock surface. Figure 3.4 is an example of the San Rock Art found within the reserve, which is rapidly losing painted surface because the surface of the rock is detaching.

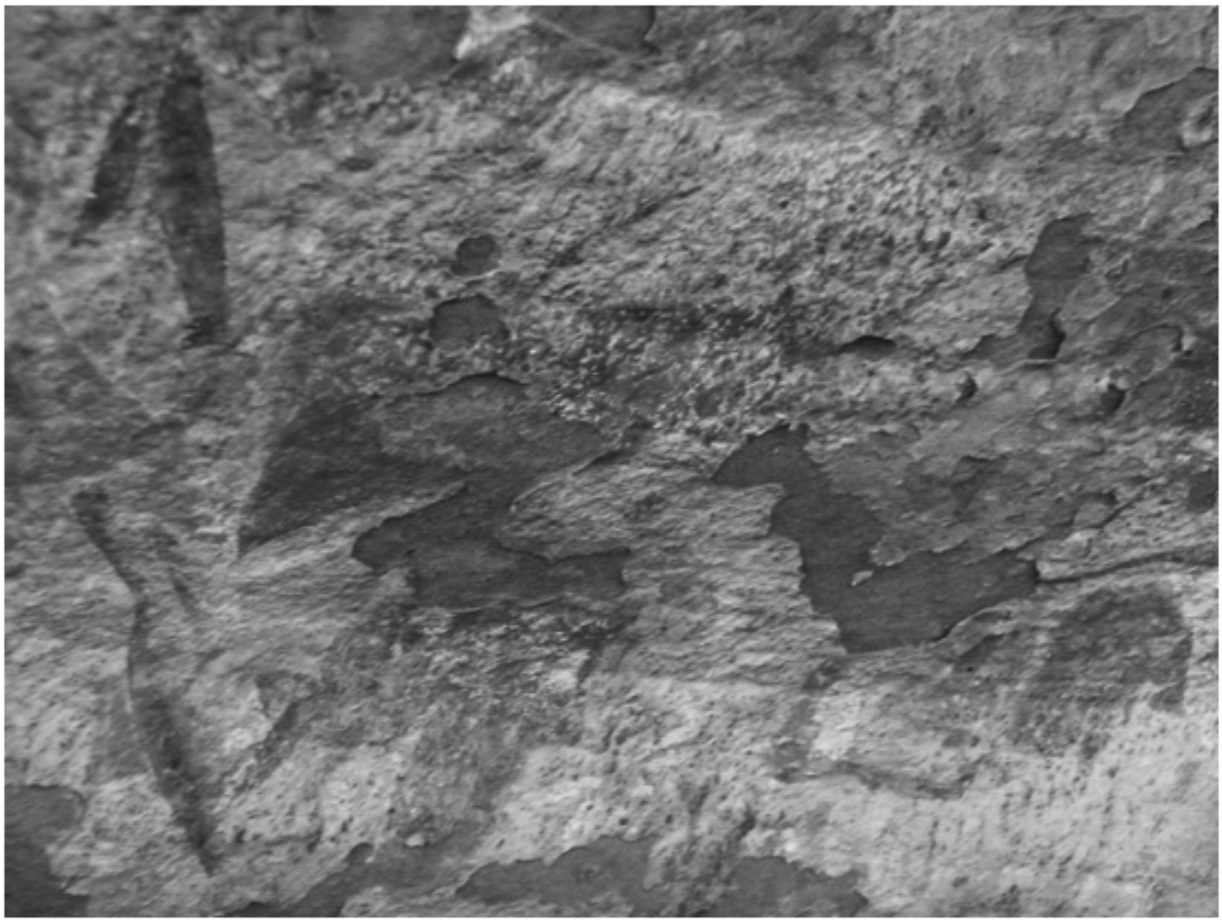

Figure 3.4: Severely deteriorated San Rock Art, showing an eland surrounded by hunters.

Initial ERT measurements show that, contrary to assumptions made by Meiklejohn (1994, 1997), the sandstone is permeable enough to allow moisture to pass through relatively freely. Figure 3.5 shows the sandstone face at site 1, where at approximately 1.5 m above the horizontal surface water is freely pouring out of the rock. All outlets are situated at roughly the same height within the sandstone exposure, and show that there are similar internal moisture mechanisms operating on both sites. This could be a bedding plane or another form of major fissure, for example.

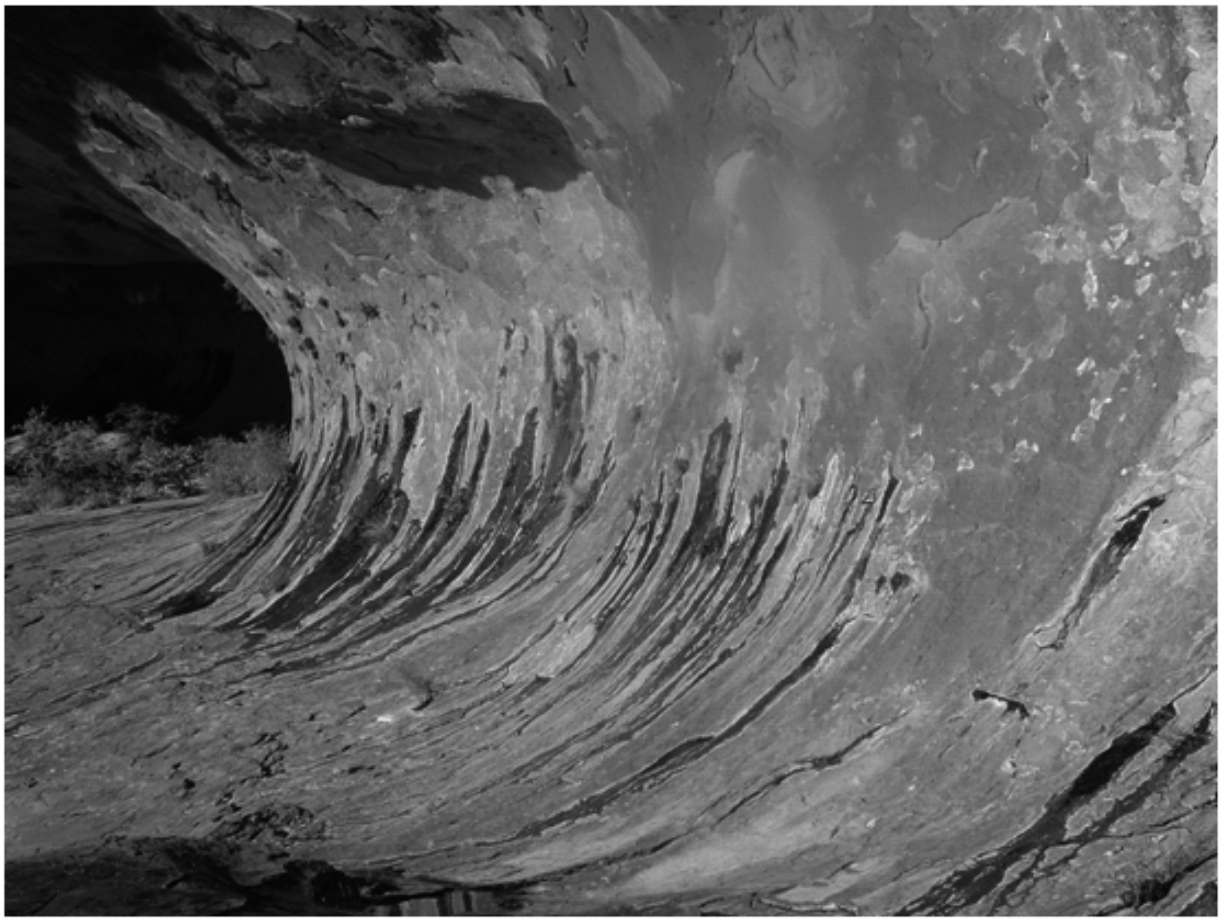

Figure 3.5: The site 1 rock face, showing moisture outlets. Dark streaks on the face are the result of moisture coming out of the rock at specific points.

However, upon closer examination the most significant difference between the two sites is that site 1 (figure 3.6) is drier than site 2 (figure 3.7). This is surprising because site 1 is situated under a large overhang, recorded lower temperatures in April 2008, and the surface receives very little exposure to wind and sun. In contrast, site 2 is a fully exposed rock surface that is protected by only a minor overhang and that showed high rock surface temperatures. One would expect that site 2 would therefore be significantly drier than site 1, and this reversal is testament to the importance of internal moisture. This reversal is caused by the wider setting of the sites, site 1 being capped by very thin topsoil that does not store water very well. Site 2, however, is embedded in a larger slope, with a thick layer of topsoil situated over and around the site. This makes it extremely suitable for

water storage during the wet season (December to January) and gradual release of this moisture during the dryer season (May to September).

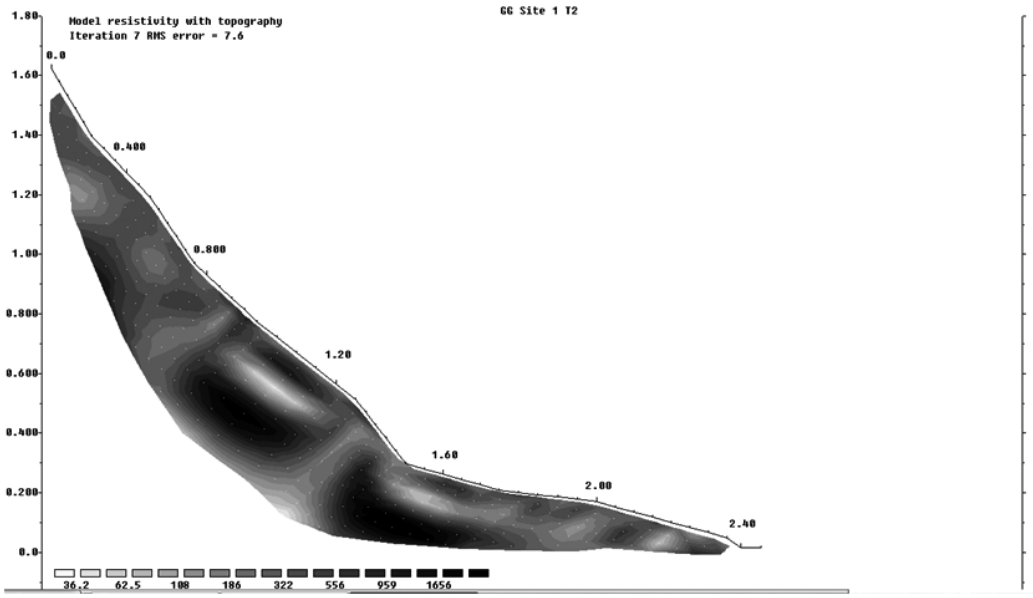

Figure 3.6: A pseudo-section of Golden Gate site 1, approximately 2.45 m long. The wet 'outlets' (low-resistivity sections, light tones) are clearly visible around the drier core of the rock face (dark tones).

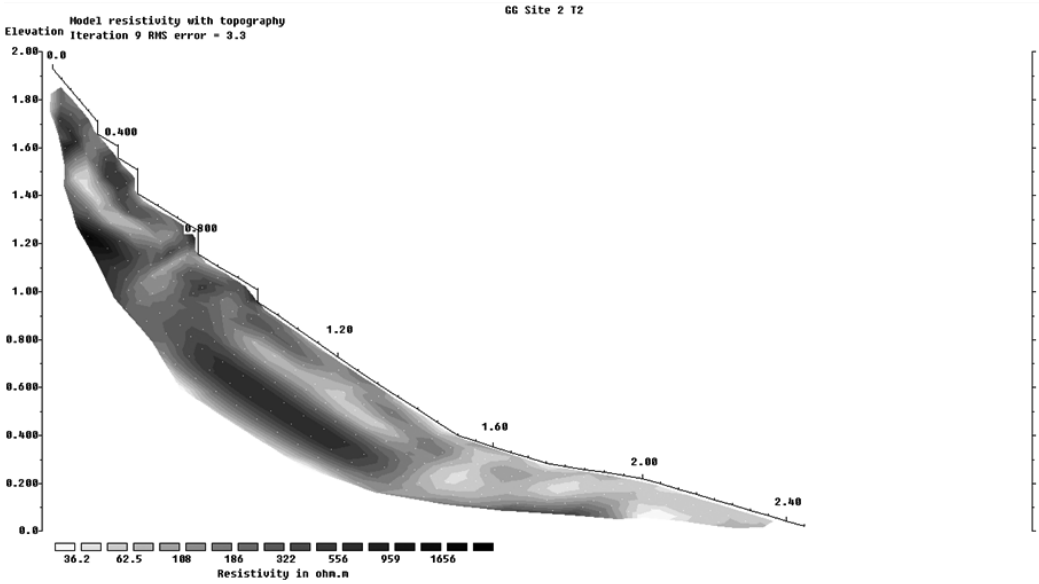

Figure 3.7: A pseudo-section of Golden Gate site 2, approximately 2.45 m long. The wet 'outlets' (low-resistivity sections, light tones) are dominant towards the lower end of the section, and moisture appears to be more superficial in the middle section.

This is important in that it would be very easy to assume that site 2 is drier on the basis of the fundamental geomorphological understanding of rock weathering. In addition, the ERT measurements highlight a different regime that could be very significant for conservation of the rock art and could be otherwise undetected. These are the same sort of surfaces that have been used as a canvas for San Rock Art for millennia, and their deterioration poses significant conservation problems.

3.6 Further application of ERT in Archaeological sites

Although this ERT method is still relatively new and to date not widely used, it could be very advantageous for both the further study of archaeological sites and also as a tool for the monitoring of heritage sites that are threatened by increasing stone weathering. ERT in a similar form has been used by Tsokas (Tsokas *et al.* 2006a, 2008) to survey the south wall of the Acropolis and to explore sensitive religious structures such as the Kapnikarea Church in Athens, Greece. However, they used this technique in a different form and with an entirely different aim to the one that we describe in this paper. For instance, the way in which they have used ERT is in the more conventional mode of a large-scale prospecting soil survey, to identify archaeology buried within the sediments (in this case, behind the walls on the Acropolis and Kapnikarea Church). Moreover, they used large-scale electrodes to survey the stone surface of the surveyed area, but they did not focus on moisture regimes within a rock or stone mass, as is proposed in this novel ERT application. Thus, the ERT employed in these other applications differs, as it is still used largely as a prospecting surveying tool, compared to the use of the new technique (presented above) as a means of studying weathering processes.

To illustrate the potential uses of this new ERT application, we evaluate two case studies. The first, the Sphinx (Giza plateau, Egypt), traditionally dated to the Fourth Dynasty (Stadelmann 2000;

Shortland and Doherty 2001), was claimed by Reader (2001a,b) to date from the predynastic period, with its associated widespread cultural activity, on the basis of his superficial analyses of weathering patterns focusing on the origins of bed 1. Yet archaeological evidence only reveals sporadic predynastic activity (Wilkinson 2001) and such arid regions have highly complex weathering systems (Smith *et al.* 2005), which are renowned for their problems with salt-induced weathering through groundwater rise (see, e.g., Arief *et al.* 2002), which is a possibility not thoroughly researched by Reader. Indeed, salt weathering caused by capillary force has been reported elsewhere in Egypt (Smith 1986; Fitzner *et al.* 2003). The second case, Petra (Jordan), is regularly listed amongst the most endangered sites (World Monuments Fund 2009) due to increased magnitudes of weathering (Waltham 1994; Akasheh 2002; Paradise 2005), exacerbated by burgeoning tourism (Lubick 2004), with the consequent problems of humidity and erosion (see, e.g., Smith 1986). In particular, tafoni formation, distinct honeycombed cavities formed through rock flaking, has intensified. This is due to the growth of fractures in the sandstone through seismic activity and freeze–thaw processes facilitating water accumulation, a process most acute on east–west aspects that are frequently wetted from storms or morning dew and then heated by the sun. Increased salinity caused by modern irrigation practices, with associated water table issues, also contributes to weathering (Waltham 1994; Paradise 2005).

Both case studies are ideal subjects for the new ERT, as they are concerned with water movement in the rock. It would be a valuable research tool for tracing the movement of groundwater through the stone—not just assessing the source of internal weathering in the Sphinx (which is key to Reader's claims for its age), but also confirming or excluding the possibility that rising salt could be of consequence to weathering sequence interpretation. It could also prove an essential conservation tool at Petra, through the monitoring of moisture levels, which are directly responsible for tafoni in the rock, and it would also facilitate an enhanced understanding of the hydrology that would enable the formulation of more appropriate long-term conservation strategies.

3.7 Conclusions

To conclude, we have summarized how electrical resistivity has become an essential tool in archaeology, particularly as a ground-based prospecting tool, and that its development is directly related to the changing needs of the discipline. Importantly, we can see that we are at another convergence point, where ERT can now be used as a tool not only to prospect the material culture within sediments but actually on walls of structures, whether caves or buildings.We contend that this new technique potentially opens up a new window of opportunity for archaeology, not only as a way of understanding current and past environments, and hydrology, but also as a tool in the arsenal for conservation purposes. It may also prove to be a useful prospecting tool for standing structures of any age.

In particular, the results presented demonstrated the potential of this technique for understanding hydrology and weathering processes within different rock types, through case studies at both Hertford College and at the San/Neolithic rock shelter (Golden Gate Reserve). We then showed the potential applications of this new technique for resolving questions of archaeological research related to weathering processes such as the controversy concerning to the age of the Sphinx. We also outlined the technique's possible use as a means of better understanding the hydrology and weathering within different rocks, and together with the portable nature of the apparatus used and the understanding this technique enables, we contended that it is potentially a vital new tool for the conservation of world heritage. These are just a few examples of applications (provided as an illustration) of how this new technique could be employed in both archaeological research and the conservation of heritage. However, we believe that this new ERT technique will provide additional solutions to archaeological problems as it is developed further.

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CHAPTER 4: INVESTIGATING SANDSTONE WEATHERING: A DETAILED FIELD METHODOLOGY

4.1. Summary

To collect the field data for this research, two periods of fieldwork were carried out in the Golden Gate Highlands National Park (GGHNP), South Africa. Several different methods were applied to assemble a multi-variate dataset. These included ERT, Protimeter, I-button dataloggers, Equotip and Karsten tubes. The approach taken for each of these methods is described in this chapter.

4.2. Introduction

To gain an understanding of the development of cavernous weathering in sandstone as found in the GGHNP and how this relates to internal moisture two fieldwork seasons, April 2008 and March/April 2009, were spent collecting data on surface hardness, saturation, internal moisture and weathering features. The first season took place in April 2008, and two sites were evaluated to determine the suitability of the GGHNP sandstone for this project, to collect data on the Clarens sandstone and to assess the condition of the San rock art found in the area. All of these goals were achieved and the GGHNP continued to be the focus of this research.

The complexity of the weathering processes that are evident in the Clarens sandstone adds not only academic interest but also poses a large problem for San rock art conservation. At all sites crumbling, flaking and cracking were evident within small areas and high weathering rates were noted during the second field season in April 2009. Therefore, a larger number of

sites were investigated to assess the variability of weathering processes within the Park and to correlate any specific occurrences with aspect and exposure. As well as Protimeter and Equotip readings along each transect, larger scale surveys were conducted to establish rock surface hardness and saturation on a meso-scale, using grids of 5m x 3m and taking nine measurements within each square meter.

Samples were taken at all sites for laboratory investigations, including porosity and WAC, microscope, SEM and conductivity. Samples were taken along each transect, at the top, the middle and the bottom. Larger sections of rock were also taken from representative rock faces to analyse mineralogical composition of seemingly oxidized and non-oxidized rocks.

In comparing ERT with other methods, Maillet *et al* (2005) used GPR and ERT to assess root volume in pine and poplar forests. They found that *"whereas seismic tomography and GPR surveys can (…) provide detailed visualisation of the shallow subsoil and channel infills these methods do not provide lithological information and they are not directly sensitive to salinity and porosity*." They found instead that ERT was a very useful tool for mapping resistivity distribution, which can be used as an indication of salinity and porosity. Results such as these suggest that ERT is a promising method especially when salinity and porosity need to be understood as a factor within weathering processes.

However, there are issues within the larger research context that need to be discussed first, such as the correct scale for rock art research. Many different studies have been conducted on rock art deterioration. Often these are limited to a specific scale, micro (pigment and grain scale), meso (individual rock faces) and macro (shelter formation within the larger landscape). Most rock art research focuses on the micro-scale, which is not necessarily the best approach as it does not address the wider problems that surround rock art

conservation. Therefore, the wider scale issues within rock art research and the placement of this research within this context are discussed first.

4.3. Scale issues in rock art deterioration research

Not only in rock art research, but in the physical sciences as a whole, field methods are subject to constant revision and adaptation with the ever changing needs of sciences. It is therefore of utmost importance that any methodological design is adjusted to not only suit the purpose of the research but also employ the techniques in a scientifically responsible manner as well as adjust to the environmental circumstances of the work. As far back as 1939, Hartshorne argues that landforms should only be studied as a set of interrelated features, which, applicable as it may be to large-scale landform development studies, does not provide a good basis for the approach necessary for this study. This has been confirmed in more recent studies such as Church and Mark (1980), de Boer (1992), Andrle (1996) and Gustavsson and Kolstrup (2009).

This research is based on meso- and micro-scale measurements and observations of sandstone weathering, both because of the scale of the San rock art and the nature of the weathering processes in the Clarens sandstone. Scale issues in weathering research have been drawn to the attention of the wider research community (see for example Viles 2001 and Smith *et al* 1994). These usually prove to be a difficult point, as micro-scale measurements cannot be extrapolated to macro-scale level without compromising on resolution, or risking generalized conclusions that are not necessarily accurate.

Rock art deterioration research is a well-established field, with many publications over the past century. These range from observations of increased flaking, to pigment analysis to

geomorphic assessment, the approaches to rock art research vary greatly. Table 4.1 gives an indication of the wide range of research techniques and environments. Individual research projects have been grouped together to show that different researchers in widely different locations apply the same approaches and techniques. There is a geographical bias towards southern Africa, but this is due to the vast number of rock art sites in this particular part of the world.

Micro-scale			
Focus	Location	Technique(s)	Author(s)
Rock art pigment analysis	Lower Pecos and Big Bend, Texas, USA Catamarca, Argentina	Raman Spectrography	Edwards *et al* (2000)
	Napier Range, Western Australia	microscopic examination, wet chemical analysis and X-ray analysis	Ford *et al* (1994)
	Southern Africa	XRD and SEM analysis of pigments, infrared and thermocouple thermal data collection	Hall *et al* (2007)
	Game Pass Shelter Kamberg Nature Reserve uKhahlamba-Drakensberg, South Africa	Temperature sensors on simulation block in laboratory circumstances	Hœrlé, S. (2006)
Rock surface weathering (mineralogical scale)	Luxor, Egypt	X-ray diffractography	Wüst and McLane (2000)
	Game Pass Shelter, Kampberg, uKhalamba-Drakensberg, South Africa	Rock surface and air temperature monitoring, relative humidity	Hœrlé (2006)
	Giant's Castle Game Reserve, uKhalamba-Drakensberg, South Africa	Rock and air temperature monitoring, chemical analysis through laboratory simulation	Meiklejohn *et al* (2009)
	Western Norway: Stavanger and Sogn og Fjordane	Thin section microscopy	Walderhaug (1998)
	Whoopup Canyon, Wyoming	Microscopy and x-ray analysis	Tratebas *et al* (2004)
Meso-scale			
Rock surface deterioration	Golden Gate Highlands National Park, South Africa	ERT, Equotip and Protimeter	Mol and Viles (2010)
	Mapungubwe National Park, South Africa	Raman Spectroscopy analysis of rock hyrax damage	Prinsloo (2007)

	Two Rock art sites, uKhalamba-Drakensberg, South Africa	GPR analysis of rock wall flaking	Hœrlé *et al* (2007)
	Sydney Basin, Australia	Geomorphological field appraisal and granulometry	Hughes (1978)
	Southern Australia (not specified)	Air and rock surface temperature monitoring in caves as well as relative humidity	Dragovich (1981)
Macro-scale			
Rock wall deterioration	Game Pass Shelter, Kampberg, uKhalamba-Drakensberg, South Africa	GPR monitoring of fracture development along shelter walls	Denis *et al* (2009)
	Writing-On-Stone Provincial Park, Alberta, Canada	Visual classification and Schmidt Hammer tests	Campbell (1991)
	Drakensbergen, South Africa	Literature review of case studies in rock art conservation and weathering to investigate overall patterns	Sumner *et al* (2009)

Table 4.1: Overview of some of the research published on rock art, divided by scale

Even though this is only a selection of studies conducted on rock art it is evident from this table that the majority of rock art studies work on a micro-scale, investigating mineral matrix and pigment deterioration on a microscopic level.

However, as encouraging as it may be for rock art research as a discipline, it could be argued that focussing on a single scale does not solve the wider issues which conservationists face, especially concerning the interaction between processes which operate on different scales. The problem is that different scales often need entirely different approaches and are generally subdivided among disciplines. Table 6.2 shows an overview of the three most commonly used terms in weathering studies, their scale and associated methods, and how they relate to the various techniques used in this research (modified from Viles *et al,* 1997 *in:* Baer and Snethlage 1997)

Term	Scale	Examples of measurements of deterioration	Nature of assessment of deterioration	Research method in this study
Degradation	Micro-scale (cm or less)	Mass loss, dimension, change, porosity change	Quantitative	PSR readings, thin section microscopy, Karsten Tube readings, XRD analysis
Distress	Meso-scale (cm-m)	% of surface damaged, presence of a range of deterioration features	Semi quantitative	ERT readings, Protimeter and Equotip transect surveys, rock art site surveys
Decay	Macro-scale (whole facades or buildings)	Structural stability, lifetime left, aesthetic appearance	Quantitative to qualitative	Large scale surveys with Protimeter and Equotip, weathering feature surveys

Table 4.2: Overview of three of the most common terms referred to in weathering studies, scale, methodology and the test performed during fieldwork. Modified from: Viles et al, 1997 in: Baer and Snethlage 1997

Figure 4.1 shows the importance of the multi-scale approach in this type of research. Weathering processes operate at all scales and are related through positive feedback (process enforcement) and negative feedback (process slowing) connections.

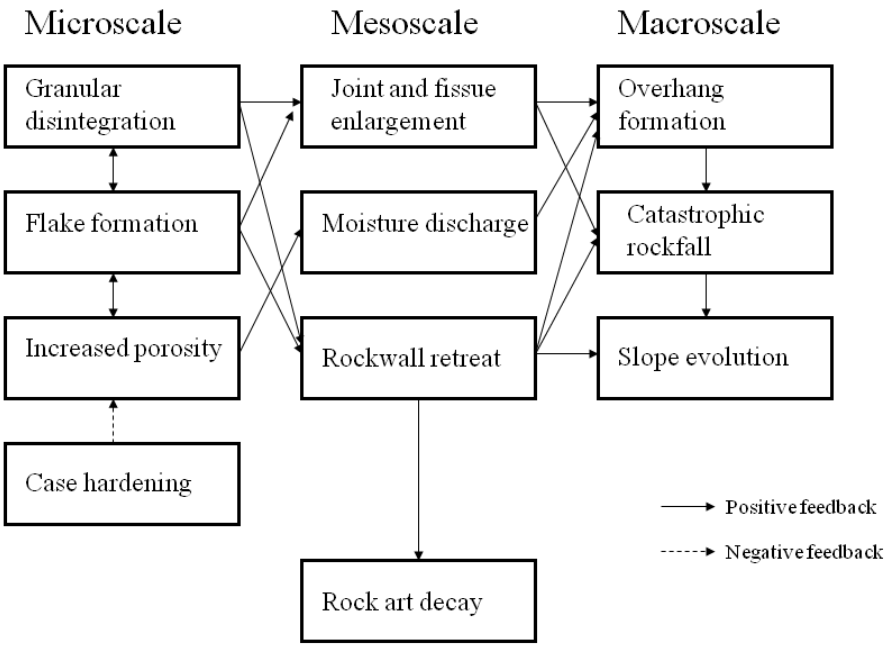

Figure 4.1: Relationships between different scales in the GGHNP rock shelters

When comparing table 4.2 with this diagram it is clear that often research will fit into one of the categories but fails to place itself into the larger setting of factors that affect rock art deterioration through rock surface decay. This research aims to combine meso- and micro-scale to understand macro-scale processes which form the rock shelters. As the diagram shows, the deterioration of rock art is not merely a product of pigment deterioration, rock surface deterioration, or continual rock shelter formation, but the result of a combination of all these processes.

4.4. Golden Gate Fieldwork

Lisa Mol, Heather Viles and Stefan Grab (University of the Witwatersrand, Johannesburg) undertook a reconnaissance visit in April 2008, to survey the potential sites and develop a general understanding of the area as well as carry out preliminary fieldwork. This visit was followed up by an extended visit in April 2009.

4.4.1 Introduction to the Golden Gate Highlands National Park, South Africa

The GGHNP is situated on the northeast border of Lesotho, in KwaZulu-Natal, South Africa (see figure 4.2). It lies in the foothills of the Drakenbergen within the Rooiberg Mountain Range among the foothills of the Malutia Mountains at elevations between 1892 and 2837 m. a.s.l (Wessels and Wessels, 1991). Although it is not officially part of the Drakensbergen World Heritage Site it already gained National Park status in 1926. Average monthly air temperatures for January range from 13.2 to 25.8 °C and 0.3 to 15.2 °C in July (Wessels and Wessels, 1991). This area is also known as the 'Kopjesbergen', where large parts of the Boer Wars were fought under the leadership of soldiers such as Jan Smuts. The geological formation of the GGHNP is one of distinct phases which have led to the formation of the

rock outcrops as they are seen today. Groenewald (1986) assembled the most detailed description of the geology to date which is very difficult to surpass. He writes:

> "The Golden Gate Highlands National Park is underlain by stratigraphic units belonging to the upper part of the Karoo Sequence. These units include part of the Beaufort Group and the Molteno, Elliot, Clarens and Drakensberg Formations. Dolerite dykes and sills are intruded into the succession while recent alluvium and scree cover the valley floors and mountain slopes. The Beaufort Group is represented by red mudstone and light brown fine-grained feldspathic sandstone of the Tarkastad Subgroup. The Molteno Formation consists of medium- to coarse-grained trough cross-bedded sandstone, while the Elliot Formation comprises a thick succession of red mudstone, siltstone and interlayered fine- to medium-grained, light yellow-brown sandstone. The most characteristic feature of the park is the yellowish sandstone cliffs of the Clarens Formation. Cave formation is caused by exudation, differential weathering due to different degrees of carbonate cementation and undercutting of the sandstone. The highest peaks are capped by numerous layers of amygdaloidal and massive varieties of basaltic lava of the Drakensberg Formation. (...) The strata in the park show very little structural deformation and the only obvious structures are faults which are intruded by dolerite." (pp. 165)

The result is a wonderful collection of mushroom formations, overhangs and shelters and cave formations which make the Clarens formation in the GGHNP aesthetically very pleasing.

4.4.2 Site locations

In total, seven sites were surveyed over the course of 2008 and 2009. The first two are situated within a short distance of one another, and were used for the pilot study in 2008. These are marked as S1 and S2 in figure 4.2. The remaining sites (S3-S7) were only surveyed in 2009, and are accordingly marked on the map. In addition, four rock art sites were located and surveyed using the Protimeter and the Equotip. Unfortunately they were inaccessible for GeoTom work because of their somewhat hazardous locations, which made transporting the heavier equipment to these sites impossible. In addition, due to the ethically sensitive nature of the rock art sites the aim of the site selection was to study sites similar to the shelters in which rock art is found while covering numbers exposure levels and aspects. The rock art sites are marked RAS1 to RAS4 in figure 4.2. The exact locations of the surveyed sites and their aspect is summarized in table 4.3.

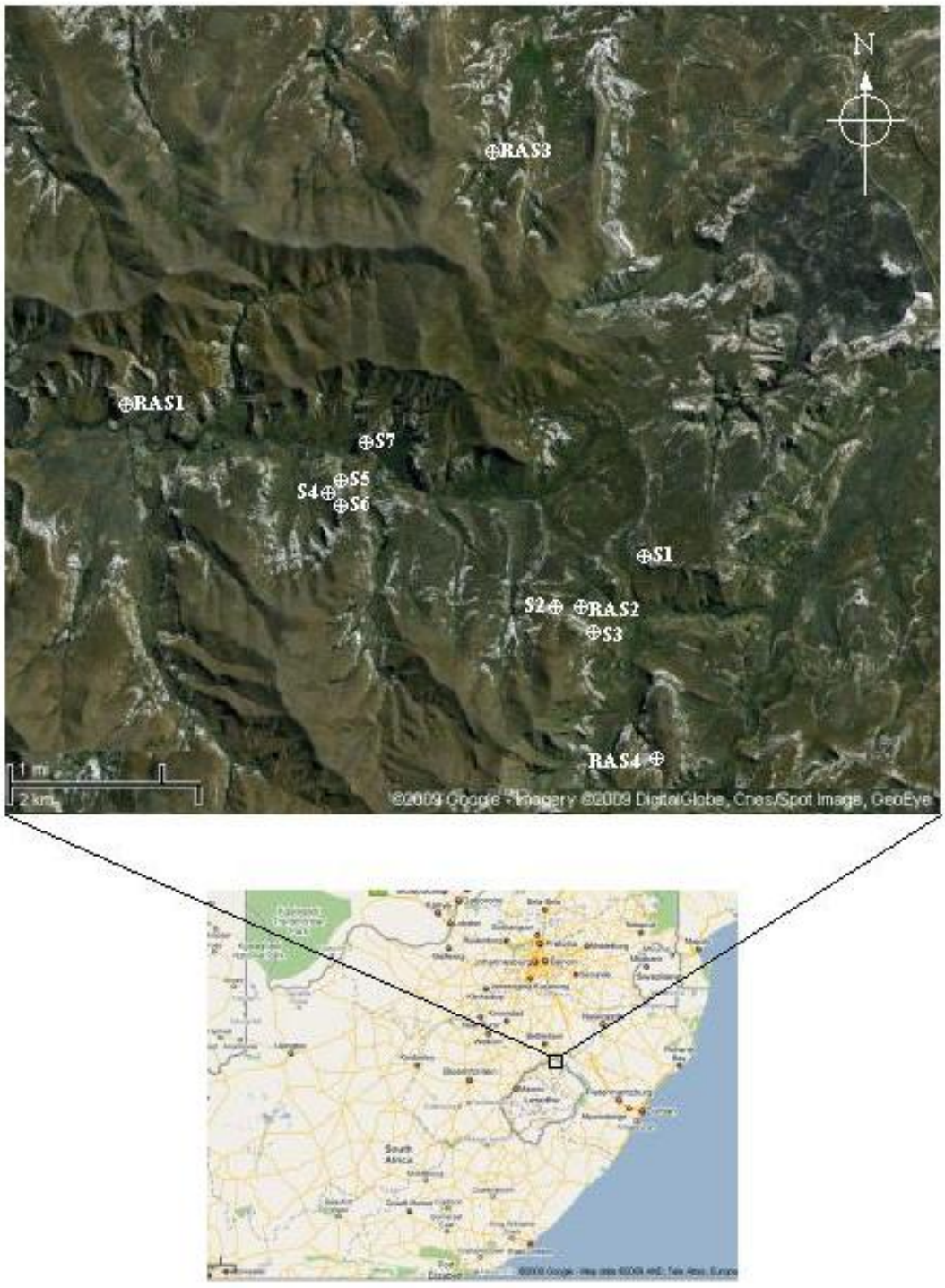

Figure 4.2: Site locations. Source: Modified from Google maps

Site number	Latitude	Longitude	Aspect
S1	-28 51 61.93	28 65 48.33	WSW
S2	-28 52 29.8	28 64 23.73	NNE
S3	-28 52 59.97	28 64 75.23	NEN
S4	-28 50 71.91	28 61 00.65	WNW
S5	-28 50 8398	28.60 99.36	N
S6	-28 50 83.98	28 60 99.36	E (cave)
S7	-28 50 22.13	28 61 45.71	S
RAS1	[redacted]	[redacted]	WWS
RAS2	[redacted]	[redacted]	On open ground
RAS3	[redacted]	[redacted]	NNE
RAS4	[redacted]	[redacted]	ENE

Table 4.3: Site labelling, locations and aspect. The exact locations of the rock art sites are blocked to conform with rock art site protection guidelines (locations available from author upon request).

4.4.2.1 Site selection March/April 2008

During this reconnaissance visit two sites were selected for initial measurements and to assess suitability of the area for this research. The most important factor was representation of the most common weathering features found in the park, as well as aspect, site morphology and accessibility. The GGHNP hosts an abundance of exposed rock faces. However, many of them are situated in areas which are too hazardous for humans to reach, especially when burdened with equipment. Therefore, a compromise had to be reached between accessibility and representation of weathered surfaces. However, the dataset does comprise a wide variety of aspect, weathering features, rock type and shelter development.

4.4.2.2 Site 1

Site 1 was found to be particularly interesting because of the sheltered position, as it is situated underneath a substantial overhang within a larger scar of large-scale rockfalls, shielding it from the most direct impact of strong winds and precipitation. The overhang is situated an estimated 75 meters above the bottom of the valley floor, and effectively appears as an incision at the top of a solid rock face (see figure 4.3). The shelter underneath the overhang is approximately 45 m wide, with a depth ranging from 1 to 8 m and an average height of 4.5 m. The overhang itself is approximately 4 m thick.

Despite this sheltered position, active weathering was observed throughout the length of the site, and moisture streaks covered large areas of the rock face. Its west facing nature ensures that it is not fully exposed to the most intensive heat as it only receives early morning sunshine.



Figure 4.3: An overview of Site 1

There is ample vegetation growing under the overhang, ranging from small shrubs to creeping vegetation on the floor and growing out of the rock face. Algae are present around all the water outlets, which also contain larger organisms such as mites. Drainage channels

run throughout the shelter, which channel the water from the moisture outlets to the larger pools of water found at the floor of the shelter (see figure 4.4).



Figure 4.4: Site 1 showing the vegetation growing on the rock wall and the shelter floor as well as the drainage channels from the moisture outlets

A series of large blocks is situated on the edge of the shelter floor, which indicates that rock falls are a common occurrence. Some of these blocks are rather large in size (> 2 metres diameter), which shows that catastrophic rock falls are not uncommon.

4.4.2.3 Site 2

Site 2, in contrast, is very exposed as it is situated within a convex hillside and is overlain by a relatively shallow overhang. This, in combination with its orientation to the north, means it receives sunlight throughout the day and is exposed to the most intense heat. The site is therefore an ideal comparison with site 1 as it is situated on the opposite side of the same valley and facing southeast rather than north. Despite this, it shows identical weathering features to Site 1. Figure 4.5 shows an overview of the shelter, with an indication of the areas surveyed in 2008 and 2009.

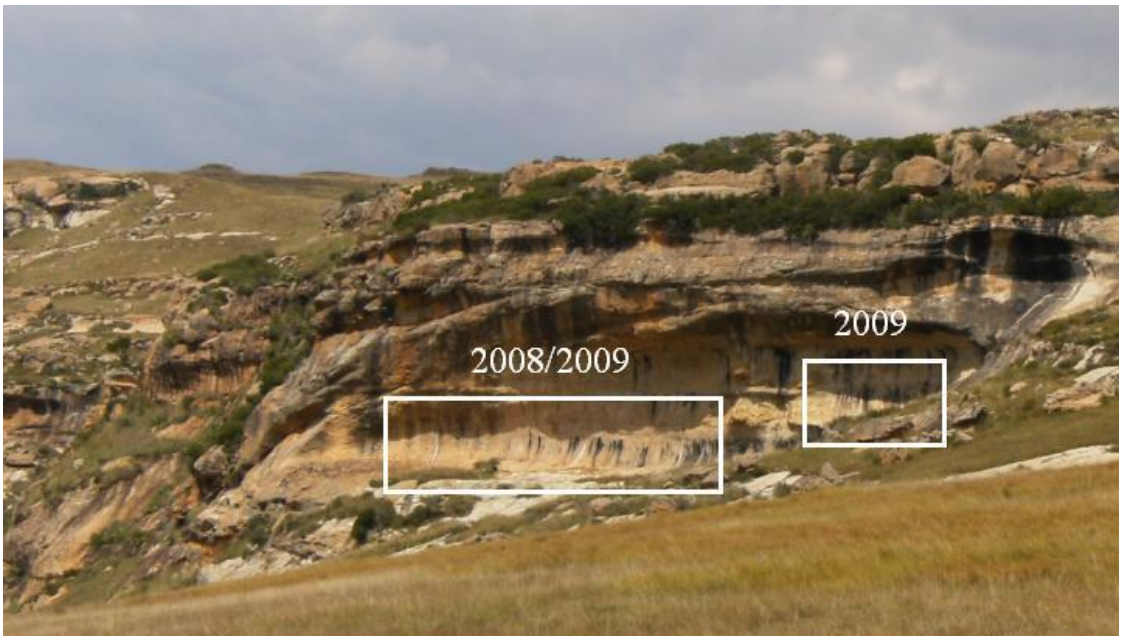

Figure 4.5: Overview of site 2

The site itself consists of a large shelter which has been subdivided by differential weathering into a larger section, which was surveyed in 2008 and 2009, and a smaller hollow which is situated further on the slope and therefore relatively higher (see figure 4.5) which was surveyed in 2009.

Both hollows show extensive moisture movement through outlets which are situated at regular heights within the rock face, raising the idea that these are directly related to horizontal bedding planes, which have been created either through a existing weakness in the rock at a specific height or changes in sedimentation during the deposition stages of the sandstone (see figure 4.6). These outlets have been identified as weep holes (Smith, pers. comm. 24/05/2011) which are karstic in nature and often found in limestone environments.



Figure 4.6: Small shelter surveyed in 2009, showing T4 and T5 of site 2

4.4.3 April 2009 site selection

Site 1 and 2 were revisited to assess annual change in internal moisture patterns. However, site 1 had to be reassessed as increased moisture and algae on the rock face had made transect 2 too slippery and therefore too dangerous to re-measure, considering the sheer cliff in very close proximity, and a new transect was installed in an area which was deemed to be representative. However, we were able to re-measure the other two transects, as well as the three transects at site 2. In addition to the previous transects at site 2, two additional transects were installed to the right (when facing the shelter) of the original transects, enabling data collection on a higher part of the rock face due to the slope situation (see figure 4.5).

Additional sites were sought to expand the dataset and further understanding of rock face processes. These were mainly chosen based on aspect, size and state of weathering, ensuring an array of sites which reflects the diversity within the GGHNP.

4.4.3.1 Site 3

Site 3 is a hollow in the rock within the same rock mass as site 2 (see figure 4.7). However, its northeast orientation means that it receives sunlight in the morning, but is mostly shadowed during the afternoon. Its relatively small size indicates that is a comparatively young feature within the larger exposure and high levels of weathering activity, as indicated by the intensely flaked and crumbled surface, are rapidly enlarging it. The surface is very crumbly and material is loosened from the surface upon the lightest touch.



Figure 4.7: Overview of site 3, showing its position within the larger rock face

The surface is in parts covered with very fine mineral deposits, possibly gypsum ($CaSO^4$) although this is unconfirmed. Figure 4.8 shows a close-up of the surface. These deposits cover virtually all the rock face in this particular shelter. Protimeter measurements show an extremely dry surface and subsurface, which correlates to the exposure of the shelter to sun for most of the day.



Figure 4.8: close up of gypsum crust on surface of site 3

The site itself measures 5.3 metres across, is 2.8 metres high at its maximum height point and has an average depth of 0.75 meters. Figure 4.9 shows the transects at site 3. As is evident, transect 3 (to the right), is slightly lower than the other two transects, this is because of difficulties with sampling on such a friable slope.



Figure 4.9: Overview of the hollow, including the transects T1 –T3 (left to right)

4.4.3.2 Site 4

Sites 4, 5 and 6 are all situated within the same rock outcrop, on the opposite site of the valley from the 'Brandwag', the symbol of the GGHNP and its most prominent landmark. The outcrop on which the sites are situated displays a wide range of weathering stages. Site 4 is appears to be a relatively undeveloped overhang (see figure 4.10) as the rock shows very little discolouration and case hardening development as was recorded at site 1 for example. There was some difficulty connecting the ERT equipment to the rock face as the heavily crumbling surface meant very little stability for the electrodes, an indication of the high weathering rates. The rock face was covered in a layer of dust, which is attributed to the release of very fine sediments from the rockface itself through water washing (field observations), comprised of very small mineral particles, which had to be removed before any attempt could be made to attach the electrodes. The overhang is rather low compared to the overhangs previously discussed (see figure 4.11) and relatively undeveloped, but actively weathering as the crumbly surface attests to.



Figure 4.10: Overview of location of site 4

Figure 4.11 shows transect 3, which is under the steepest part of the overhang. It also shows the non-oxidized state of the rock as it is still predominantly grey with no evidence of the red hue which dominates the more exposed part of the sandstone (see site 5 for a comparison). There is, however, evidence of salt presence, and moisture transport through the stone.



Figure 4.11: Transect 3 at site 4, also partially showing the resistivity equipment

6.4.3.3 Site 5

Site 5 is just 'around the corner' from site 4 (see figure 4.12), but shows a very different weathering regime. The rock face is of a rather bright red hue, which also corresponds to the high levels of exposure it receives, as it is north facing. For reasons as yet unknown, the GeoTom did not provide any useable measurements within an acceptable error % band (<12%) on this particular rock face, even though it did not have any problems with measurements at sites 4 and 6, which are situated in the same rock outcrop. It is possible that the rock contains such a high iron content that the electric currents were scattered within the rock mass, making measurement impossible. Groenewald (1986) attributes the

red hue of the lower half of the Clarens formation to the leaching of iron from the higher parts of the rock into the lower parts of the rock where it cannot pass beyond the Elliot mudstone, causing a concentration of iron in the lower half. Due to the technical problems caused by this iron build up, the ERT measurements were discontinued after the two transects. However, Karsten tube, Protimeter and Equotip tests were done regardless, which provided information on the difference in stone, as well as samples taken which were sent to Queen's University, Belfast for thin sectioning.



Figure 4.12: Site 5 location, showing the larger rock face and the highly oxidized state of the surface.

One of the very interesting aspects of site 5 was the very unusual colouring of the rock face. Figure 4.13 shows the area covered by the larger Equotip and Protimeter survey. The patterns on the rock appear to be somewhat haphazard at first sight, but when looking at them more closely appear to be related to sediment deposition patterns. However, these

patterns have not been found as distinctly in other areas of the park and are seemingly restricted to this one outcrop.



Figure 4.13: Showing the oxidation patterns found on the rock wall of site 5

4.4.3.4 Site 6

Further along the same rock face as site 5 a small cave is visible which is accessible to the public. It is 12 meters wide, at its widest point, and 13 meters deep, as measured from the entrance to the cave (see figure 4.14). Only indirect daylight reaches the back of the cave, and alongside all the walls the same moisture outlets are visible as are seen throughout the park (see figure 4.15). Weathering features are also strikingly similar, although not as prominent as at the more exposed sites such as sites 2 and 3.



Figure 4.14: Location of site 6



Figure 4.15: Interior of left side of cave

However, one feature distinguishes this shelter from the other sites, and that is the honeycomb development towards the entrance of the cave, which is partially visible on the left hand side of figure 4.15 but more clearly shown in figure 4.16. These cavernous weathering features have been found elsewhere but at much smaller scale (clusters of >1m)

and much less developed than at this particular site. It is not clear what causes this difference in weathering patterns, as this research has not looked into this feature further, but it is possible that the lack of direct exposure to sunlight, rain and wind enables the features to develop rather than eroding before they can extend further.



Figure 4.16: Honeycomb formation clearly visible at the entrance of the cave. The section shown measures approximately 4 metres across.

ERT readings were taken only at the back of the cave as this area was deemed to most closely resemble the setting and possible moisture regimes found in the shelters which had already been surveyed.

4.4.3.5 Site 7

This shelter is oriented fully to the south which means that it gets little to no exposure to direct sunlight during the day (as it is situated in the southern hemisphere). It is a rather large shelter, measuring on average 30 metres across and up to 12 metres high. On its

western end it is protected by the Brandwag outcrop, which shields it from direct impact of precipitation. It is near sites 4 and 5, approximately 400m northeast from these sites, but located on a different rock outcrop. The same moisture outlets are visible in this shelter as elsewhere in the Park (see figure 4.17). The rock face is fairly uniform in size and slope curve, and there is some evidence of small scale rock failure but an absence of the large boulders indicating more catastrophic failure, as found at Site 1 for example.



Figure 4.17: Section of Site 7, showing the smooth curve of the rock face and the presence of moisture outlets.

In addition to the shelters surveyed, a number of rock art sites were located within the Park. These were not surveyed with the ERT as often there were in areas inaccessible for larger equipment or, in the case of rock art Site 1, fenced off to protect the paintings from human interference. Instead, Protimeter and Equotip surveys were conducted in the vicinity, but not on-, the rock art which can be compared against the similar surveys conducted in the

shelters, and ERT data can therefore be extrapolated to estimate moisture regimes at these sites as well.

4.4.3.6 Rock art Site 1

This site is located near the entrance of the Park at the top of a sleep scree slope, which is vegetated, at the boundary between the exposed rock face and the vegetated area. At the junction of these, an overhang is visible which houses depictions of hunters and eland (see figure 4.18).



Figure 4.18: Rock art Site 1, closed off shelter

These paintings are rather faded and are partially disappearing due to continued flaking of the surface. Most of the flakes appear to be very superficial and do not leave deep scars (see figure 4.19). However, flaking does wholly remove the painted surface, thereby causing irreparable damage to the rock art. The weathering patterns on this site closely resemble those on site 5, showing the same superficial flaking and crumbling of the surface.



Figure 4.19: Damaged painting of two eland

4.4.3.7 Rock art Site 2

This site has not been extensively surveyed as it is a petroglyph, rather than a painting, which is etched into the rock surface of a horizontal exposure in an open field. Its setting and nature do not make it comparable with the paintings found in the shelter, but it is included in this section because of its significant historic interest as it depicts a white farmer at the time of the Boer Wars (1880 – 1881 and 1899 – 1902), as indicated by the style of the hat and the gun in its hand (see figure 4.20). It is a legacy of the guerrilla war fought in the area by the Boers, the Van Reenen family amongst them, against the British Army.

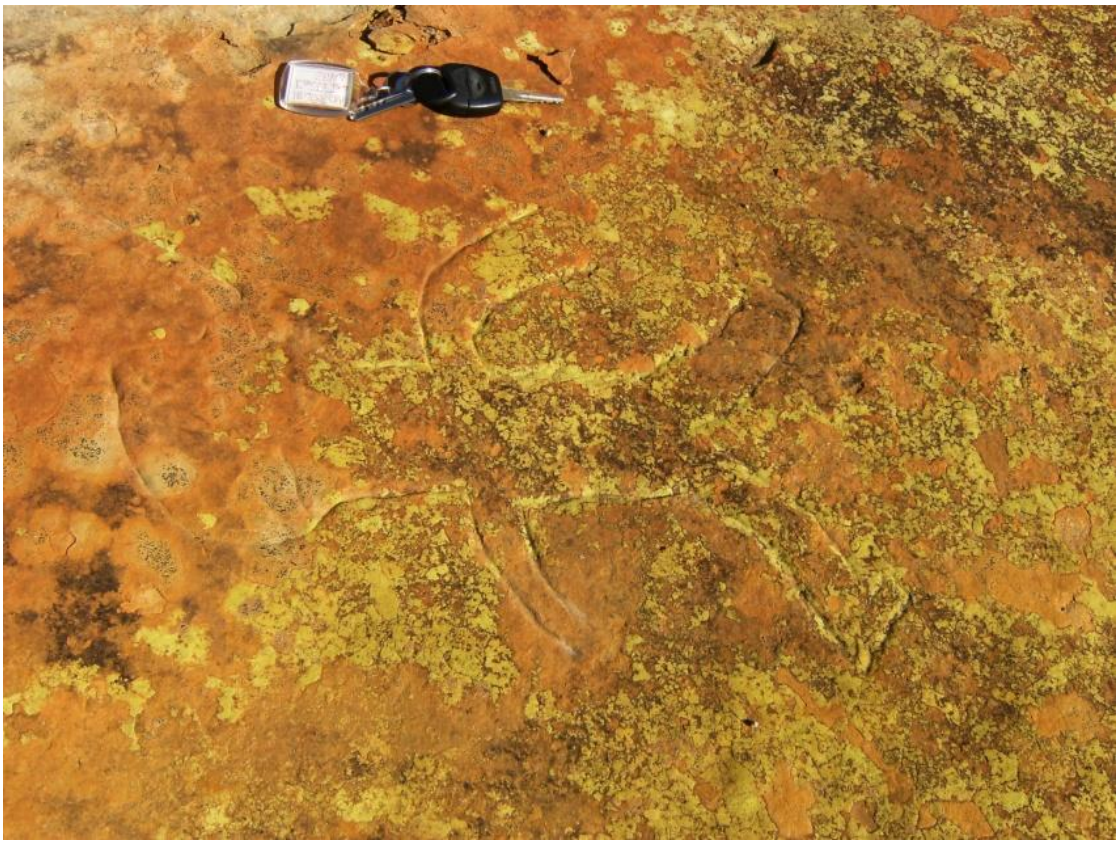

Figure 4.20: Remnant of the Boer Wars petroglyph

4.4.3.8 Rock art Site 3

Out of the four rock art Sites, this shelter most closely resembles the sites investigated with ERT. It shows the same curvature of the rock wall, the same moisture outlets and the same flaking of the surface (see figure 4.21). Its orientation towards the north should indicate that it receives a significant amount of direct sunlight but because of the shelter depth the back of the shelter receives relatively little exposure to elevated temperatures.



Figure 4.21: Back wall of RAS 3 shelter showing moisture outlets and vegetation. The rock art panels are just out of view in this photograph (to the left) but this particular photograph is a very good representation of the weathering features of the site.

According to Moses, the San guide, the entire shelter was originally covered in paintings. The date of the paintings is unknown, but the last known San Art painters died approximately 150 years ago, after which rock art painting stagnated.

In April of 2009 only two small panels remained, which shows the high rates at which rock surface weathering is affecting these sites. Panel 1 consists of an intensely weathered depiction of probably a bok species. The head has flaked off, and large sections of the pigments are missing (see figure 4.22)



Figure 4.22: Panel 1 at rock art Site 3 showing a partial depiction of a bok species

The second panel is a collection of Eland (see figure 4.23). These have mostly faded away and the area around the panel has chipped off and flaked over the years. There is evidence on the sides of the panel of recent removal of material, as the surfaces are still fresh and do not show the same amount of detritus build-up as is found on other surfaces around the panel. Especially the area at the far right of the panel appears to be recently removed. The colours on this panel, however, are more vivid than those of the depictions found on panel 1. This is possibly due to the distance to the shelter overhang, which in the case of panel 2 is greater providing a larger degree of protection from sunlight and rain.



Figure 4.23: Panel 2 at rock art Site 3 showing a small herd of Eland and a creature which is possibly a porcupine but is near impossible to identify (bottom right on panel)

4.4.3.9 Rock art Site 4

The final rock art site is located high at the top of a natural gorge in the rock in an area referred to as 'Cleopatra's Pools', named after the pools of water which have formed in the sandstone of the gorge. It is a much smaller shelter (5 metres width and 2.45 metres depth) than the previous sites, and resembles rock art Site 1 in terms of shelter development. The rock art is situated on the almost horizontal surface of the overhang at roughly 1.5 m from the ground (see figure 4.24).



Figure 4.24: Overhang of rock art Site 4. The paintings are situated above the people shown in the photograph.

A substantial weathering crust has formed on the rock surface, as well as accumulated dust. The panel itself appears to be case-hardened but variable Equotip results showed that there are potential air pockets trapped underneath the panel, indicating some potential flake formation and therefore a risk to the rock art. A flake had recently fallen off the shelter ceiling which upon closer inspection showed dark deposits, presumably magnesium dioxide, as well as evidence of calcium leaching. The weathering of the surface closely resembles the weathering found at site 1, showing large flake detachment and crumbling of the surface.

The panel itself depicts a group of three figures, two Therianthropes (half man – half animal, see Vinnicombe (1976) for a comprehensive overview of San rituals) and a woman who appears to be worshipping the other two figures (see figure 4.25). The hues are still vivid and

there is no evidence of this having been part of a larger panel. A possible explanation for this is the remote location of this particular shelter.



Figure 4.25: A depiction of two Therianthropes and a woman at Cleopatra's Pools.

4.5 Field tests

A variety of field tests were undertaken to compile a comprehensive dataset of Clarens sandstone properties, based largely on a transect sampling methodology. Table 4.4 shows an overview of the methods used at each site. As is evident, the most intense work was done on non-rock art sites. The rock art surveys were mainly carried out as a control measure to make sure the type of shelter and condition of the rock surface were similar.

Site	Weathering features	Protimeter and Equotip large survey	ERT (number of transects)	Protimeter transect (along each ERT)	Equotip transect (along each ERT)	Karsten Tube	iButton temperature log	Water conductivity sampling
S1	X	X	4	X	X	X	X	X
S2	X	X	5	X	X		X	
S3	X	X	3	X	X	X	X	
S4	X	X	3	X	X	X	X	
S5	X	X	1	X	X		X	
S6	X	X	3	X	X	X	X	
S7	X	X	3	X	X		X	
RAS1		X					X	
RAS2		X						
RAS3								
RAS4		X						

Table 4.4: Use of methods at each site

4.5.1. ERT transects: parameters set and observations recorded

At each site a minimum of three transects were set out for ERT measurements using the Geolog2000 GeoTom. Each site was first visually assessed to determine the most representative areas. As the transects are spatially constricted to in this case 2.45 meters using a 5 cm spacing, measurements were taken to ensure electrode 1 was placed at a similar height at each transect, to be able to trace constant features such as bedding planes and to increase accuracy of the comparisons. The reason the transects were spatially constricted is because larger transects would lead to too much loss of detail, as a wider

spacing does increase transect width and depth into the rock face, but still uses the same number of measurement points to cover the area, thus leading to a lowering of resolution. Because the aim of this research is to investigate the link between moisture patterns and surface weathering, a higher level of detail in the subsurface and lower subsurface was required than a wider spacing could provide. ECG electrode stickers were used to attach the electrodes to the rock face (see figure 4.26), as the gel pad provides excellent cohesion, and therefore enhanced conductivity, between the electrode and the rock face.

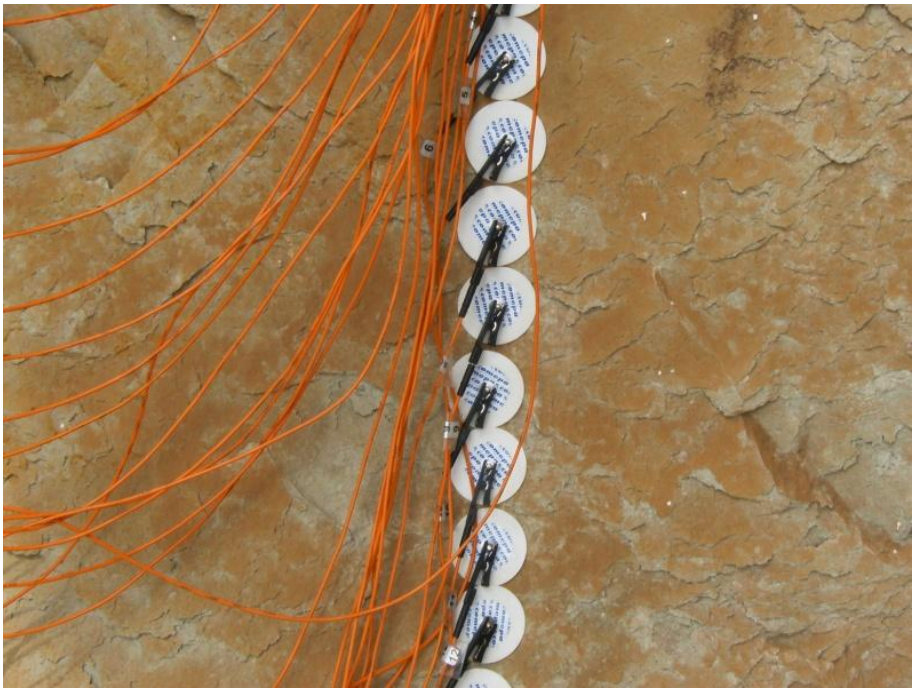

Figure 4.26: ECG electrode pads attaching the GeoTom electrodes to the rock face at site 3, transect 2, electrodes 10 –20

Figure 4.27 shows the framework for a sequential Wenner array the GeoTom software sets up at the start of each measurement series, and figure 4.28 shows the completed transect, in this case site 3, transect 1 (2009) .

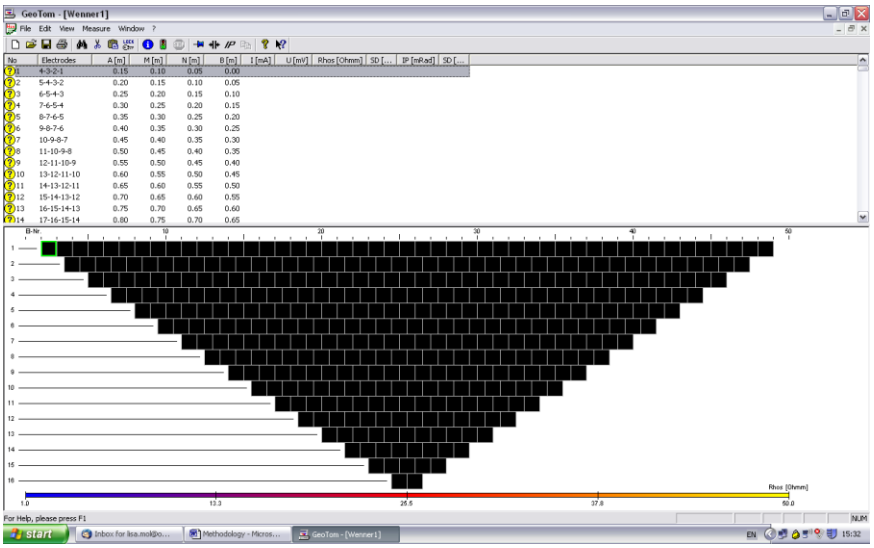

Figure 4.27: Example of the GeoTom software, screenshot of empty data framework

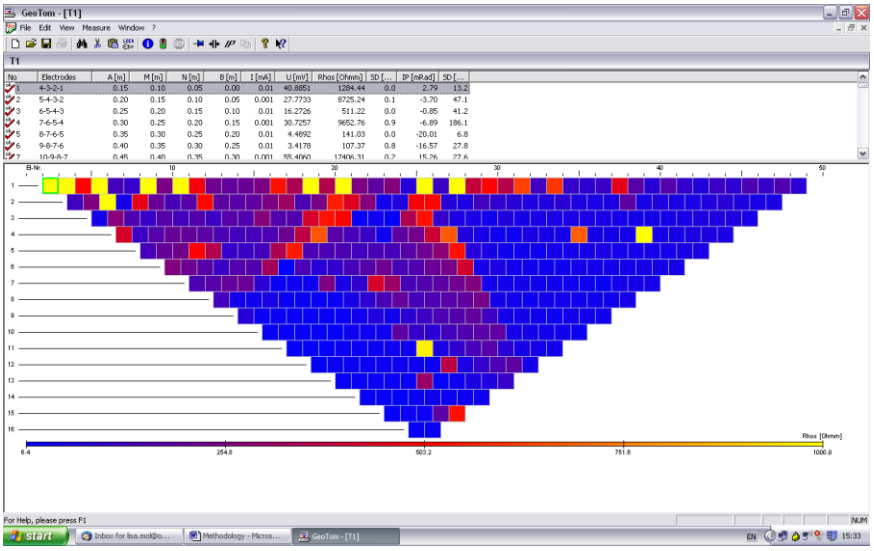

Figure 4.28: Example of a completed set of GeoTom measurements (S3 T1, GGHNP 2009)

Of course there are still issues with the usage of ERT, especially in this new context of rock weathering research such as the lack of calibration for salt and clay content, which enhance conductivity thereby lowering resistivity measurements (Shevnin *et al*, 2007). Beauvais *et al* (2004) suggest that to accurately interpret ERT readings, all data should be compared against borehole data. This is not an option when investigating rock surfaces as drilling and retrieving a core is not as easy with a solid rock mass as it is in soil. However, to address this

problem a water conductivity kit was used to test water excreted from the rock face as compared to the water from the stream running through part of the GGHNP. At site 1, 12 different pools at the floor of the shelter were tested. The stream running through the GGHNP was tested near the Gladstone Environmental Centre, where the stream has increased in size to a width of 3.5 m and up to 50cm depth, using a Hanna Instruments HI 9034 TDS meter.

In addition, the collected samples were tested in the laboratory for salt content using conductivity meters.

4.5.2. Protimeter

The Protimeter is a handheld device which allows the researcher to assess percentage surface saturation to a minimum of 6% at approximately 25.4 millimetres below the surface (manufacturer's specifications). It follows the same principles as ERT measurement, namely using resistivity measured between two points, the pins of the Protimeter, to assess surface saturation (see figure 4.29). It is a 'rough and ready' device which is easy to employ in the field and allows for rapid measurements in quick succession. It has been used previously in moisture studies in heritage and geomorphological research, and is considered very useful for getting quick indications of the subsurface saturation of a sample (see for example Lai and Tsang, 2008; Waragai *et al,* 2006).



Figure 4.29: Protimeter Survey Master

A Protimeter measurement was taken aside each electrode point, creating a 50-point dataset for each transect. These were used to compare the surface saturation fluctuations, both within the spatial constraints of the transect, but also to establish whether there are significant differences in subsurface saturation between transects at the same site and transects at other sites.

4.5.3. Equotip measurements

The Proceq Equotip (figure 4.30) is a rock hardness testing device that uses the same rebound principles as the Schmidt Hammer, but with a smaller impact on the rock surface. We specifically used the D-type which has been successfully used in a number of studies (Viles *et al*, 2010). The hardness is estimated by bouncing a small ball off the surface of the rock, the rebound of which is dependent on the surface elasticity, and correlating the value to the mechanical strength of the rock (Aoki and Matsukura, 2008). The advantage of using this device is that it does not leave the same deep marks that the Schmidt Hammer does,

but it is also not as sensitive to very small surface variations as smaller rock hardness equipment, such as the Piccolo (also produced by Proceq).



Figure 4.30: The Proceq Equotip 3

Equotip measurements were taken in two different ways. First of all, ten measurements were taken in the near vicinity of each tenth electrode (i.e. at electrode 1, 10, 20 etc.) to assess both the variability of rock hardness within a small area around the electrode but also to avoid creating a bias in the measurements by assessing rock hardness based on one specific point within the vicinity of the electrode. This also allowed for analysis of both mean and variability of the measurements. Figure 4.31 shows Prof Heather Viles using the Equotip at the top of transect 3 at site 1. This approach was applied both in 2008 and 2009, to allow comparison over a year.

The influence of the angle of slope on the measurements is automatically adjusted for by the Equotip as it is able to detect the angle at which the measurement is taken.

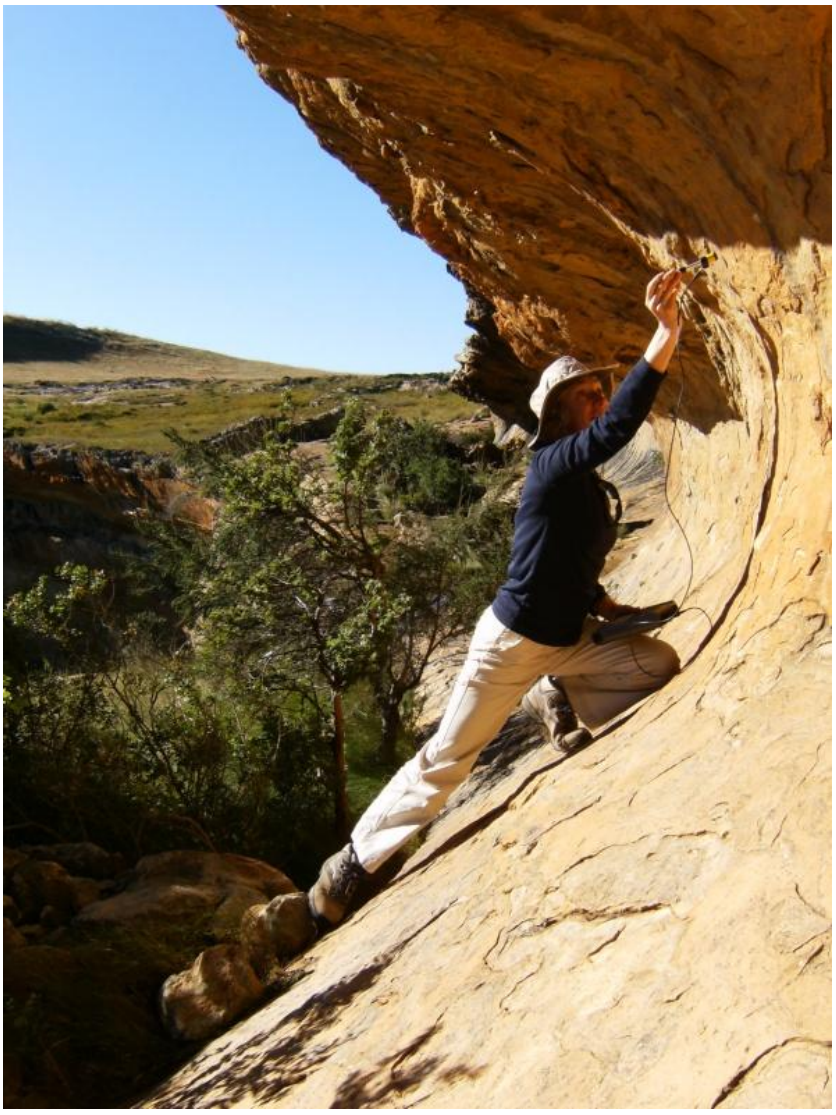

Figure 4.31: Equotip measurements at Site 1, GGHNP

4.5.4 Large scale surveys

Additionally, both the Protimeter and the Equotip were used to survey larger areas of the rock face. A grid of 5 metres by 3 metres was set out at each site, and within each square metre 9 measurements were taken (see figure 4.32).

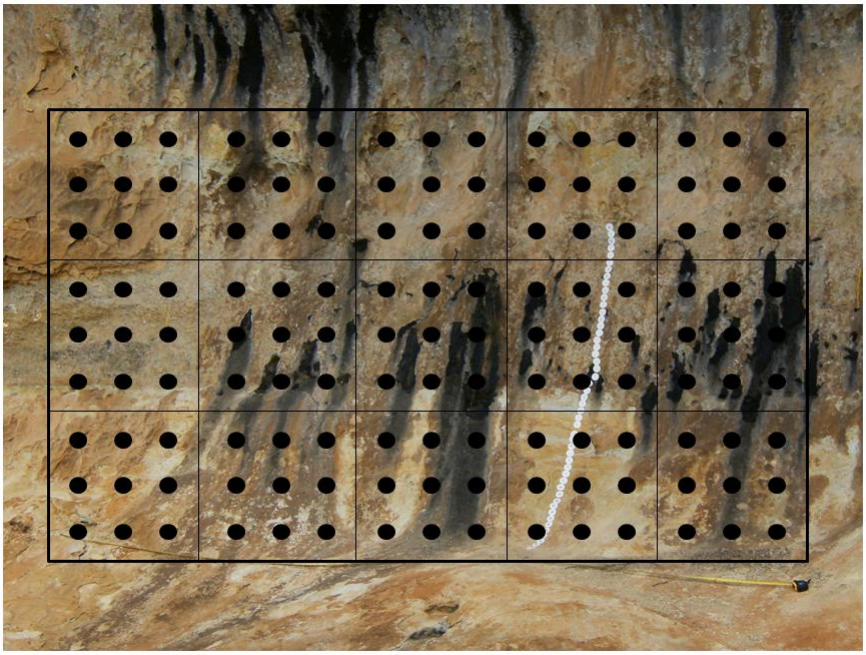

Figure 4.32: Example of a large survey grit (site 2, 2009 measurements, transect 4 is visible)

The data obtained by this survey was then used to analyse rock strength and saturation variations within a larger area and to correlate surface feature distribution to these measurements.

4.5.5 Weathering feature analysis

The overall condition of the rock wall at each transect was analysed by using 'weathering feature grading diagrams', which were prepared in advance and based on Fitzner *et al*'s 2003 model. An example of the factors evaluated can be found in the example of an assessment sheet (see table 4.5). These sheets were also used as a basis for the large scale surveys, which have been discussed in section 4.5.4 of this chapter. Each transect was divided into sections of ten electrodes which were assessed for each weathering feature described in table 4 on a scale of 0 (not present) – 5 (extensive). This table shows the results

for the top ten electrodes of each transect per site. The assessment was then repeated for each consecutive set of ten electrodes.

	S1				S2				S3			S4			S5			S6			S7		
Back weathering	4	2	4	0	0	3	0	3	0	4	5	5	0	3	1	4	3	4	3	3	1	2	3	1
Relief	3	1	4	2	1	2	0	2	3	4	4	5	1	3	1	4	3	0	2	3	2	1	3	1
Break-out	2	1	2	0	0	0	0	1	1	1	5	5	2	2	2	0	0	0	0	0	0	0	1	0
Discolouration	4	3	2	2	5	2	5	3	2	3	3	2	1	0	0	5	5	4	4	3	3	2	2	2
Soiling	0	0	0	3	5	3	4	2	2	1	2	1	3	3	3	2	2	0	4	3	3	0	3	1
Loose salt deposits	3	1	5	1	1	1	4	3	2	2	2	1	0	0	0	0	0	0	2	4	1	1	5	0
Crust formation	0	3	2	0	5	2	4	2	1	4	4	4	0	0	1	1	0	2	5	3	3	2	0	3
Granular disintegration	1	2	3	3	1	5	4	2	1	5	5	2	3	2	5	2	2	0	0	2	1	0	2	0
Crumbling	0	3	0	0	1	5	4	1	1	5	2	4	3	3	4	0	2	1	1	2	0	0	0	0
Flaking	4	2	5	2	3	2	4	3	3	5	2	2	2	2	1	0	3	3	3	4	4	2	2	2
Detachment of crusts	2	2	5	1	2	1	1	1	1	5	5	5	3	0	2	1	1	2	1	2	3	1	4	1
Independent fissures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dependent fissures	1	0	0	0	0	0	0	0	0	4	3	5	0	5	4	0	0	2	0	0	0	0	0	0
Lichen present	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Honeycombing	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	0	0	0	0

Table 4.5: Weathering feature analysis results for the top ten electrodes of each transect

4.5.6 Karsten Tube measurements

Karsten tubes are small open-ended glass vials which can be attached to the rock face to measure water absorption capacity and infiltration rates (Galán *et al*, 1999). By measuring the decrease in water content over a set period of time within the tube the water absorption per square centimetre can be calculated. The tube is attached to the horizontal rock face, usually on the floor of the shelter, with Blue-tack (see figure 4.33) to seal any openings and then left for 60 minutes to ensure full absorption was reached (Nwaubani *et al*, 2000). Unfortunately due to the rough topography of the rock wall this method did not have a high success rate but two full sets of measurements have been obtained which are discussed in chapter 7.



Figure4.33: Karsten tube attached to rock surface at site 5

4.5.7 iButton measurements

iButtons are small temperature loggers which closely resemble a somewhat oversized watch battery. They can be attached to the rock face using a simple adhesive such as Blue-tack (see figure 4.34 for an iButton attached at site 3, top right corner)



Figure 4.34: iButton near flaking at site 3. Spot the lizard.

Initially two sets of iButtons were attached at sites 1 and 2 for the duration of the first field study (April 2008). At the end of the study two iButtons were left at each transect of both sites and programmed to log temperature for the duration of 12 months. The data was used to compare temperature differences between the two sites and can be found in chapter 8. In addition, iButtons were installed at all 7 sites investigated in 2009 as well as rock art Site 1 which logged temperature for the duration of the field study. This data has been used in chapter 9 to illustrate the environmental differences between the measured sites and the influence of temperature on moisture regimes.

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CHAPTER 5: INTERNAL MOISTURE AND CLARENS SANDSTONE WEATHERING; APRIL 2008 RESULTS

This chapter has been submitted as a publication for *Geomorphology* and reports the results of the pilot study in the Golden Gate Highlands National Park, April 2008. This pilot study was undertaken initially to assess whether or not the Clarens sandstone formation were suitable for the cavernous weathering research that was planned. We identified two suitable sites which were measured using ERT, Equotip and Protimeter. In addition, the data obtained in this field research was used as a dataset to be compared with data obtained in following fieldwork seasons. It also provided the opportunity to install iButtons for longer term (annual) near-surface temperature monitoring at both sites.

In terms of the broader aims of this thesis, this paper is the first stage of cavernous weathering investigations, analysing the initial data obtained in this pilot study. It was necessary to carry out this pilot study in order to establish if this particular field site was suitable for investigating the influence of internal moisture on rock surface weathering. Previous ERT work had been predominantly carried out on walls around Oxfordshire, and this study was also in part carried out to establish whether or not the equipment would be able to cope with concave walls.

We found that there is indeed a relationship between subsurface moisture and rock surface hardness. We also found that with the right parameters set for the equipment both in the field and in the office the ERT could cope well with concave surfaces, but that care needed to be taken when working with very fragile surfaces. The Equotip measurements proved to be an excellent addition to the ERT readings, while the Protimeter was less reliable.

Submitted: 01/07/2009. Reviewed: 31/12/2009. Accepted: 10/01/2010

Published in: Geomorphology 118 (3-4) 280 – 287

GEOELECTRIC INVESTIGATIONS INTO SANDSTONE MOISTURE REGIMES: IMPLICATIONS FOR ROCK WEATHERING AND THE DETERIORATION OF SAN ROCK ART IN THE GOLDEN GATE HIGHLANDS NATIONAL PARK, SOUTH AFRICA

Mol, L., Viles, H.A.

Abstract

The Clarens sandstone in the Golden Gate Highlands National Park, South Africa, is the canvas for a collection of San (Bushmen) Rock Art, dating from Neolithic times until as recently as 150 years ago. This Rock Art is under threat from human interference but also, to a greater degree, from weathering processes on the rock surface. The dominant weathering processes occurring in the rock shelters which host the Rock Art are flaking and honeycombing. Two rock shelter sites in the Highlands National Park have been investigated using electric resistivity tomography (ERT) and supportive methods for measuring surface moisture (Protimeter) and surface hardness (Equotip). These non destructive techniques can be used *in situ* to assess the extent of weathering within a rock outcrop and are especially suited for investigations in sensitive areas such as Rock Art sites. Moisture movement has been mapped and related to the weathering processes observed on the surface. The aim of the study is to aid Rock Art conservation in the Golden Gate Highlands National Park through a better understanding of the driving processes of surface weathering. The evidence shows that the extensive flaking and honeycombing found in the rock shelters is most likely caused by water pockets in the near-surface zone, which are replenished through internal moisture transport, driving the superficial weathering processes. These weathering processes pose a

significant problem: Rock Art in the Golden Gate Highlands National Park shows severe deterioration due to flaking. Conservation strategies should therefore take internal processes into account as much as their superficial expression.

5.1 Introduction

The Golden Gate Highlands National Park in South Africa is home to an important collection of Rock Art of the San People who inhabited the area from Neolithic until recent times and have created a wealth of paintings on the Clarens sandstone. These are not only interesting to anthropologists, archaeologists and historians as a record of tribal development but also provide very good reference points for the development of the Golden Gate Highlands National Park as a dynamic environment both from an ecological and geographical / geological point of view. The Drakensbergen listing as a World Heritage Site in 2000, which includes the Golden Gate Highlands National Park, shows the importance of these Rock Art Sites. In the words of this listing document “the Rock Art of the Drakensberg is the largest and most concentrated group of rock paintings in Africa south of the Sahara and is outstanding both in quality and diversity of subject. The San people lived in the mountainous Drakensberg area for more than four millennia, leaving behind them a corpus of outstanding Rock Art which throws much light on their way of life and their beliefs” (UNESCO, 2000).

Unfortunately, these rock paintings are subjected to various degrees of weathering and a large number of them are deteriorating rapidly (see figure 5.1), not only due to human interference but mainly through natural weathering processes of flaking and honeycombing within the outer rock surface layer. Paintings are at risk in both the sheltered environments which were seemingly preferred by the San people, and on surfaces that are exposed to rain, hail, dust and intense sunshine (Smits, 1983). There is still a lack of knowledge about the conservation status of many sites, and how the Rock Art is deteriorating. One problem affecting progress is the limited availability of

efficient and accurate non-destructive assessment methods for Rock Art research. Due to the nature of the work required, sampling is often necessary, which can in itself lead to or accelerate alteration and deterioration of the Rock Art. The development of non-destructive methods for Rock Art assessment is therefore urgently required (Hoerlé et al, 2007).

Moisture is a key factor in many processes of weathering and deterioration affecting porous sandstones (Goudie and Viles, 1997). As the surfaces within the rock shelters are sheltered from rainfall, other sources of moisture must be involved, e.g. capillary rise from groundwater. Whilst Meiklejohn (1994; 1997) measured an average porosity of 6 to 8% in nearby rock shelters in the Clarens Formation sandstone, which he considered this to be low and unfavourable to capillary movement of moisture into and within sandstone, our field observations showed much evidence of water movements within the rock. Indeed, the largest source of moisture run-off on the rock surface appeared to be from internal moisture transport especially along bedding planes and large fractures where porosity and permeability are locally higher. Given these observations and the reported need for non destructive methods, the purpose of the fieldwork undertaken was to analyse the internal moisture distribution through electric resistivity tomography (ERT) with supporting methods such as surface moisture monitoring (Protimeter), surface temperature monitoring (iButtons) and rock surface hardness (Equotip) in order to investigate the relationship between internal moisture transport and deterioration of the outer of the layer sandstone.

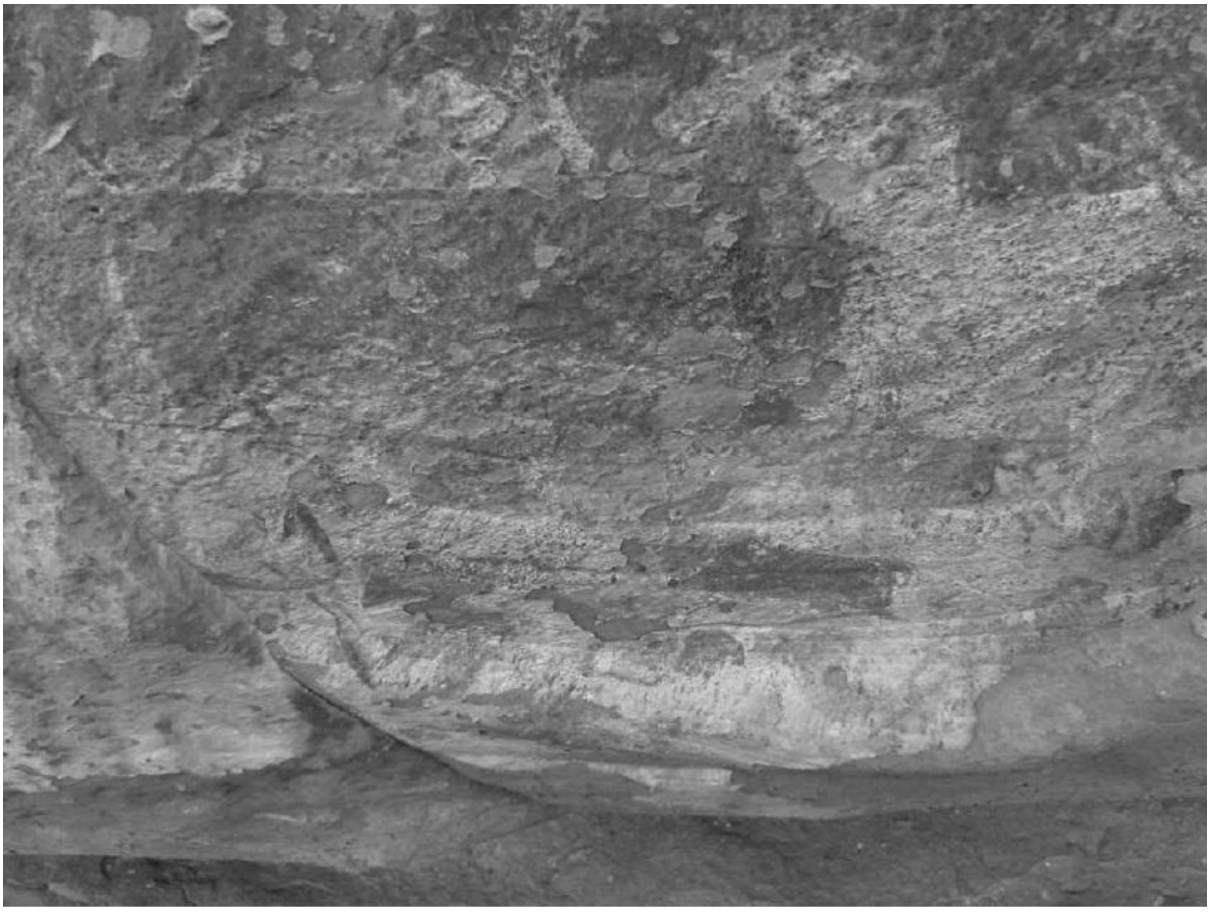

Figure 5.1: Severely damaged painting of an eland, Golden Gate Highlands National Park, showing significant blistering which is probably caused by internal moisture build up underneath the pigments and case hardening.

5.2 Site description

5.2.1 Geographical situation

The Golden Gate Highlands National Park is situated in South Africa (see figure 5.2) on the northeastern border of Lesotho and is part of the Drakensbergen. It falls within the Rooiberg Mountain Range among the foothills of the Malutia Mountains at elevations between 1892 and 2837 m. a.s.l (Wessels and Wessels, 1991). Average monthly air temperatures for January range from 13.2 to 25.8 °C and 0.3 to 15.2 °C in July (Wessels and Wessels, 1991). During the fieldwork in April 2008

temperatures recorded ranged from 11.7 to 32.4 °C (site 1) and 11.2 to 33.2 °C (site 2), as measured by iButton data loggers (Dallas Thermochron Temperature Logger DS1921).

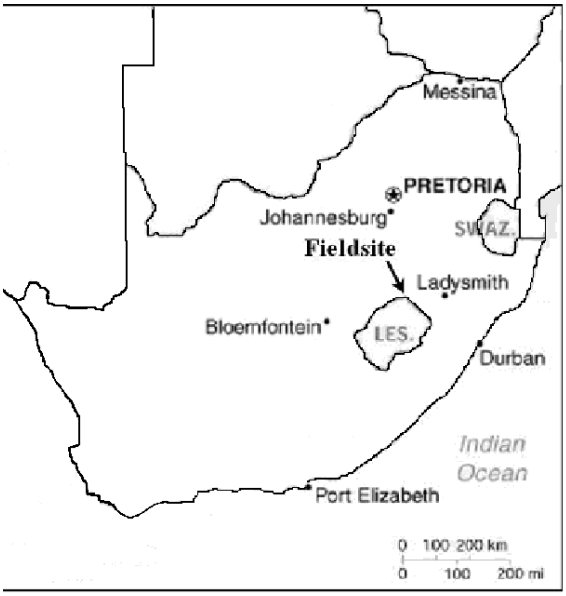

Figure 5.2: Location of field sites. Source: Modified from Bodleian Library Map Collection, Oxford University

5.2.2 Geology

The geology here consists of a range of sandstone formations capped by a harder basalt, creating mushroom shaped outcrops through differential weathering along the steep slopes. The weathering of the sandstone thereby creates the rock shelters which were the favoured canvasses for the San people. The upper sandstone formation, the Clarens sandstone, is uniformly graded and fine grained with quartz being the most abundant mineral, and is mostly of aeolian origin. (Castro and Bell, 1995). The Clarens sandstone is overlain by Drakensberg basalt from the Jurassic (Hoerlé et al, 2007), flows of which can reach a thickness of approximately 1,000 m (Moore and Blenkinsop, 2006) but on average reach around 5 m in the Golden Gate Highlands National Park. The Clarens sandstone is underlain by the Elliot (formerly Red Bed) and Molteno formations (Smits, 1983).

5.2.3 Individual sites description

Two sites were selected for this research, which are similar in size and stratigraphical position within the Clarens formation. The sites are located 5 km southwest of Glen Reenen on opposite sides of a valley which runs through the Golden Gate Highlands National Park, allowing for an aspect and exposure comparison. Site 1 faces east whereas site 2 has a NNE aspect, and site 1 is protected by a large overhang whereas the entire rock face of site 2 is exposed. These differences lead to the assumption that they are subjected to very different exposure conditions (see figure 5.3). At both sites flaking and honeycombing were present. Water marks, consisting of staining and algal growths on areas of the rock surface, showed that the rock face functions as an outlet for internal moisture rather than an inlet for precipitation. These water outlets appear to be common in the Clarens Formation as they have also been identified by Hoerlé et al (2007) at the Game Pass Shelter, which lies approximately 100 km southeast of the Golden Gate Highlands National Park.

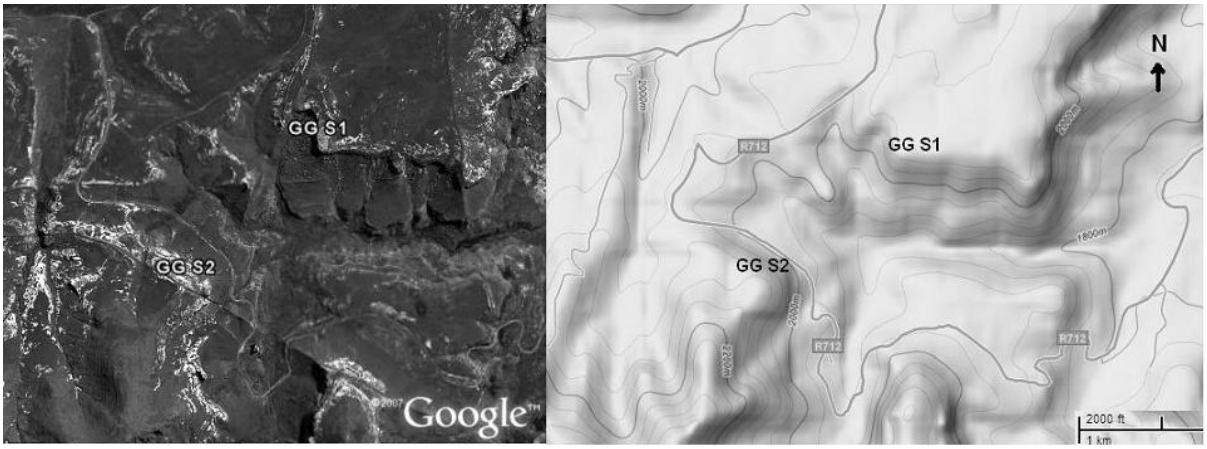

Figure 5.3: Satellite and relief image of site locations. Source: Google maps

5.2.3.1. Site 1

Site 1 is situated in a west-facing scar of a large rockfall, at the top of a 75m high cliff. At the top of the cliff a large overhang is created by the retreat of the Clarens sandstone capped by a resilient basalt layer. The shelter underneath the overhang is approximately 45 m wide, with a depth ranging

from 1 to 8 m and an average height of 4.5 m. The overhang itself is approximately 4 m thick. Water outlets are present throughout the site and prominent honeycombing is visible especially around areas where larger quantities of water appear to travel through the rock face, as well as along the horizontal bedding planes. Salt deposits are very clear in areas where water has evaporated during run-off and are also seen around areas where water has saturated the rock. There is significant flaking of the rock surface under the overhang, and where flakes are detached moisture and salt accumulations are visible (see figure 5.4). An extensive network of both shallow and deeper fractures, all at right angles, dominates the top of the overhang.

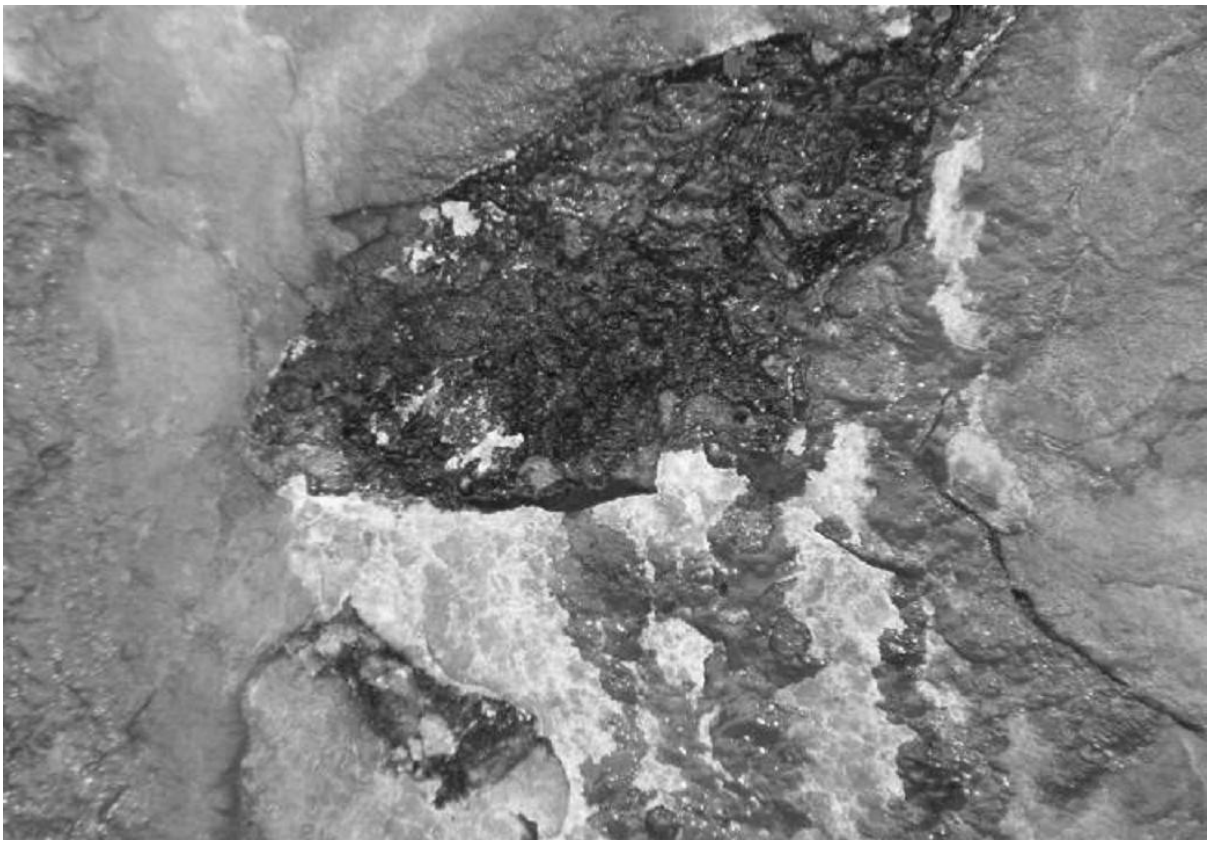

Figure 5.4: Detached flake showing moisture and salt accumulations. The dark area shows the freshly exposed, and wet, surface covered in algae. The white streaks are soluble salts which have dried onto the rock surface after the moisture in which they were originally transported has evaporated.

There is a variety of vegetation on the plateau above the rock shelter, mostly shrubs and grasses, while moss dominates the walls within the shelter especially at the height of the water outlets. At

14:30 07/04/08 (15:30GMT), early autumn in the southern hemisphere, iButton data showed that when ERT measurements were taken most of the site is exposed to sunlight, but the back wall of the overhang is constantly in the shade. For an overview of the site, see figure 5.5.



Figure 5.5: Site 1 overview showing the overhang and the sheltered position of the site. Transects are also marked, T2 and T3 are visible, T1 is just outside of the figure.

5.2.3.2 Site 2

Site 2 is far more exposed to wind, precipitation and sunshine than site 1. Even so, many of the weathering processes found on site 1 are also present at site 2. There are several water outlets at a similar height as those found at site 1 (approximately 1.5 to 7 2 m and again at 5 and 8 m height), and extensive flaking is present on both the platform and the overhang ceiling. Unlike site 1, there is very little or no vegetation present in the immediate rock shelter environment, with the exception of mosses growing around the water outlets. Along the bedding planes there is evidence of

honeycombing, and nodules of harder material can be seen along the wall of the overhang. Darkened areas on the rock surface indicate previous water run-off, and moisture was observed to be continuously trickling out of the wall. Where flakes were removed, accumulated water was visible, maintaining well-developed moss and algal colonies with an abundance of microbiota. Even though salt accumulations were not as visible as at site 1, they were present around the water outlets. See figure 5.6 for a site overview.

At 14:30 (15:30 GMT 08/04/2008) our iButton data showed that temperatures were slightly elevated at the time of ERT measurements compared to those at site 1, which was a result of the longer exposure of the site to direct sunlight, and also consistent with temperatures on 07/04/08. Even though the site faces NNE, the entire rock wall is exposed, unlike site 1 which is sheltered by the overhang.



Figure 5.6: Site 2 overview showing the exposed position of the site and its vulnerability to rain and sun.

5.3 Materials and methods

All data presented in this article were collected from the 7th to the 9th 189 of April 2008, which is autumn in the southern hemisphere. Each site was surveyed once in detail during this reconnaissance study. Care was taken to take particular sets of measurements at the same time of day. iButtons were installed to monitor temperature fluctuations to compare conditions between sites and between surveys. Three ERT transects were taken at each site, as well as a Protimeter measurement at the position of each electrode on the transects and ten Equotip measurements every tenth electrode. Ten Equotip measurements in a small area are required to obtain a reliable estimate of rock hardness on weathered surfaces (Aoki and Matsukura, 2007).

5.3.1 ERT

ERT, or electric resistivity tomography, uses multiple resistivity measurements to produce cross-sectional images of the variation of resistivity within a porous body. Resistivity measurements are produced by applying a current to a porous body through two current electrodes and measuring the resulting voltage difference at two potential electrodes. ERT requires many sets of measurements using different spacing between electrodes to produce a 2D image. A GeoTom device (Geolog2000) was used with two cables each with 25 insulated clips which attach to ECG electrodes on the rock surface to produce multiple resistivity measurements. We used 5cm spacing between electrodes, which produces a transect of 2.45m and allows a penetration depth of up to 40 cm into the porous body. Previous studies have shown this method to be very efficient in the mapping and tracing of moisture movement within rock bodies (Beauvais et al, 2004; Sass et al, 2008). However, no previous research has been conducted using this technique on the behaviour of moisture within the Clarens sandstone. The Wenner measurement configuration was used as it has been recorded to provide a particularly good resolution and a good signal-noise ratio (Sass and Viles, 2006). RES2Dinv inversion software was used to create a best-fit model of the resistivity distribution within each transect. This

software uses the smoothness-constrained least-squares method inversion technique to produce a 2D model of the sub-surface from the apparent resistivity data.

Low ohm measurements signify low resistivities and are inferred to be increased moisture levels (white and light grey tones in the RESDinv generated images such as those in figures 5.7 and 5.8) whereas higher ohm measurements indicate higher resistivities and inferred dryer areas (dark grey and black tones). However, porosity, salinity and high silicate content can also affect resistivity measurements (Friedel et al 2006) and so any conclusions about moisture regimes from resistivity data must be made with caution.

As the data from the Golden Gate were obtained on similar rock walls comprised of the same rock type we can compare the resistivity profiles from different sites (as we can assume porosity and silicate contents are similar), but cannot relate them to absolute moisture values without further calibration of the technique, nor can we rule out the possibility that salt contents vary between rock walls. Three transects were taken on each site, At each transect, electrode 1 was placed at the same height, or as closely to the height of the other transects as possible, along the rock wall. Slope geometry determined how far down the rock wall it reached.

5.3.2 Equotip

The Equotip is a rebound device like the Schmidt Hammer, recently used to measure rock hardness for geomorphological purposes (Aoki and Matsukura 2004; 2007), which provides an accurate set of rock hardness measurements while being a non-destructive method. It is suitable for application across a wider range of hardness than the Schmidt Hammer, and is especially useful for relatively soft rock surfaces. This makes this method extremely suitable for working on fragile sites such as historic buildings and Rock Art areas (Hack et al, 1993; Verwaal and Mulder, 1993; Van de Wall and Ajake, 1997). Measurements were taken (without any surface pre-treatment) along each ERT

transect at every tenth electrode, with ten measurements on each measuring area. The average of these ten measurements was then taken as an indicative measurement of the hardness of the surface area and thus the degree of weathering.

5.3.3 Protimeter

The Protimeter is one of a number of simple field instruments used to assess surface and near-surface moisture content based on resistivity. This method is commonly used for building surveys and has already been employed in several previous studies of heritage structures (Galdieri and Alva, 1981; Akiner et al, 1992; Lai and Tsang, 2008). It is a highly portable, non-invasive, low precision method of assessing moisture contents within the near-surface zone (up to a few millimetres beneath the surface). A Protimeter measurement was taken directly next to each ERT electrode along each of the transects.

This field study has used the combination of the Protimeter and ERT as an opportunity to compare the performance of the Protimeter in measuring near surface moisture in relation to the moisture distribution deeper within the rock mass as measured by the GeoTom. Furthermore, the additional use of the Equotip allows us to compare moisture and hardness data to infer the links between moisture and weathering. In order to be able to correlate ERT, Equotip and Protimeter measurements, all measurements were taken along the same ERT transects.

5.4 Results and discussion

The Clarens sandstone in the Golden Gate Highlands National Park shows very consistent weathering patterns at both sites, with similarities and differences in the moisture regimes. However, even though the weathering features are of the same nature, the weathering is much more advanced and active at site 2 than it is at site 1. The ERT profiles all have very low % uncertainties (<5% RMS error)

and generally show quite low resistivity values in comparison with many other reported measurements on rock walls (see for example Sass, 2007). The ERT profiles from both sites show diversity in resistivity values both between upper and lower portions and between inner and outer areas of the rock, with many showing drier conditions at the upper parts of the profile and wetter conditions around the middle of the profile. However, the sites show clear differences in moisture regime with site 1 possessing generally higher and more variable resistivity than site 2. Looking first at site 1, along the retreating back wall at 1 – 1.5m height there is visual evidence of water outlets which sustain accumulated mosses and colonies of microorganisms. ERT measurements show evidence for flows of water from inner to outer parts of the profile in the upper and middle sections (see arrows in figures 5.7a and 5.7c for example). Transects 2 and 3 have some large areas of high resistivity, but there is evidence for moist patches both at depth and nearer the surface. The circle in figure 7.7b shows an area of moisture sandwiched between two drier zones, potentially reflecting the concentration of moisture flow along surface-parallel joints.

The ERT transects give evidence of very active and sustained moisture regime within the sandstone. This is in contrast to Meiklejohn's (1997) opinion that the porosity of the rock is too low and unfavourable to allow capillary movement in the sandstone. In fact, these ERT moisture measurements show that there is a significant amount of moisture transport through the Clarens sandstone, with water able to move from the internal regions towards the surface. This moisture appears to play a role in the development of flaking on the surface on the sandstone, one of the major threats to the San Rock Art, as observed by Hoerlé (2005) at the Game Pass Shelter.

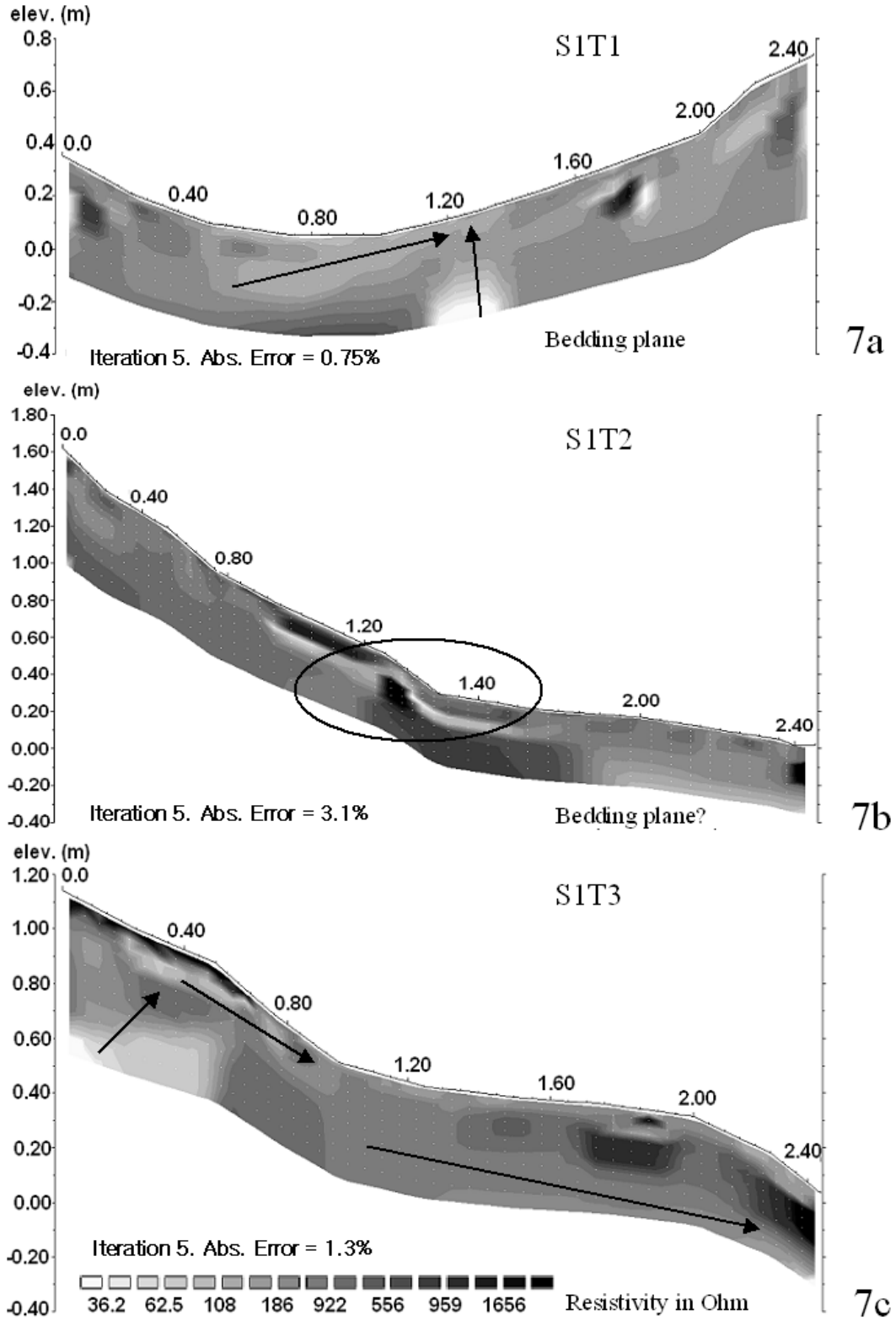

Figure 5.7 ERT transects from site 1, a) Transect 1, b) Transect 2, c) Transect 3. Each transect has been adjusted for topography and plotted on the same resistivity scale. Note that the top of each transect is shown on the left side of each panel.

Site 2 shows a very different pattern of sub-surface moisture, even though on the surface the weathering features are very similar; they both show flaking of the surface and moisture outlets. However, the superficial differences between site 1 and site 2 are substantial; site 2 has much more advanced, and active, weathering. The flaking has progressed to a larger degree and field observations show that the surface is much more susceptible to loss of material. Figure 5.8 gives an overview of the ERT transects 1, 2 and 3, which show that site 2 has substantially lower resistivity values than site 1 (all transects are plotted on the same colour scale). This is contradictory to what could be expected on the basis of the relative exposure of the two sites. Because this site is far more exposed to sunlight and would therefore be expected to dry out rather quickly, we would expect much higher resistivity values. The results indicate that there is a steady supply of internal water which is moved towards the rock surface in rather large flows (transect 3 shows this trend with upper, middle and lower portions of the profile showing linked wet patches in subsurface and surface zones, see figure 5.8c). The lower half of each profile exhibits wet conditions, as indicated by low resistivity values, within the near-surface zone.

Why does site 2 exhibit much lower resistivity values? As the measurements were made at sites which are part of the same Clarens sandstone, at the same height within the formation and showed a very similar mineralogical composition and porosity when assessed in the field, the only causes of this difference in resistivity levels could either be the internal supply or the salinity of pore waters. If the supply of water is greater at site 2 than at site 1, to the extent that increased exposure to wind and sunshine is unable to even dry the rock out to the same levels as the rock surface at site 1, this might explain the trends observed. However, these trends might also be explained by the fact that increased exposure enhances evaporation and the salinity of the pore waters.

A good argument could be made that the cause of differences in resistivity between the two sites relates to differences in water contents related to differing water flows in the wider environment of

each site. Site 1 is overlain by a very thin layer of soil, often interspersed by bare bedrock, which cannot store precipitation from the wetter summer months effectively. Site 2 is situated within a larger slope with a significantly thicker soil layer, with a much larger capacity for moisture storage. A gradual release of this moisture during the drier months (such as April, in which these measurements were taken) would supply moisture to the rock face which acts as a natural outlet for the larger slope. A second, and viable, possible explanation of the resistivity variations could be a much higher soluble salt content within the rocks at Site 2 (providing lower resistivities). Soluble salts are known to enhance conductivity, and thus lower resistivity (Viles and Goudie, 2007; Florinski et al 2009; Galve et al, 2009). One possible explanation for this increase in salt levels could be the higher levels of exposure of the rock face, compared to site 2, leading to higher evaporation rates, which facilitates increased capillary pull. An increase in moisture passing through the rock would cause an increase of residual salts after evaporation; hence an increase in overall salinity levels which is known to be detrimental to rock structure and aid weathering rates (Goudie and Viles, 1997).

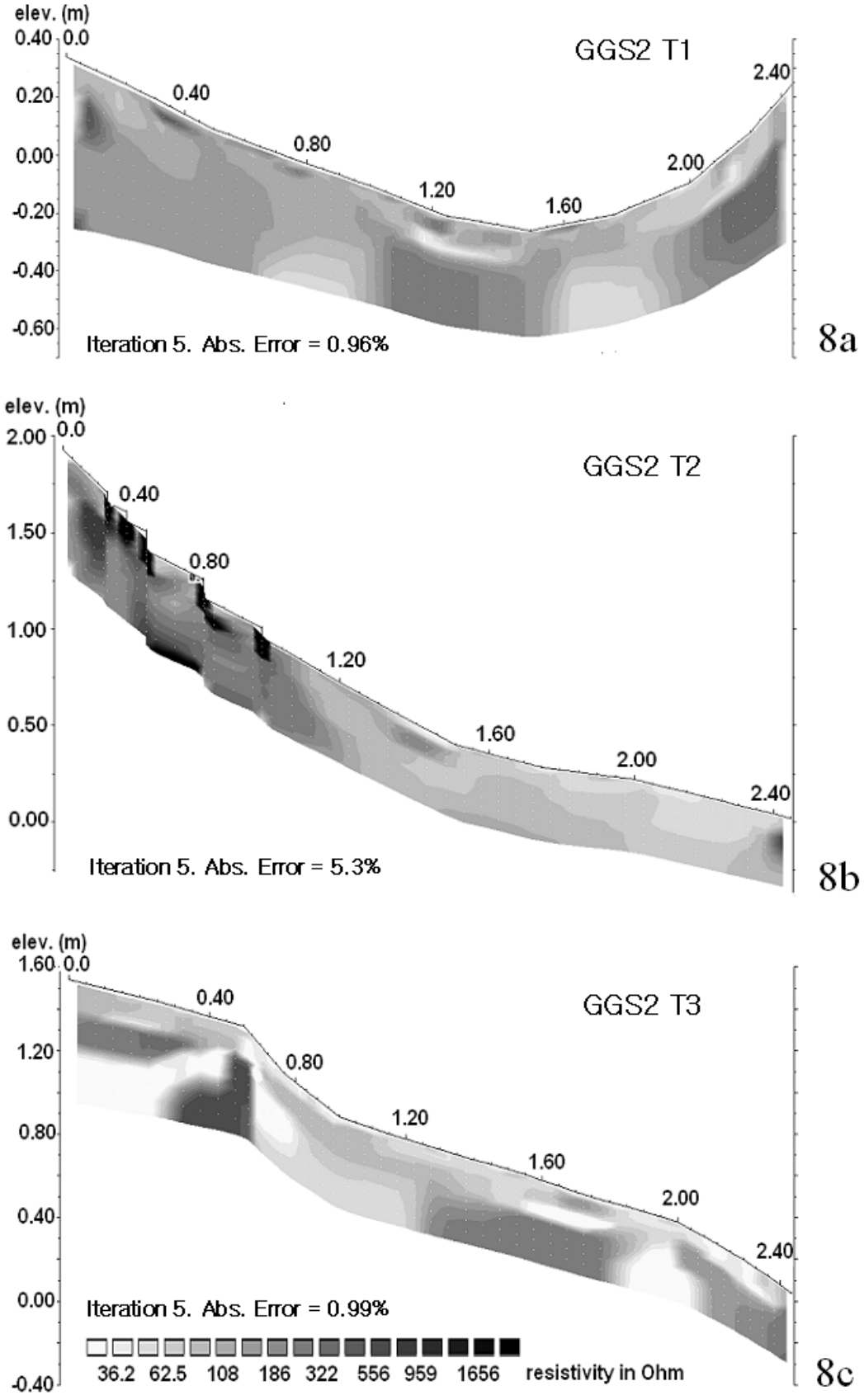

Figure 5.8 a-c ERT Transects 1, 2 and-3 of Site 2

These results have been compared to the individual Protimeter and Equotip results, and results are presented here for transect 1 from site 1 and transect 1 from site 2 as these are both representative of their respective sites. As can be seen to a limited degree in figure 5.9 and more clearly in figure 5.10, peaks in the Protimeter data are matched by low resistivity areas near the surface in the ERT data giving some confirmation of the patterns. However, the Protimeter dataset is too small to allow any statistical comparisons of the datasets. The Protimeter values show much higher variability at site 2 with higher average values, showing some support for the lower resistivity found in the ERT profiles there. The Equotip data shows some interesting differences between the two transects. The variability at site 2 is much greater (figure 5.10a) than at site 1 (see figure 5.9a, note that the measurement of 0 at 1.1. is due to technical restrictions and is not part of the statistical analysis), both in terms of mean variability across the transect but also variability within the same reading set (per electrode section, i.e. 1-10, 11-20 etc) and overall mean hardness values are lower for site 2. At site 2 there is a correlation between subsurface moisture pockets, intense surface weathering and lowered Equotip values (see figure 5.10). The variability of the Equotip is either caused by the heavy weathering of the surface of site 2 or by the higher water content within the rock, as rebound values are lowered by increased moisture. ERT values show that the rock at site 2 is indeed wetter; assuming that lower resistivity indicates higher moisture content, therefore making the assumption that the lower Equotip values are caused by elevated moisture levels reasonable. However, visual evidence shows that site 2 is far more heavily weathered than site 1. The surface consists mostly of crumbling flakes and shows signs of accelerated weathering in the areas near moisture outlets.

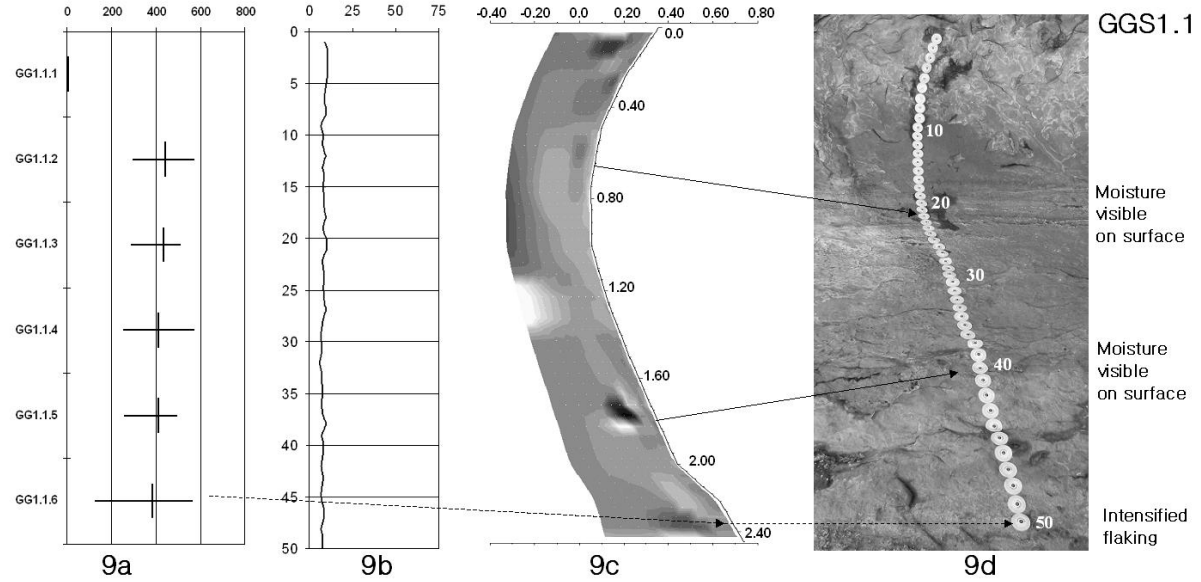

Figure 5.9: ERT, Protimeter and Equotip measurements for Site 1, Transect 1. a) Means and ranges of Equotip hardness values (Leeb hardness units) at electrode positions 0, 10, 20, 30, 40 and 50, b) Protimeter values for each electrode position (%wood moisture equivalent units, c) ERT profile, d) photo of transect with main weathering features illustrated.

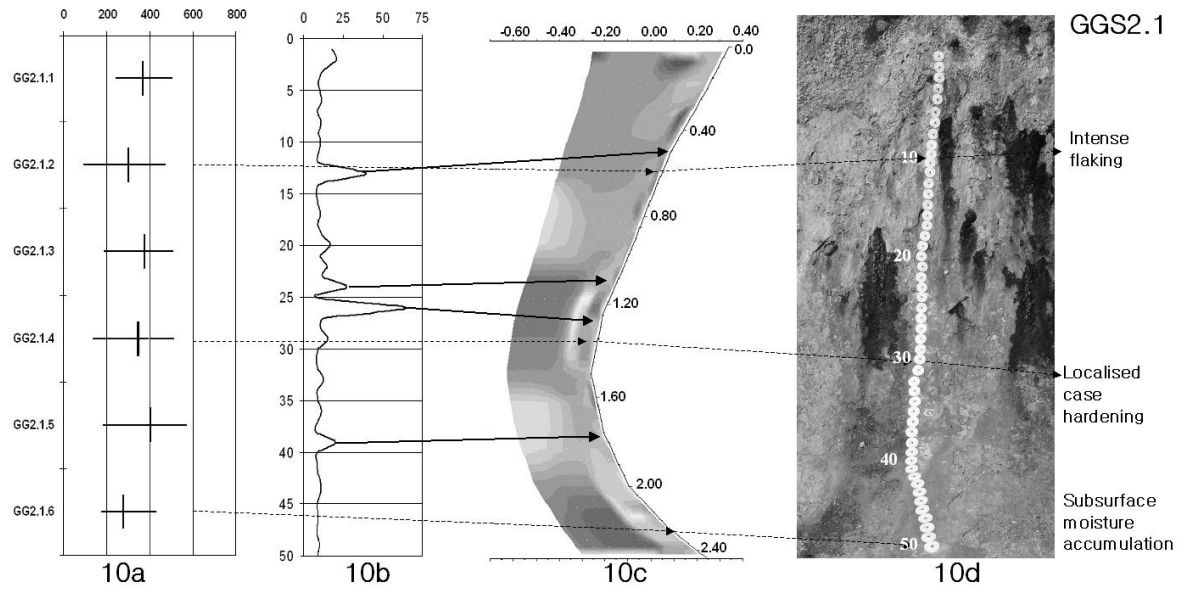

Figure 5.10: ERT, Protimeter and Equotip measurements for Site 2, Transect 1 a) Means and ranges of Equotip hardness values (Leeb hardness units) at electrode positions 0, 10, 20, 30, 40 and 50, b) Protimeter values for each electrode position (%wood moisture equivalent units, c) ERT profile, d) photo of transect with main weathering features illustrated.

Based on these observations, the conclusion can be drawn that the majority of the weathering features that are observed on the surface are in fact related to internal moisture transport rather than external sources, as shown by the correlation between internal moisture, surface weathering and Equotip and Protimeter measurements and the more severe weathering and lower resistivity values found at site 2. This poses an increased problem to the Neolithic Rock Art as not only do the external deterioration factors need to be assessed but also an equal, if not greater, deterioration factor can be found within the rock face. However, ERT measurements are strongly influenced by both the presence of water and soluble salts within the sample and further tests are necessary to distinguish between high moisture contents and high salinity. Figure 5.11 summarises a simple feedback model proposed based on the findings on this research.

We propose that an increase in weathering is the result of a feedback cycle, where an increase in moisture causes accelerated weathering and vice versa. This is already a well-known effect (Roth, 1965; Hall, 1986; Halsey et al 1998; Sass, 2005), but our model incorporates the effect of internal moisture, causing internal weakening of the rock structure. High exposure levels lead to weakening of the rock surface which allows for increased moisture transport through the surface, unless the development of case hardening is more rapid, which leads to a higher internal moisture content.

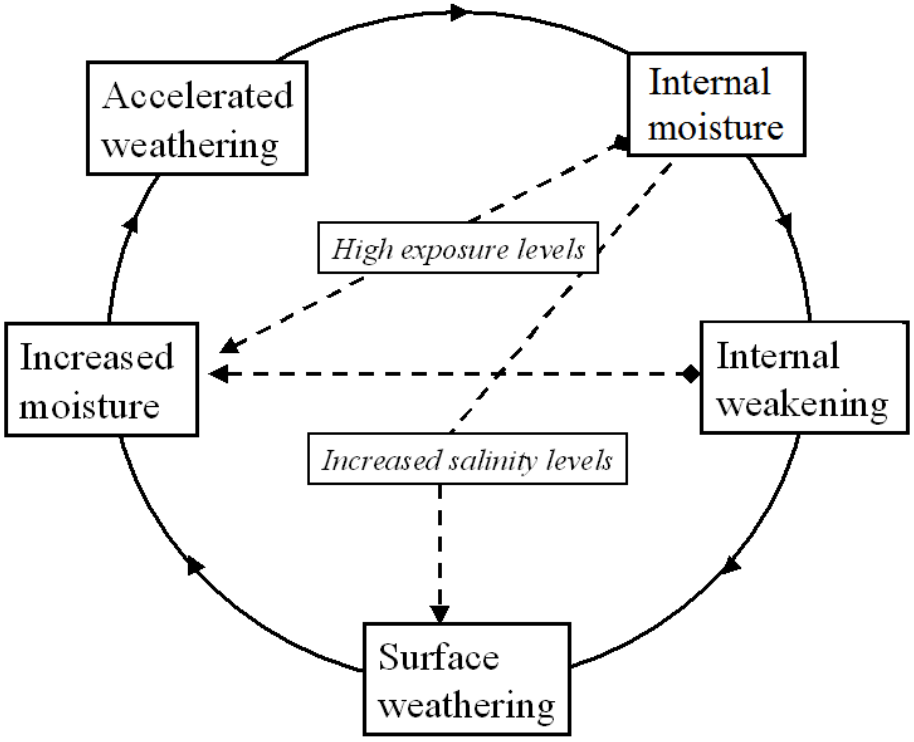

Figure 5.11: Feedback model for Clarens sandstone weathering, indicating the cycle of weathering and the main internal processes which drive the deterioration of the rock surface.

A change in any of the factors in this model could cause an acceleration or deceleration of weathering rates of the sandstone. In relation to the data obtained from the Golden Gate Highlands National Park, this model shows that internal moisture can cause weakening of the rock mass which is manifested in increased surface weathering. The increased volumes of moisture passing through the rock weaken the structure and the high evaporation rates, caused by the exposure of the rock, allow for rapid throughput.

5.5 Conclusions

This research has shown through ERT measurements that a major contributor to the formation of surface weathering features on the Clarens Sandstone in the Golden Gate Highlands National Park is internal moisture transport. The site (site 2) with lower resistivity values throughout the ERT profiles

is the site with more severe weathering. The rock wall is an outlet for water that is transported from the interior of the rock mass, and as the water exits so it contributes to weathering and the reduction in hardness of the rock surface. Honeycombing, for example, along the bedding planes facilitates water outlets, resulting in a drier rock face, but the movement of moisture in these areas decreases the rock strength. Flaking caused by sub-surface moisture accumulations where no outlet is present occurs actively at both sites, as shown by the ERT profiles and field observations. These processes combined are the main source of weathering within rock shelters in the Clarens formation as found in the Golden Gate Highlands National Park.

Our findings illustrate that research into the deterioration of Neolithic Rock Art within such sites needs to consider internal factors as well as external factors such as precipitation and human activity in order to draw-up effective conservation strategies.

Acknowledgements

We would like to thank Stefan and Jayden Grab of Witwatersrand University, Johannesburg, for making this fieldwork possible and providing excellent company in the field and Alan Trenhaile and an anonymous reviewer for their very helpful comments.

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CHAPTER 6: CHANGES IN MOISTURE REGIMES ON AN ANNUAL BASIS AND ITS INFLUENCE OF ROCK SURFACE HARDNESS

This chapter has been submitted as a publication for *Catena* and discusses the importance and influence of moisture pattern changes over a year. This is the follow up to the data discussed in chapter 5, as the same transects were measured using the same equipment and sampling schemes. Combining the data of 2008 and 2009 provided an insight in the changing moisture regimes and their relation to surface weathering, which is inferred from rock surface hardness. This provides an addition to the conclusions drawn in the previous chapter as it add a temporal dimension to the investigation. It also provides the second step in determining the influence of internal moisture on surface weathering as the temporal and spatial changes shed some light on the influence of exposure and aspect on internal moisture regimes. The iButtons which were installed during the 2008 season logged temperature in high resolution and provided a very interesting record – they showed that site 1 experienced lower temperatures in winter and higher temperatures in summer than site 2, which may be due to the morphology of the shelter as the deep overhang traps warm air in summer and prevents exposure to sunshine in winter. The influence of these annual temperature changes adds further information and forces a rethinking of the conclusions drawn in chapter 5. In addition to the relationships outlined in chapter 5, this chapters shows that there is a non-linear relationship between subsurface moisture and rock surface hardness.

Submitted: 26/01/2011, reviewing process started: 08/02/2011[1]

[1] Nb. Revised and resubmitted to Catena: 02/08/2011 as "Investigations into the relationship between changes in internal moisture regimes and weathering over a one year period in cavernous sandstone weathering features (Golden Gate Highlands National Park, South Africa)" as per the suggestions of an anonymous reviewer

WHAT A DIFFERENCE A YEAR MAKES: ANNUAL CHANGE IN ROCK HARDNESS IN RELATION TO INTERNAL MOISTURE REGIMES IN THE GOLDEN GATE HIGHLANDS NATIONAL PARK, SOUTH AFRICA

L. Mol, H. Viles

Abstract

Sandstone is a friable stone type which weathers rapidly and is susceptible to the influence of moisture build up within it surface and subsurface. Previous work by Mol and Viles (2010) carried out in the Golden Gate Highlands National Park shows that there is a direct correlation between the weathering of Clarens sandstone in shelters and the behaviour of internal moisture using Electrical Resistivity Tomography (ERT) and rock surface hardness (Equotip). We gave evidence that internal moisture is as important a weathering driver as external processes and environmental factors. To extend this work, we measured the same transects within these shelters a year later to assess the behaviour of internal moisture on an annual basis and investigate its influence on surface weathering, using ERT, Equotip data and near-surface temperature data. Using temperature loggers installed in April 2008 and collected in April 2009 we show a detailed dataset of temperature changes in both shelters and relate these to the moisture changes found. We have found that there is a non-linear relationship between changes in subsurface moisture accumulation and rock surface hardness. Using the well-known role of moisture in slope stability as an analogy we propose a new model for interpreting the relationship between rock surface hardness and internal moisture.

6.1 Introduction

Moisture movement within both building stone and natural rock material is a widely researched subject (Hall, 1986; Hall and Hoff, 2002; Sass, 2005; Warke *et al*, 2005). However, little is known about small-scale effects of moisture regime changes on an annual basis, especially in vulnerable sandstone, and its effect on surface hardness. Moisture is known to be a key factor in the deterioration of building materials, both as an agent for salt transport (Hosono *et al*, 2006; Kamh, 2007; Viles and Goudie, 2007), and a key component in mechanical weathering processes such as freeze-thaw. However, little is known about the influence of internal moisture in arid and sub-arid environments and the role exposure to heat plays in the acceleration or deceleration of surface weathering. In this study we therefore investigate the hypothesis that weathering features such as blistering and flaking can be triggered and/or accelerated by changing moisture regimes, weakening the surface and over time causing the rock walls to retreat. Features like these are not only found in natural environments but are also a cause for concern in the built environment, and numerous studies (for example Fitzner *et al*, 2003; Friolo *et al*, 2003; Waragai *et al*, 2006; Leucci *et al*, 2007) have discussed the problems associated with deterioration of sandstone stonework and the threats to the future of monuments and world heritage sites.

To further the understanding of these deterioration processes, a range of laboratory studies have investigated moisture movement through sandstone (Goudie *et al*, 2002; Pender, 2004; Smith *et al* 2005), but mostly on a shorter time span and a smaller (individual block) scale. This raises the question of extrapolation and to what extent laboratory studies are valid indicators of what is happening in 'the real world'. Viles (2001) has previously raised the issue of finding the most suitable scale for weathering studies (both spatial and temporal) and concluded that "scale issues are fundamental to the study of the causes, nature and consequences of weathering, but are difficult to conceptualize and even more difficult to

operationalize in real-world studies". This is especially important when investigating weathering on large-scale rock faces which show small-scale weathering features, subsurface weaknesses and variations in hardness within smaller sections of a larger eroding surface, as is demonstrated in this research. In addition, this research investigates annual changes in moisture regimes using Electrical Resistivity Tomography, a geophysical method which allows us to record resistivity distributions along a 2D transect within a rock mass. Comparatively little is known about behaviour of moisture on an annual scale. Previous studies have used this method for monitoring purposes using ERT to monitor seasonal, annual and long-term variations in large scale transects, such as slope stability and aquifer investigations (Cassiani *et* al, 2006; Hilbich *et al,* 2008; de Franco *et al*, 2009; Monego *et al*; 2010). In the same manner, smaller scale transects have been used to investigate moisture movement through stone walls (Abu Zeid *et* al, 2006; Abu Zeid *et al,* 2010; Sass and Viles, 2010). However, this research aims to tie surface weathering directly to annual changes in internal moisture mechanisms, bringing a new dimension to the debate.

This research therefore aims to investigate the annual changes in internal moisture and surface hardness of sandstone surfaces, in particular Clarens sandstone as found in the Golden Gate Highlands National Park (GGHNP), South Africa. Measurements were taken in early April 2008 (see Mol and Viles, 2010) and repeated in early April 2009, using Electrical Resistivity Tomography to investigate changes in internal moisture regimes, using transects of 2.5 meters which allow a high resolution analysis in a transect reaching 40 centimetres below the surface of the rock. Our previous work in the GGHNP indicated that it is in this area that moisture accumulation or drying of the rock mass can cause significant changes in weathering rates and features. This approach gives the advantage that weathering can be studied in detail, as ERT readings show high-resolution changes in moisture content, but also over a span of several meters and by combining transects from each site, on a cross-shelter

scale as well. This approach was previously successfully applied by Mol and Viles in the 2008 study, and repeated in the follow-up 2009 study. In addition, Protimeter and Equotip measurements were taken to assess annual changes in rock surface hardness and saturation in order to link surface weathering to internal moisture regimes. We hypothesise that there should be a clear link between moisture distribution (ERT), rock surface hardness (Equotip) and rock surface saturation (Protimeter) as subsurface moisture accumulation will weaken the rock. In addition, we assume that there is a significant difference in moisture distribution on an annual basis, due to seasonal changes in precipitation and shifts in the moisture pathways within the rock, and that this can be correlated to rock surface weakening. However, due to the non-linear behaviour of wetting and weathering cycles we assess the theoretical influence of moisture on the stability of the rock surface, by proposing a new model based on slope stability research.

6.2 Site description

6.2.1. Geographical situation

Following research conducted in April 2008 (see Mol and Viles, 2010 for details), two sites which were surveyed in 2008 were revisited in April 2009 in the GGHNP. The Park is situated near the northeast border of Lesotho, in the foothills of the Drakensbergen. This mountain range consists of an interesting interplay between the Elliot mudstone formation, which in turn is overlain by Clarens sandstone and capped by Karoo basalt (for a comprehensive overview of the Golden Gate geology, see Castro and Bell, 1995 and Hœrlé et al, 2007).

The area is renowned for its impressive sandstone formations, which are the result of Clarens sandstone weathering at a higher rate than the more resilient overlying Karoo basalt. These units include part of the Beaufort Group and the Molteno, Elliot, Clarens and

Drakensberg formations. The Molteno formation consists of medium- to coarse-grained trough cross-bedded sandstone. The underlying Elliot formation consists of a thick succession of red mudstone, siltstone and interlayered fine- to medium-grained, light yellow-brown sandstone (Groenewald, 1986). There are two types of overhangs, caused by differential weathering and undercutting of the sandstone, found in the Golden Gate National Park; the famous mushroom formations which can be seen around the National Park (see figure 6.1), secondly, the shelters which appear to be set within the larger slope, which were selected for this research (see figure 6.3, showing site 1 and figure 8.4 showing site 2).

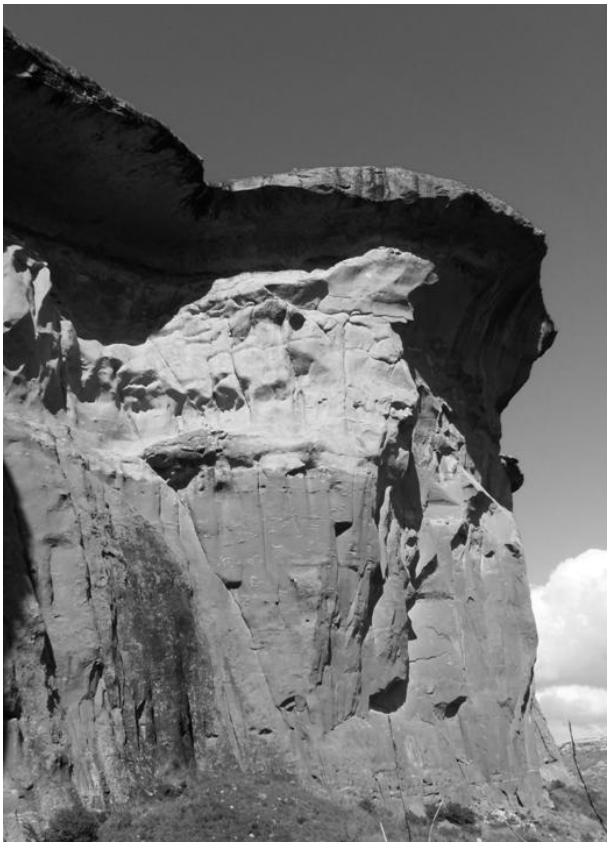

Figure 6.1: showing the mushroom formations which can be found within the National Park. Despite the change in colour, from grey near the top to red towards the bottom of the rock face, these formations are all Clarens sandstone, capped by Karoo basalt, which can be seen at the top of the sandstone.

The individual sites are located close to each other, on opposite sides of a v-shaped valley, located at latitude -28. 5162.79, longitude 28.6542.68 (Site 1) and latitude -28.52229.91, longitude 28.6421.23 (Site 2). Figure 6.2 shows the exact location of the sites within the park.

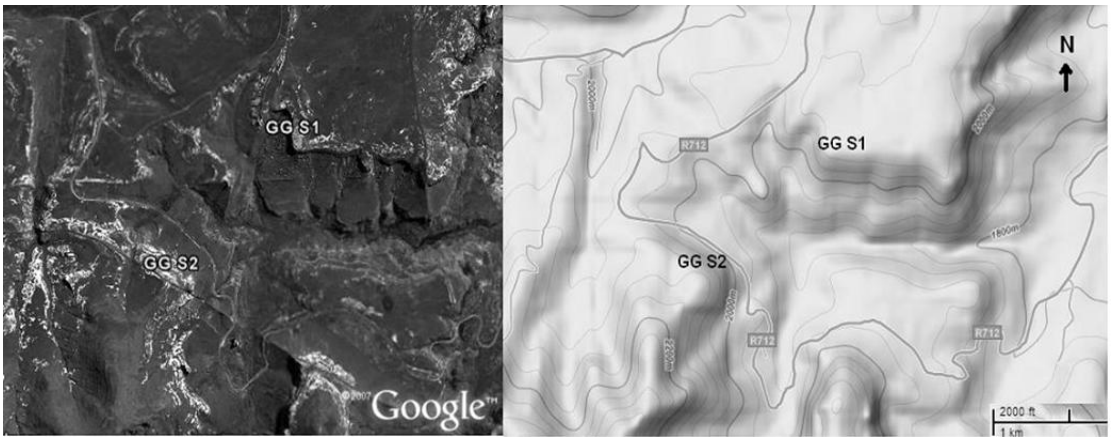

Figure 6.2: Site locations within the Golden Gate National Park. Source: Mol and Viles (2010)

6.2.2. Site 1

Site 1, as shown in figure 6.3, consists of a large overhang of Karoo basalt, forming a shelter situated at the top of a steep cliff, which is approximately 75 meters high. The shelter itself measures approximately 45 metres wide, with a depth ranging from 1 to 8 metres. The site faces west, meaning it gets most sunlight in the late afternoon and evening. The overhang is too deep to allow sunlight to penetrate to the depths of the back wall. The measurements were taken on the walls which are exposed to sunlight, as marked in figure 6.3. It was not possible to take viable readings at the back wall, as the high surface moisture content and thick wall vegetation made adhesion of the electrodes to the rock face very difficult. In addition, one of the transects (transect 2, site 1) which was measured in 2008 was no longer

accessible in 2009, as higher moisture content on the surface had enabled algae colonies to expand substantially, rendering the slope inaccessible.

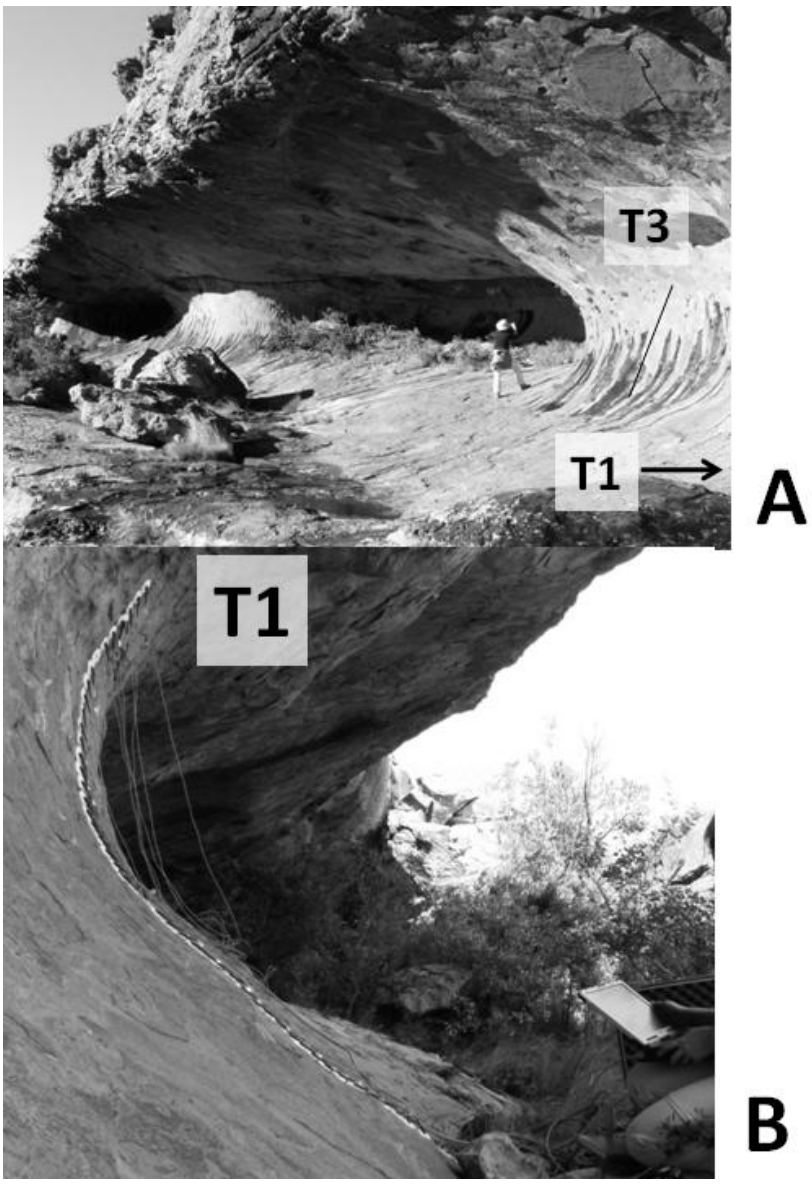

Figure 6.3: showing site 1, a large shelter at the top of a sheer cliff, visible at the left edge of the photograph. The shelter depth varies but the weathering features are similar along the entirety of the exposed surface (A).Figure 6.3B shows transect 1, site 1 as marked by the ERT electrodes.

6.2.3 Site 2

This site is much more exposed to sunlight and rain than site 1 (see figure 8.4). The shelter depth is significantly less, ranging from 2.32 to 4.79 metres and due to the height of the shelter, which reaches up to 12 meters within the main section, there is little shadow during the day. The shelter contains several bands of moisture outlets, possibly related to a number of bedding planes and associated piping and honeycombing. The moisture outlets did not appear to be as active at site 2 as they are at site 1, and there has not been the same increase in algal colonies between 2008 and 2009 as found at site 1.



Figure 6.4: showing site 2 and its position within the wider slope. Site 2 consists of a number of overhangs, creating one large and several smaller shelters. Transects were only taken in the main shelter, as marked in the figure.

6.2.4 Temperature data

iButtons temperature dataloggers were installed both at site 1 and site 2 in March 2008 and collected in April 2009. Two were left at each site, one at transect 1 (both sites) and one at transect 2 (site 1) and transect 3 (site 2). The year-long dataset shows that temperatures fluctuated between 9ºC and 25ºC (see figure 6.5). The data was derived from a 16,000 point dataset, with four measurements taken every 4 hours at 4 locations at each site. In order to produce a composite dataset, the average of all four iButtons per site was plotted out using a moving average per 25 points. This simplified plot therefore shows overall trends rather than individual points. The data corresponds with the temperatures reported by Wessels and Wessels (1991).

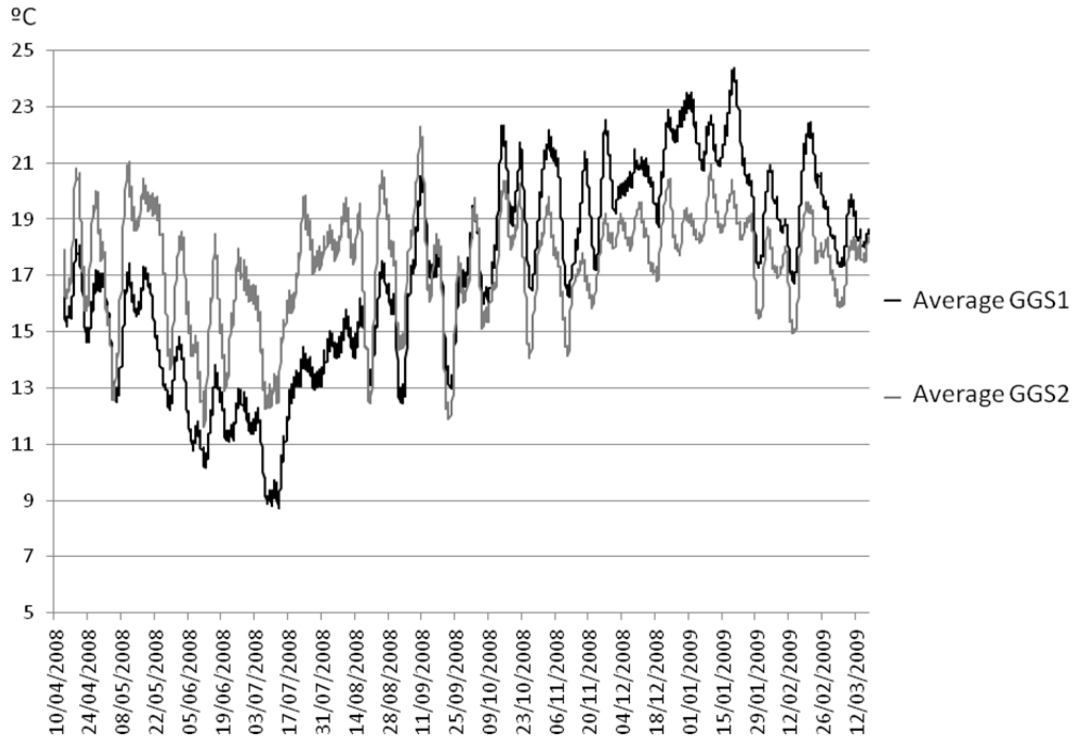

Figure 6.5: Average temperature data for site 1 (GGS1) and site 2 (GGS2)

This data shows that Site 1 experiences more extreme seasonal fluctuations during the year than Site 2. It is likely that the direct exposure of Site 2 to sunlight in winter raises the temperature at rock surface level, whereas Site 1 receives very little sunshine in winter but due to its deep overhang is able to trap any heat it receives during its direct sunlight exposure hours in summer (see figure 6.6), creating larger fluctuations of temperature between winter (June – August) and summer (December – February).

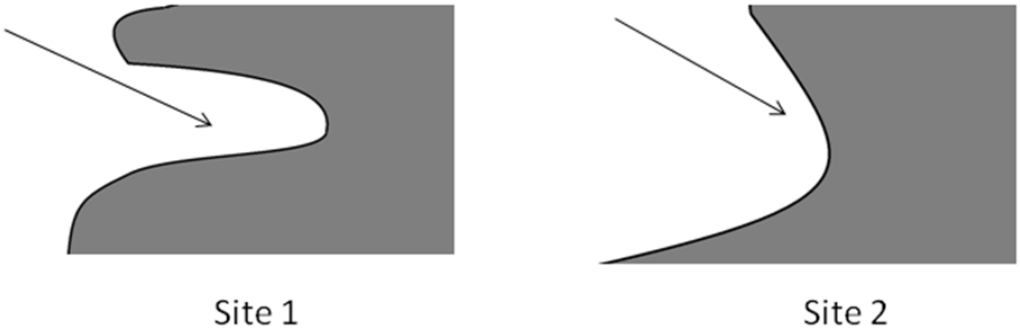

Figure 6.6: Diagram of slope angle and overhang development at sites 1 and 2. The arrow indicates rock surface exposure to direct sunlight.

Short-term iButton data obtained during the initial visit to both sites in 2008 showed that sunlight exposure is gradual during sunrise due to the curved nature of the slope, resulting in increased near-surface temperatures and significant differences in thermal stress caused by exposure differences. This creates a micro-climate that can enhance weathering rates (Smith, 1978). Also, Hœrlé (2006) shows that a modest increase in air temperature can lead to a much larger increase in temperature within the surface and subsurface of the rock face. This means that the near-surface temperature measured at site 2 could be lowered by wind for example, but the prolonged exposure of the rock face to direct sunlight can increase rock

temperature to far above those of site 1. Field observations confirm this, as site 2 rock surfaces were generally higher in temperature than those at site 1.

During both field visits (April 2008 and April 2009) conditions were mild, air temperatures reached around 20°C accompanied by the occasional rain- and thunderstorm, while rock surface temperatures at site 2, which was fully exposed, reached up to 40°C.

6.3 Materials and methods

6.3.1 Electrical Resistivity Tomography

Electrical Resistivity Tomography (ERT) uses low voltage (12V) electric currents to measure resistivity of a porous body between two points. In this case, GeoTom equipment (Geolog2000) was used to obtain the ERT readings. By sending voltages through different combinations of electrodes attached in a straight line along the rock face, a 2D pseudo-transect is built up. This method was first used in the medical sciences to monitor for example bone fatigue (Leng *et al*, 2008), but has been adapted to suit geological and more recently geomorphological needs (Abu-Zeid, 2006; Sass and Viles, 2006 and 2010; Mol and Preston, 2010).

A GeoTom was used to obtain ERT transects at each site. The electrodes were attached to the rock surface with ECG electrode pads, at a spacing of 5 centimetres, producing a 2.45 meter long transect. Using the Wenner configuration, the set of 50 electrodes produced a 16 row 2D pseudo-section. An inversion programme (RES2Dinv) was used to produce the pseudo-sections, based on most likely distribution using an adapted version of Loke and Barker's (1996) algorithm, and incorporated into a smoothness-constrained least-squares method (see Mol and Preston (2010) for more details). We also used this programme to evaluate the estimated errors, which were very low as they ranged between 0.33 and 7.0%.

Considering we were measuring weathered rock surfaces these errors are an indication of the quality of the measurements as the errors are based on variability within the transect and geological probability.

6.3.2 Equotip and Protimeter

The Equotip is a device similar to the Schmidt Hammer, measuring rock hardness through rebound values. It has been previously used in both field settings (Aoki and Matsukura, 2007) and laboratory studies (Yoshida *et al*, 2001), and shown to be very effective as it gives accurate results, but is non-destructive due to the lessened impact and size of the rebound element. Viles *et al* (2010) conducted a comprehensive field experiment which compared the measurements of the Equotip with a number of other rebound devices. They showed that the Equotip is particularly effective in areas that could be affected by edges, which in the case of this particular research is an advantage as most surfaces surveyed were heavily flaked and cracked. Furthermore, they discussed the role of moisture in rock hardness measurements, showing that the Equotip is relatively insensitive to surface moisture compared to the Schmidt Hammer, but that care should still be taken. We therefore recorded any visible surface moisture for each Equotip measurement. Previous research in the Golden Gate also showed that Equotip hardness values could be affected by moisture accumulation (see Mol and Viles, 2010) but when used in combination with ERT, which visually identifies moisture accumulations it is a very helpful tool in determining the link between rock surface weakening and subsurface moisture accumulation. At each tenth electrode of the GeoTom transect ten measurements were taken which were averaged out to minimize the influence of small scale fluctuations.

A Protimeter Surveymaster was used to assess surface saturation. The Protimeter is a non-destructive commercial moisture meter which measures resistivity between two prongs at a

set distance of 3cm. The numerical values represent the wood moisture equivalent (WME) of masonry and other building materials. We have therefore used these measurements as a relative indication of surface saturation. One measurement was taken at each GeoTom transect electrode, resulting in a 50-measurement dataset for each transect.

6.4 Results

6.4.1 Results per transect

All data was assessed per transect using a combination of the ERT, Protimeter and Equotip results. We initially assess the linkages between the datasets qualitatively to investigate trends visible followed by a semi-quantitative assessment of percentage changes between the 2008 and 2009 measurements.

6.4.1.1 Site 1, Transect 1

Site 1, transect 1 (S1T1, see figure 6.7) shows a moderate decrease in moisture content between 2008 and 2009. There is an interesting trend in the middle of the transect (ending at roughly 1.60m) where the wetting front appears to be moving towards the bottom of the transect. However, from 1.20m towards the bottom of the transect, a drier layer appears to have formed during the year, which is approximately 20cm thick and continues to the bottom of the transect. At the bottom of the transect an area of very high resistivity is developing. In the centre of the transect a moisture inlet, which is visible at 1.20m in 2008, has completely disappeared in 2009 indicating that it is either a deflected or no longer active. Alternatively, it has moved further into the rock, out of the ERT measurement band, as the area around the previous location of the inlet is still relatively wet, showing that there is still moisture brought into this part of the rock.

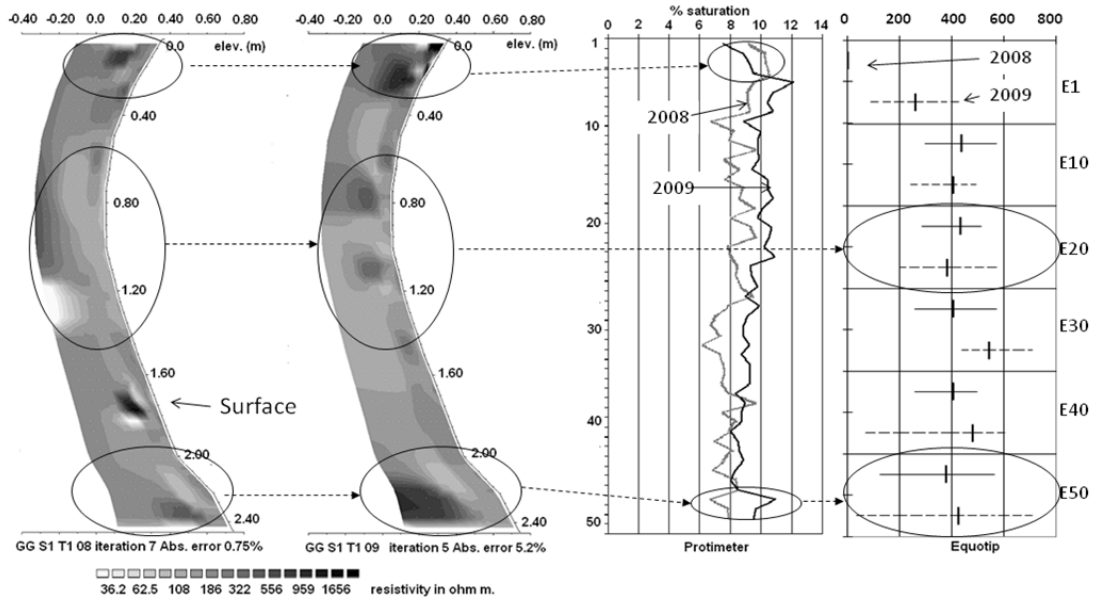

Figure 6.7: All results from Site 1, Transect 1 showing ERT results of 2008 (left) and 2009 (right) plus the results of Protimeter and Equotip measurements. E1 (on the right) stands for electrode 1 (0 cm), E10 for electrode 10 (45 cm) etc. Note that there is no 2008 Equotip measurement at E1, which is therefore labelled '0'.

The Protimeter data shows that overall there is little change in the general trends. However, the 2009 data is slightly elevated from the 2008 data, as the mean Protimeter value per transect has increased on average by 12.38 %, with the exception of the top 20 cm which has decreased by 15.26 %. This correlates with the higher resistivity areas which appear to have developed at the top of the transect between 0.0 and 0.20m. In the same way, in the drier area at the bottom of the transect a high resistivity area has developed, indicating a decrease of moisture content not only in the high resistivity area but also in the immediate subsurface (0-8cm into the rock face).

The Equotip measurements echo the changes shown by the ERT measurement to some extent. The upper middle section shows weakening of the rock surface where the

subsurface has become wetter, whereas the bottom section has increased in hardness, which coincides with a drier surface and subsurface.

6.4.1.2 Site 1, Transect 3

Transect 3 shows a significant increase in moisture content, especially in the middle of the transect and the bottom (see figure 6.8). At 1.20m, an area which had the potential for developing a moisture inlet, as it already displayed relatively low resistivity in April 2008, had indeed developed further in April 2009. The high resistivity area which is located circa 2- to 40 cm into the rock, was previously seen at approximately 1.10m, appears to have diminished and absorbed into an area of lower resistivity. It appears that the area of low resistivity which is visible between 1.0m and 1.40m functions as an inlet for moisture which is then redistributed along the subsurface, both towards the top of the transect and the bottom of the transect. This is especially evident in the area at 0.70-0.80m. The Equotip confirms these observations as surface hardness at electrodes 20 and 30, which cover the middle section of the transect, show a decrease in mean hardness, as well as higher variability.

At the bottom of the transect, a very similar process is happening as an inlet of moisture appears to have become increasingly active. It follows an area which was already lower in resistivity than the surrounding area (see 2.10m, 2008). The Equotip measurements show that the average of the hardness has not decreased significantly, which is possibly due to the 2009 average moisture content at the subsurface staying roughly equal to the 2008 measurements. But, more significantly, the variability of the measurements has increased substantially, showing possibly increasing instability of the subsurface which could result in accelerated weathering.

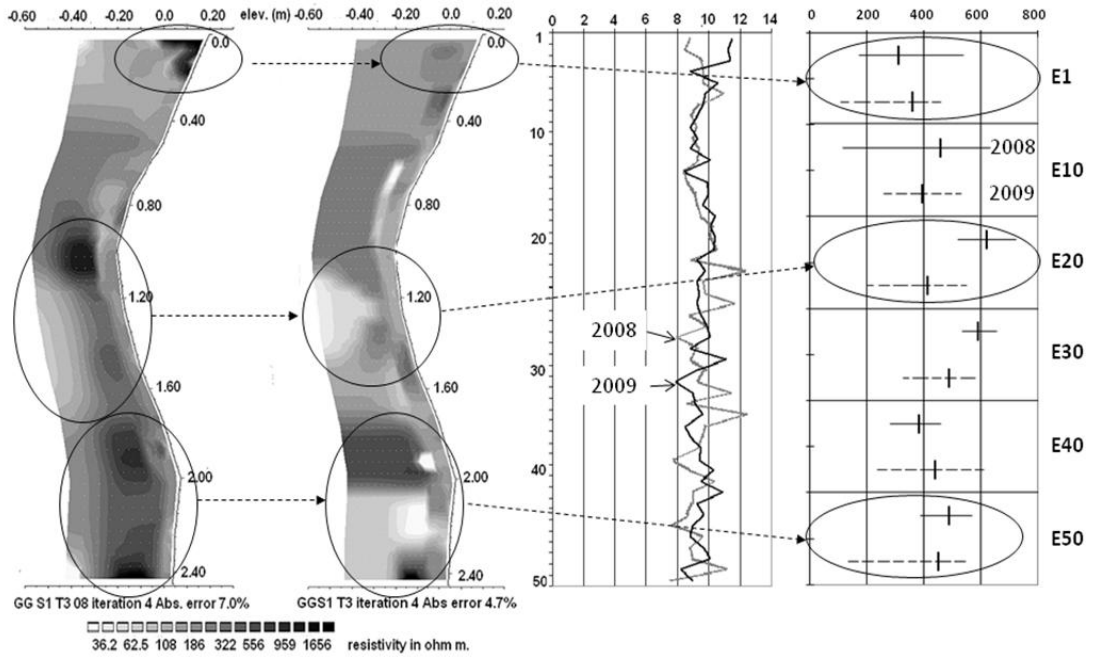

Figure 6.8: All results from Site 1, Transect 3 showing ERT results of 2008 (left) and 2009 (right) plus the results of Protimeter and Equotip measurements.

6.4.1.3 Site 2, Transect 1

This transect shows an overall decrease in resistivity between 2008 and 2009, which is assumed to be a result of an increase in moisture content. Especially in the 5 centimetres directly underlying the surface a band of moisture has formed, and has removed the drier area which was visible between 0.40 and 0.80m along the transect in 2008, which is reflected in the lowered rock hardness values (see the areas marked by the two top circles in the ERT diagram and the Equotip values which are linked to these in figure 6.9). Unfortunately there appears to be little correlation between the Protimeter and the Equotip and ERT values. This is likely because of the fragile nature of the transect, where moisture accumulations are near the surface. The sharp prongs of the Protimeter on a number of occasions penetrated the thin surface and measured the wet subsurface instead. This explains the presence of the extreme peaks that can be seen in the Protimeter measurements.

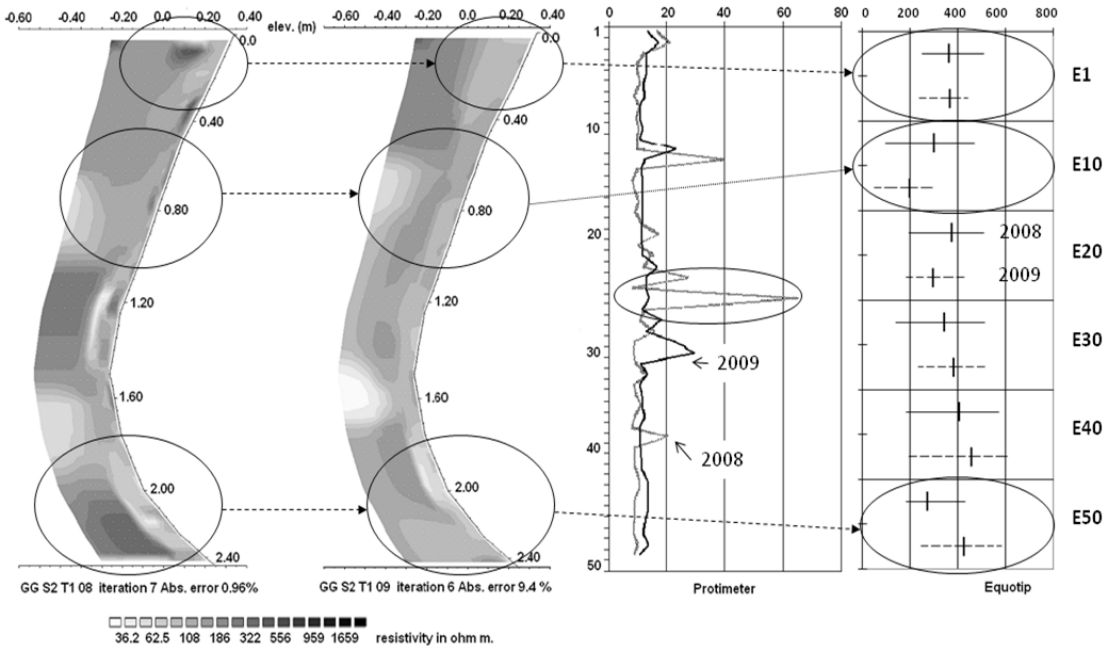

Figure 6.9: All results from Site 2, Transect 1 showing ERT results of 2008 (left) and 2009 (right) plus the results of Protimeter and Equotip measurements. The top two circles mark the areas of noted decrease in resistivity and the associated lowering of rock hardness.

6.4.1.4 Site 2, Transect 2

This transect shows less change between 2008 and 2009 compared to the other transects (see figure 6.10). The ERT transects show that the bottom of the transect has decreased in resistivity, indicating an increase in moisture content. At the centre of the transect, at 1.60 m, an outlet seems to have become more active, creating a wetter subsurface. This is reflected in the substantial lowering of Equotip values in this area, as well as much higher variability within the measurement set. The top of the transect has changed very little which is also reflected in stable Equotip values (see E20, figure 10 Equotip). In the Protimeter dataset there appear to be three outliers in 2008 which have disappeared in 2009. Field observations show that these outliers were probably caused by subsurface algae colonies which were detected by the Protimeter when it pierced the fragile surface. This appears to

not have happened in 2009. Instead, there is some increase in saturation the middle section of the transect, which is also reflected in the lowered ERT readings in this section. However, these changes are minor compared to the changes observed in the other transects, especially transect 1, Site 2.

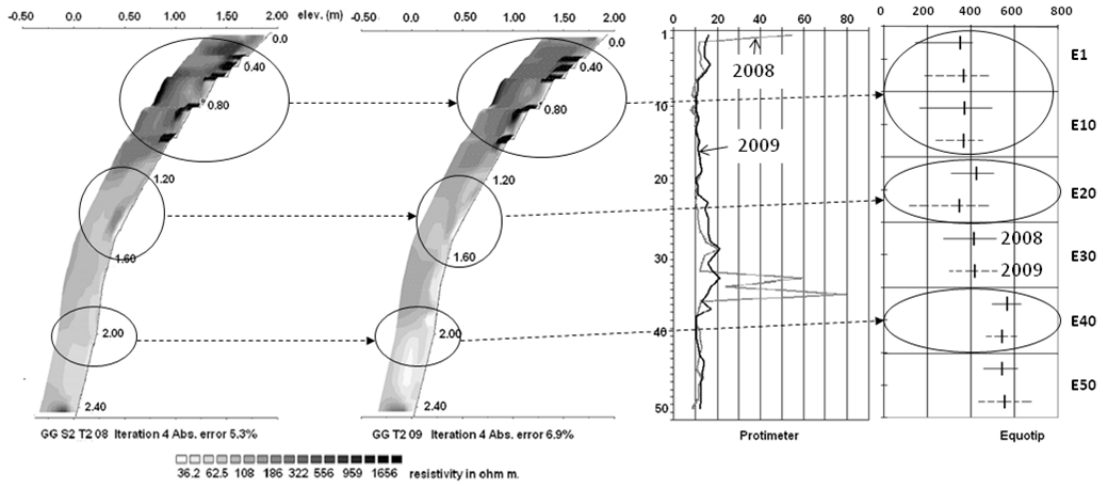

Figure 6.10: All results from Site 2, Transect 2 showing ERT results of 2008 (left) and 2009 (right) plus the results of Protimeter and Equotip measurements. The top two circle marks the area of noted increase in resistivity and the decrease in Equotip measurement variability.

6.4.1.5 Site 2, Transect 3

The final transect shows a marginal increase in moisture content between 2008 and 2009 (see figure 6.11). At the top of the transect the outlet appears to have become less active during the year between measurements. This has also impacted the middle of the transect, at 1m, as it has become somewhat drier. This is reflected in the decrease in variability of the surface hardness values as measured by the Equotip. The bottom of the transect remains largely unchanged, which is also reflected in the stable Equotip measurements which are virtually identical to the measurements taken in 2008. There are also very few changes in the Protimeter measurements; they show a similar, slightly erratic, pattern but little overall

change in surface saturation. Overall, there is very little change observed between 2008 and 2009.

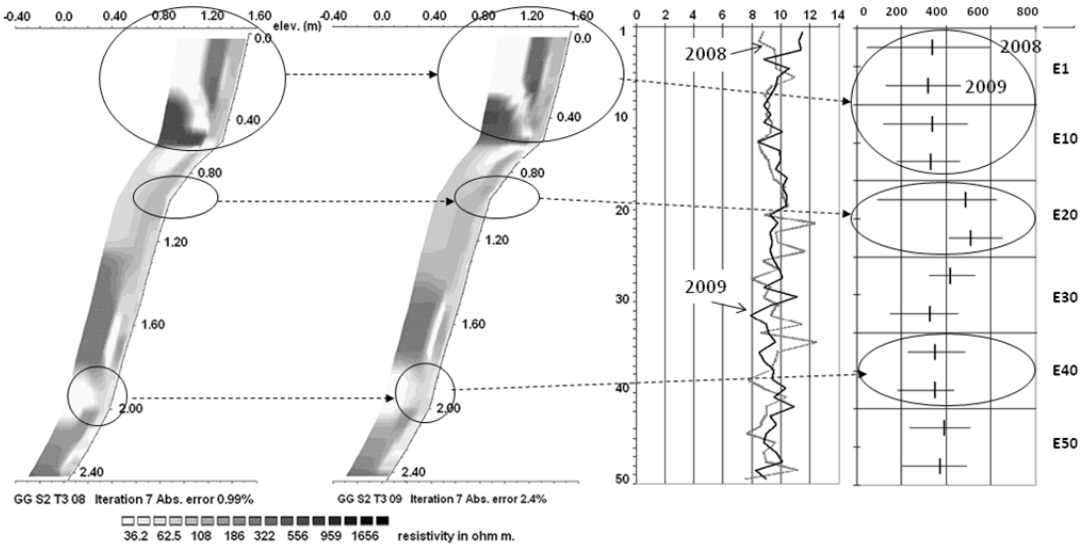

Figure 6.11: Site 2, transect 3 measurement results. The top two circles mark increased variability within the Equotip measurements associated with the decreased activity of the outlet at the top of the transect.

6.4.2 Raw data analysis

To further investigate the increase or decrease in moisture we have used the raw data of the top three GeoTom measurement layers (up to 20 cm into the rock surface) of each site. We have only used these because this is the area which is most closely correlated with the Equotip measurements, and which is of most influence on surface weathering. A lowering of resistivity values indicates increased moisture content, whereas an increase in resistivity values correlates with a lower moisture content. It has to be taken into account that outliers have not been removed from this dataset. We are therefore interpreting the overall trends rather than the individual data points.

Site 1 shows a significant increase in resistivity values at transect 1 but a lowering of resistivity values in transect 3 (see figure 6.12). However, the increase in resistivity values in transect 1 are mostly confined to the top and bottom part of the transect, which corresponds with the observations previously made that there is a lowering of resistivity towards the middle of transect 1 and in the lower area of transect 3. It is also clear than the lowering of resistivity values is more significant in the near-surface of the top of transect 3, which is related to the 2009 demise of the high resistivity area observed in 2008 (layer 1, figure 6.12), but this lowering of values is more pronounced in the deeper areas of the rock (layers 2 and 3, figure 6.12) where two moisture accumulations can clearly be seen. A paired samples T-test of the 2008 and 2009 data, using a 2-tailed approach, showed a p-value of 0.00 for transect 1 and 0.00 for transect 3, confirming that there is a statistically significant difference between the 2008 and 2009 values.

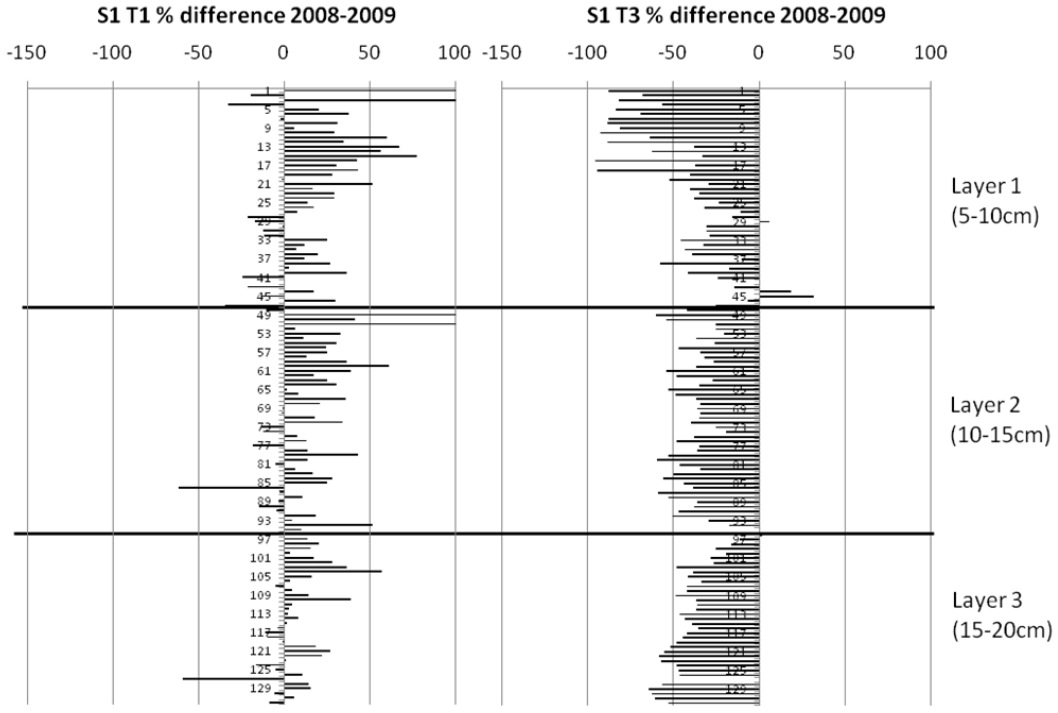

Figure 6.12: Percentage difference raw data 2008/2009 lines 1-3 (5 - 20cm depth) Site 1. At transect 1 ERT mean value increased by 14.4% between 2008 (mean: 159.06 ohm m.) and 2009 (mean: 181.99 ohm m.) Transect 3 shows an overall decrease in resistivity. ERT mean value decreased by 51.95% between 2008 (mean: 297.88 ohm m.) and 2009 (mean: 143.13 ohm m.)

Site 2 shows a very different trend compared to site 1 (see figure 6.13). The data agrees with the previous observation that there is an increase in moisture content overall between 2008 and 2009. However, each of the three transects do show a different pattern. At transect 1 the near-surface has become more saturated (levels 1 and 2) predominantly in the top of the transect. This trend carries further into the sub-surface as level 3 shows a marked decrease in resistivity as well, but less so towards the bottom of the transect. ERT mean values of transect 1 were approximately stable with only a 0.17% average increase between 2008 (mean: 108.68 ohm m.) and 2009 (mean: 108.86 ohm m.) A T-test showed that this change is somewhat statistically significant with a p-value of 0.95. Transect 2 shows a similar pattern but a far more distinct wetting of the top of the transect and a status quo towards the bottom of the transect. ERT mean value decreased by 10.11% between 2008 (mean: 104.68 ohm m.) and 2009 (mean: 94.09 ohm m.) A T-test showed that this change is statistically significant with a p-value of 0.00.

The ERT values of transect 3 increased by 4.36% between 2008 (mean: 74.57 ohm m.) and 2009 (mean: 77.81 ohm m.), confirming the previous analysis that there has been little change between 2008 and 2009. A T-test did however show that this change is statistically significant with a p-value of 0.00.

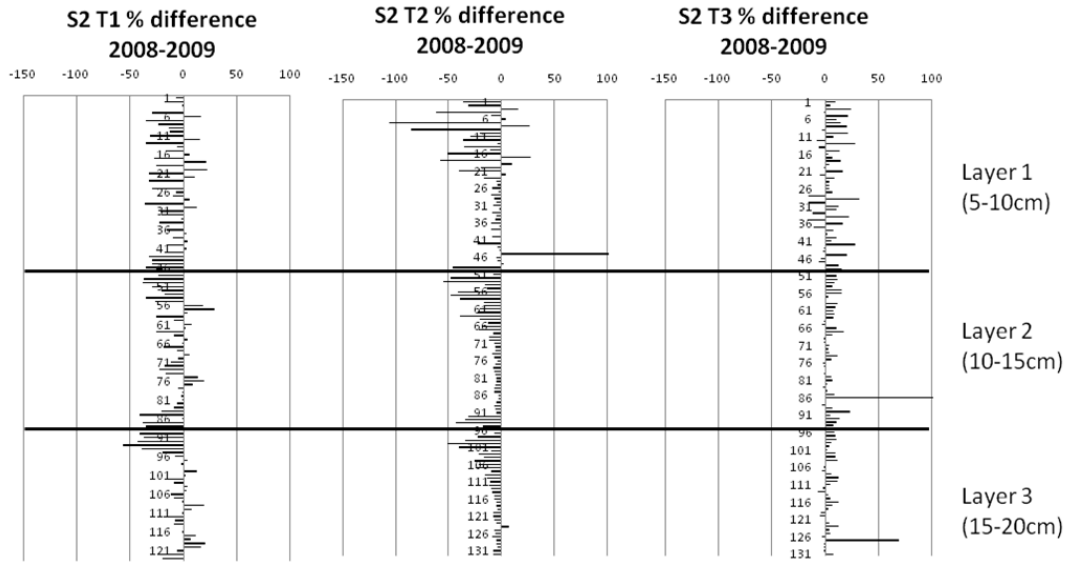

Figure 6.13: Percentage difference raw data2008/2009 lines 1-3 (5- 20 cm depth) Site 2.

To further investigate the link between rock surface hardness decrease and moisture content increase, we have averaged the Equotip values of each transect (see figure 6.14). This analysis shows some very interesting results. Whereas looking at data from each electrode position in the previous transect analyses showed a good visual correlation between moisture behaviour and Equotip behaviour, there is no clear correlation between average Equotip values per transect and percentage difference in overall ERT data. However, a striking correlation is found between the significant lowering of resistivity values and the lowering of Equotip values at Site 1, transect 3. Site 2, transect 2 also shows a correlation between a slight lowering of ERT values and Equotip values. However, these are the only clear correlations as the other transects show very little correlation between changes in resistivity and overall changes in Equotip values. They do show, however, that relatively small changes in moisture regime do lead to a change in Equotip values but these can be either strengthening or weakening.

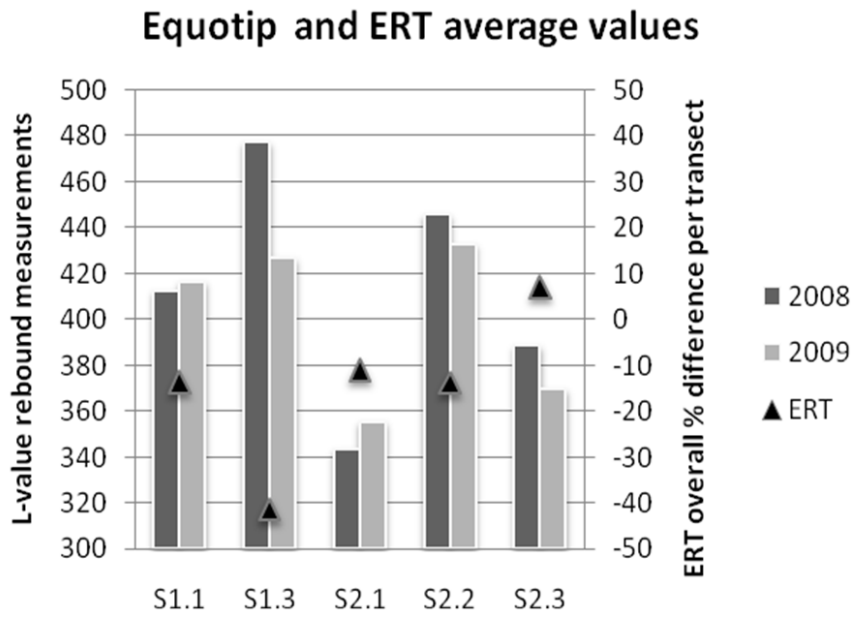

Figure 6.14: Equotip average values per transect, comparing 2008 and 2009 measurements. These show that average measurements show much less correlation with moisture changes observed, whereas correlation on a small (individual datapoint) scale showed good correlations (see figures 6.7 to 6.11)

This brings an interesting dimension of scale issues into this analysis, as the small scale correlation was successful but extrapolation to overall transect changes was not, highlighting the problems associated with generalizing a dataset which contains highly spatially and temporally variable data. This does, however, show the strength of this type of research which is the highly detailed investigation allowing for a more accurate assessment of small scale weathering processes. Previous research has quite often focussed on either the small or the meso scale but this research shows that the small scale changes are dependent on larger scale moisture fluctuations, but that is it not possible to use larger scale extrapolations to understand the small scale weathering and how this affects rock surface weathering. We therefore need to investigate small scale weathering within larger scale environmental conditions, such as moisture fluctuations, but take the spatial variations of these features into account before extrapolating to a larger scale.

We conducted an additional test to investigate if there is a statistically significant relationship between average Equotip per 10-electrode block and average ERT values for that block and found that the results are erratic at best and show an extremely poor statistical correlation. We will therefore first discuss the results we have observed in the course of these various analyses per site, followed by a discussion of the consequence of this conflicting information for our understanding of the role in moisture in sandstone weathering.

6.4.3 Results per site

Site 1 shows a good visual correlation between weakening of the surface between 2008 and 2009, and subsurface moisture accumulation (see figure 6.7). Especially in areas which were already higher in moisture in 2008, the increased accumulation of moisture between the 2008 and 2009 measurements has showed a significant impact on surface hardness. Even though in general Protimeter measurements appear to have fluctuated very little, ERT

measurements show that there is an additional accumulation of moisture in the subsurface which appears to originate in the inner sections of the rock rather than infiltration from outside such as fog or rain.

Site 2 shows an array of different moisture distributions and associated weakening of the surface between 2008 and 2009. Transect 1 shows a good correlation between the increased moisture content and surface weakening. In contrast, transect 3 shows very little change which is reflected in both the stable ERT and Equotip measurements. Transect 2 shows predominantly changes in the top of the transect, but little towards the bottom. There are several explanations for this type of trend. Firstly, a bedding plane which runs diagonally through the transects was undetected on the surface could have become more active. This, however, is unlikely as the moisture outlets on the rock face clearly demark the bedding planes and care was taken to ensure an accurate alignment of all the transects within a site. Secondly, the amount of direct exposure to sunlight could be correlated to the changes in moisture content. In this case, transect 1 receives more direct sunlight than transect 3. On intuition, this would indicate that transect 1 should have become drier over the year. This does not appear to be the case as it is transect 3 that has become drier overall. Increased capillary forcing of the moisture through the rock wall by increased temperatures could be the main driver behind these, as Camuffo suggests (1995) that increased heating can cause the meniscus to retreat, allowing the moisture to evaporate from the surface, after which the air filled pores could attract moisture from the lower subsurface, although currently little is known about this particular process in sandstone masses.

However, there are other potential reasons why the measurements of 2008 and 2009 are different. Firstly, although every care was taken to repeat the measurements in the exact

same location, small shifts of one or more cm of spatial location of the measurements could have occurred. Secondly, even though the weather conditions in 2009 were similar to those in 2008 the weather during the measurements as well as in the weeks prior to measurement cannot be identical. Thirdly, a drift in the equipment calibration could have occurred between 2008 and 2009 due to continual usage for a variety of projects.

6.5 Discussion

These results confirm the conclusions drawn from our initial work conducted on the Clarens sandstone that there is some correlation between subsurface moisture accumulation and surface weakening. The repeated measurements show that even within a geographically confined area, i.e. the same valley or even the same rock wall, moisture regimes can be very diverse and there are few changes which were found uniformly within all transects. Instead, the diversity of moisture regime shifts illustrates that local variations occur within such variations which can lead to localised weakening or strengthening of the rock surface. The link between moisture and weathering has previously been established, see for example Matsukura and Takahashi (2000) Avdelidis *et* al (2003) and Halsey *et al* (1998), especially in relation to the movement of soluble salts in natural rock and building stone (Goudie, 1986; Benavente *et al*, 2004). These studies show a clear correlation between exposure of rock to moisture and increased weathering rates, but that these changes can be erratic. However, what our research shows is that moisture patterns are changing over annual timescales and that these changes can have a profound effect on the rock surface strength. It is clear that there is substantial change in moisture distribution between the 2008 and 2009 measurements. The changes in Equotip measurements show visual similarities to the changes in moisture distributions observed within the ERT measurements, but these changes do not correlate when using statistical assessment methods. The Protimeter measurements show very little correlation with the ERT data. This is possibly due to the

heavily weathered nature of the sandstone surface and the associated algal colonies which accumulate just below the surface at Protimeter measurement depth. These profoundly influence Protimeter measurements, increasing them significantly.

Site 1, transect 3 (see figure 6.8) is a particularly good example of the effect of an influx of internal moisture to the surface. Both the middle and bottom section of the transect show clear lowering as well as increased variability of hardness values from 2008 and 2009. Interestingly, however, the top section shows increased hardness measurements even though ERT values have lowered. Considering the 2008 measurement showed an area of very high resistivity this would indicate increased moisture content here. This trend has up to now been associated with lowered Equotip measurements. Figure 6.15 shows the top part of the section, which on the surface does not show any obvious signs of increased moisture influx.

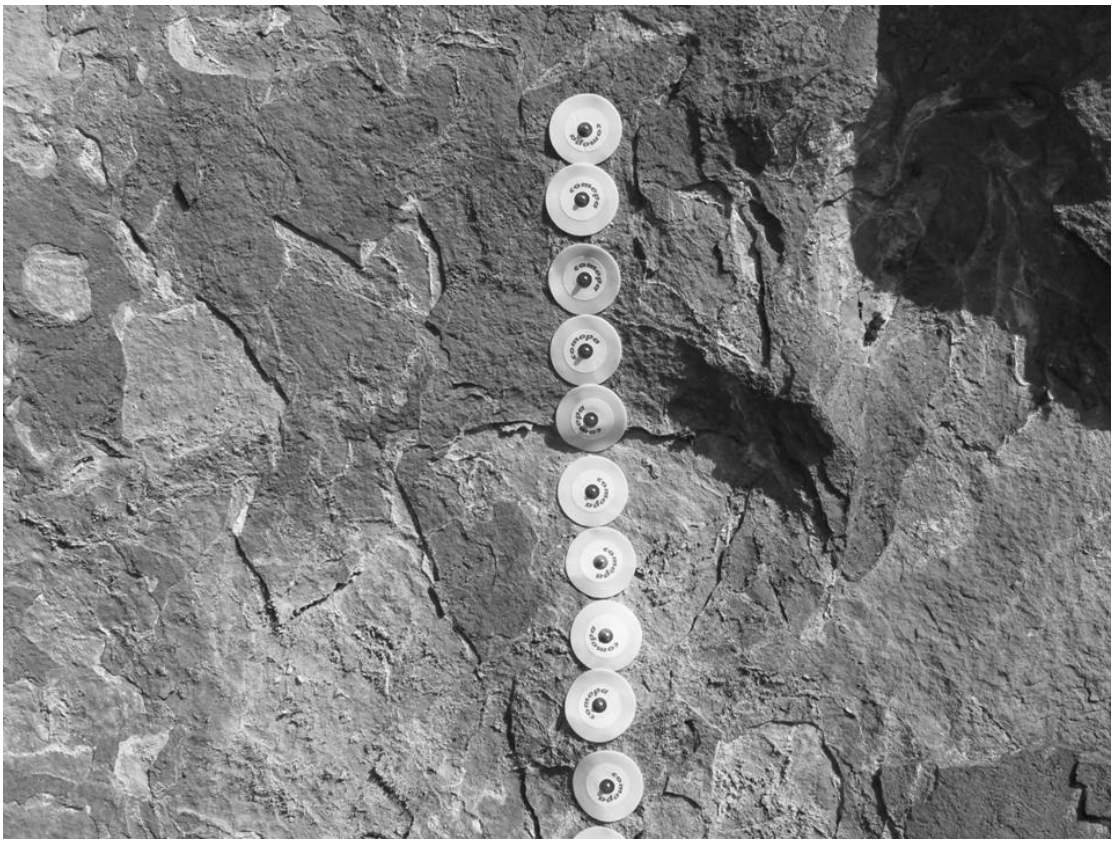

Figure 6.15: Top part of transect 3, site 1 showing flaking of the surface in 2009.

This is an interesting reversal of trends, but one that has been investigated previously. Ballantyne *et al* (1990) states that the presence of incompressible water in surface voids might actually lead to increased Schmidt Hammer values. However, this can only happen if there is no immediate drainage outlet for the pore water and fractures have not been created by the impact of the measurement. An added complication is that their research was conducted in a periglacial environment, where freeze-thaw and permafrost could still be of influence on the rebound readings. In this case, it can perhaps be assumed that at the time of the 2008 readings significant air pockets were present, which have since filled up with moisture or have ceased to exist due to flaking or crumbling. Field observations have shown that a crust had developed on the rock surface in 2008. In 2009 this crust was still present, indicating a prolonged exposure to weathering agents, rather than a fresh face. This raises an interesting point as moisture could have a strengthening role as well as being an agent of rock weathering. In the most fragile surfaces moisture, it seems, could provide temporary glue and a base for algae colonies which could also hold together the granular structure. Indeed, fieldwork observations showed that many of the flakes found on the rock surface have well-developed algae colonies underneath them. Figure 6.16 shows a schematic representation of this idea where (1) is the stage of development of algae colonies and bonding of looser grains of the surface by moisture, (2) is the optimum strength point and (3) is the period of detachment of flakes and grains due to the increased pressure from moisture and algae built-up. Even though this principle has not often been applied in rock weathering research, it is a well-known phenomenon within slope stability. A large number of studies have defined 'optimum moisture content' as an important factor in slope stability (see for example Tohari *et* al, 2007; Lee *et al*, 2008; Kamon *et* al, 2009; Ling *et al*, 2009; Matsushi and Matsukura, 2009; Xiao and Gomez, 2009) creating optimum cohesion between the individual grains within the soil structure. It is possible that this same principle

applies to instable rock surfaces, where optimum moisture content increases the strength of a fragile surface for a limited period of time.

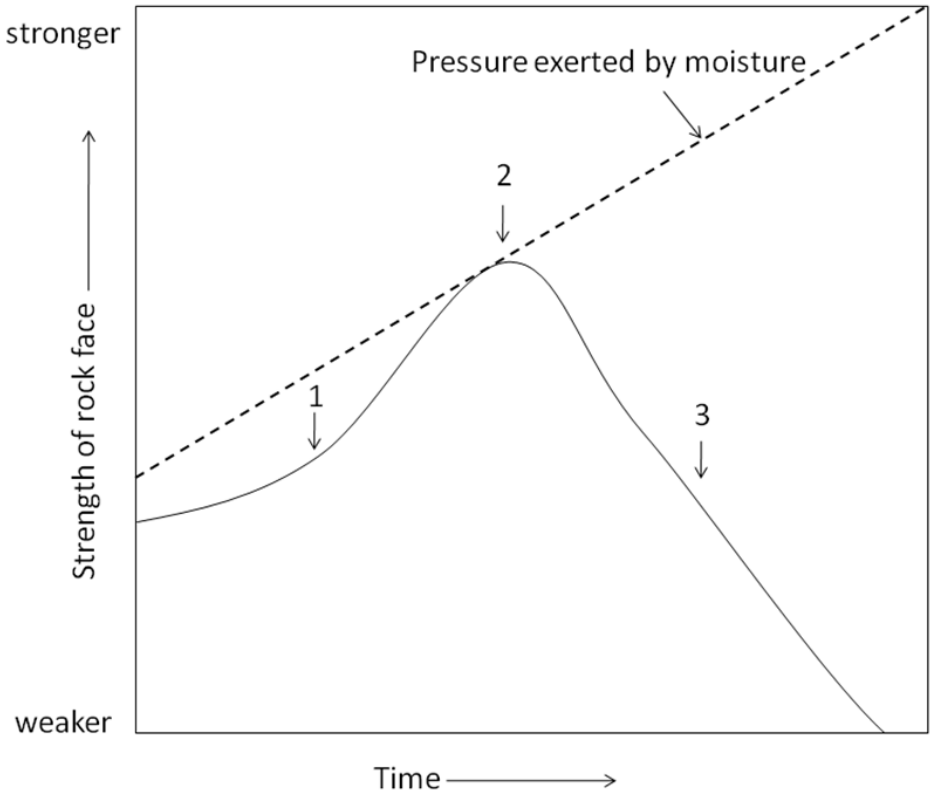

Figure 6.16: Optimum strength relationship over time between moisture pressure and rock face strength. (1) represents the growing moisture and algae stage, (2) the optimum strength point and (3) the erosion stage where flakes and grains are removed from the rock surface.

ERT measurements show that understanding fluctuations within moisture regimes can hold the key to predicting increasing loss of surface strength and the associated acceleration of weathering processes. The combination of Equotip and ERT has shown that the interaction of moisture and rock surface is complex but that the behaviour which is to a large degree visible on the surface originates from further within the rock through inlets of moisture. As these patterns change over time, so does the rock surface strength and variability. However,

this study was conducted over 2 years, and only shows short-term annual changes. A more elaborate study over a number of years is required to further investigate annual trends.

6.6 Conclusions

Our initial research in the Golden Gate Highlands National Park showed that there is a significant correlation between subsurface moisture accumulations and rock surface weakening as well as increased variability within Equotip measurements (Mol and Viles, 2010). This follow up research confirms these previous findings and also pinpoints that shifts in moisture accumulations are closely related to surface weakening and variability as measured by the Equotip.

Our temperature data shows that Site 1 experienced overall larger temperature fluctuations, reaching lower temperatures in winter and higher temperatures in summer. We concluded that this is due to trapping of heat under the overhang during summer and decreased exposure to sunshine in winter. The direct consequence for internal moisture regimes appears to be that the ERT annual fluctuations appear to be far larger than those at site 2. In addition, both within site 1 and 2 there are variations within the moisture changes, indicating that moisture regimes are geographically limited even within sites.

The changes in Equotip values showed that the correlation between moisture and rock surface strength may not be as straightforward as previously thought and that moisture may for a short period of time strengthen the rock surface. The work done previous by Mol and Viles (2010) found that there is a direct relationship between rock hardness and moisture accumulation. These new findings complement the 2010 study by adding further detail to the interaction between rock surfaces and moisture and showing that annual changes in

moisture regimes should be taken into account as important drivers of sandstone weathering.

Acknowledgements

We would like to thank all the staff at the Gladstone Offices, GGHNP, in particular Sandra and Johan Taljaard and the guides, Sam, Moses and Joseph. We would also like to thank Matt Telfer, Andrew Goudie (Oxford University) and Stefan Grab and Jennifer Lalley (University of the Witwatersrand) for their excellent comments, suggestions and company as well as Mark Larsen (Oxford University) for his invaluable help with statistical analysis. We would also like to thank the staff at the OxRBL for all their help in preparing for this fieldwork. In addition, we are very grateful for the Dudley Stamp Memorial Award which we received from the Dudley Stamp Memorial Trust in collaboration Royal Geographical Society and the Bill Bishop Award which we received from the Quaternary Research Association. In addition, we would like to thank St Cross College, Oxford for their generous financial contribution towards the research.

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CHAPTER 7: CAVERNOUS WEATHERING IN CLARENS SANDSTONE, GGHNP, SOUTH AFRICA

This chapter has been accepted as a publication for *Earth Surface Processes and Landforms* under the title 'The role of rock surface hardness and internal moisture in cavernous weathering of Clarens sandstone, Golden Gate Highlands National Park, South Africa' to discuss the complexities of case hardening and internal moisture found within the sites investigated. This chapter completes the series of three chapters which investigate the role of internal moisture in cavernous weathering. This chapter in particular shifts the focus from small-scale weathering features to larger scale shelter formation. Whereas the previous chapter (chapter 6) focussed on the temporal changes in internal moisture and it's non-linear relationship with rock surface hardness, inferred to be degree of weathering, this chapter widens the scope of the study by incorporating more sites. This focus in this chapter therefore lies on the development of cavernous weathering features in Clarens sandstone, and how it relates to processes such as case hardening and core softening. This investigation into temporal changes in cavernous weathering behaviour was carried out by ordering the sites by perceived stage of development. This was then developed into a new model which incorporates the complexities of internal moisture as related to surface hardness.

This chapter provides the final GGHNP data analysis which is focussed around aim 2 (as set out in chapter 1) which is "To understand the influence of internal moisture on sandstone weathering in the development of cavernous weathering features".

Submitted: 12/03/2011 Accepted: 11/07/2011

THE ROLE OF ROCK SURFACE HARDNESS AND INTERNAL MOISTURE IN CAVERNOUS WEATHERING OF CLARENS SANDSTONE, GOLDEN GATE HIGHLANDS NATIONAL PARK, SOUTH AFRICA

L. Mol, H.A.Viles

Abstract

Cavernous weathering is a highly complex process which remains poorly understood even though it is found in a large variety of environments. It remains a central, and contested, issue within geomorphological research despite the large number of studies reported. In particular, the role of internal moisture is unclear. In this study, we use Electric Resistivity Tomography (ERT) to map moisture distribution within cavernous features, as well as an Equotip to measure rock surface hardness to investigate the influence of internal moisture and case hardening on cavernous weathering. Using a number of shelters within Clarens sandstone, as found in the Golden Gate Highlands National Park (South Africa), we evaluate the dynamic relationship between internal moisture and case hardening. We found that by categorizing the shelters according to the stage of development of a shelter (young to established) we can simulate shelter formation over time. Our measurements showed that both case hardening and core softening play a role in the development of cavernous weathering features, which changes over time. Internal moisture distributions are connected to the changes in surface hardness observed and fluctuate according to development stage of the site. We propose a new model which illustrates the complex interaction between case hardening and internal moisture and suggests a new direction for cavernous weathering research.

Keywords: Sandstone, weathering, cavernous, ERT, rock surface hardness, temperature, exposure

7.1 Introduction

Cavernous weathering can be found in a wide variety of environments, and manifest itself in a number of forms such as shelters, caverns, alveoli and tafoni. However, the development of these cavernous features has been attributed to a large number of factors over the past 100 years. Complex interactions between both external and internal factors remain a continued point of debate, and primary processes suggested as being responsible for the formation of caverns have ranged from wind regimes (Futterer, 1897; Bartrum, 1936; Hall, 1989; Gillies *et al*, 2009) to fluctuations in moisture availability and relative humidity (Pope *et al*, 1995; Mellor *et al*, 1997). In recent years salt weathering has dominated in the literature (Mustoe, 1982; McGreevy, 1985; Young, 1987; Mottershead, 1994; Cooke *et al*, 1993 p.26; McBride and Picard, 2004; Strini *et al*, 2008; Mustoe, 2010), even though no consensus appears to have been reached over its precise role in cavernous weathering. In addition, case hardening – the formation of a layer of a few centimetres thick of increased hardness and resilience to weathering (Conca, 1985, p.3; McAlister *et al*, 2003) - is quoted as an important factor in cavernous weathering (Conca and Rossman, 1982) even though its precise role within cavern formation is not agreed upon. As Turkington and Phillips (2004) state, one of the predominant issues within cavernous weathering research is the tendency to relate it to one single formative process, whereas in many cases cavern development can be only satisfactorily explained by invoking the operation of a range of weathering mechanisms. In particular, the role of internal moisture appears to be unclear. Sancho and Benito (1990) state that the surface and internal circulation of water will have a noticeable effect on phenomena such as wetting and drying and thermal weathering as well as salt weathering. Mellor *et al* (1997) clarify this role by linking evaporation to upward movement of soluble ions by capillary action which draws them towards the outer roof surfaces of the tafoni and precipitates them in the form of near-surface cement. However, this process may be limited to the outer roof surfaces, as in the cavern area the weathering has been suggested to be more rapid due to the absence of such protective cover,

resulting in core softening – the weakening of the rock face within the cavernous feature leading to increased weathering and removal of material (Conca and Rossman; 1985; Mellor *et al*, 1997) - where material is loosened by flaking and granular disintegration. Differential wind regimes within the cavern may also contribute to the formation of these features as increased wind speeds can increase evaporation rates, thereby exacerbating salt efflorescence on the surface of the cavern wall resulting in higher porosity and weathering rates (Rodriguez-Navarro *et al,* 1999). The influence of relative humidity in this context has been discussed by (Dragovich, 1967), but its relation to internal moisture is as yet unknown.

Lamb *et al* (2006) state that the origin of alcoves [such as the cavernous weathering found in the GGHNP] remains unclear given that the ability of seepage to erode bedrock is not yet comprehensively understood, and also because the other process mechanisms might have contributed to such cavernous weathering. In addition they state that as yet seepage weathering and erosion in rock have not been quantified, nor have mechanistic rate laws been proposed in the absence of an understanding of seepage erosion mechanisms. Electrical Resistivity Tomography (ERT) offers a partial solution to this problem, as the resistivity data 2D pseudo-sections offer a quantitative approach to internal moisture mechanisms. Previous work conducted on the Clarens sandstone in the Golden Gate Highlands National Park (GGHNP) has shown that internal moisture plays a significant role in the cavernous weathering of Clarens sandstone (Mol and Viles, 2010; *under review*) and identified internal moisture regime within the rock shelters found there. The shelters show evidence of weathering processes similar to those described in the formation of tafoni. Cooke *et* al (1993, p. 25) define tafoni as caverns with overhanging margins (or visors), which maintain their own microclimate (often cooler and relatively more humid than outside the tafoni) and are often broken up by flaking or granular disintegration of the surface. Field observations showed that the rock shelters in the GGHNP show identical behaviour but at a larger scale (10s of meters) than usually reported in tafoni research, which rarely exceed volumes of several cubic meters (Cooke *et*

al, 1993, p.25). We will therefore consider these shelters a subsection of cavernous weathering and analyse the data in the context of cavity formation.

In this paper we report on field-based studies of shelter formation in Clarens sandstone in relation to internal moisture dynamics. In addition, we assess the relative influence of other factors, such as exposure and temperature, to further our understanding of the influence of internal moisture (including seepage and subsurface moisture accumulation). Using a variety of techniques and approaches, seven sites were surveyed using ERT and Equotip to assess internal moisture distribution and rock surface strength and the dynamic relationship between these two factors.

The aim of this research is three-fold. Firstly, to establish whether there is a direct relationship between exposure, temperature and internal moisture regimes. Secondly, to assess any geographical differences in moisture regimes and rock surface hardness of the sites investigated and if these can be related to the development of cavernous weathering over time. And thirdly, to establish whether or not there is a link between the severity of the rock surface weathering and internal moisture regime characteristics. This builds on previous work conducted by Mol and Viles (2010; *under review*) in the GGHNP, which showed that there is a strong correlation between rock surface hardness, weathering and internal moisture regimes both over time and space. We have continued this research to investigate further to what extent exposure, internal moisture regimes and rock surface hardness are significant for shelter formation in the Clarens sandstone.

7.2 Site description

The GGHNP is situated in the foothills of the Drakensberg Mountains, at the northeast border of Lesotho (see figure 7.1). In contrast to the steep escarpments which characterize the mountain range, the GGHNP is situated in a landscape of rolling hills with dispersed exposed rock faces and shelters. The Elliot formation, the red mudstone which is visible at the base of some of the exposed

rock faces, is situated underneath the Clarens sandstone. These sandstones are of aeolian origin and their thickness ranges from 100 m to more than 230 m (Hœrlé *et al*, 2007). The most commonly occurring weathering landforms is cavernous weathering, resulting in tafoni and cavity formation, and subsequent shelter formation in the exposed sandstone surfaces. These shelters are seen around the GGHNP in a variety of settings, and appear to be the result of a number of processes such as seepage from the rock mass or exposure to direct sunlight and wind. Parts of the Clarens sandstone show a layer of carbonate cementation, which appears to influence shelter development (see site 2 in section 9.2.2), as they weather at a much slower rate. In addition, overlying basalt provides a solid capping for the sandstone, mainly at the higher peaks (kopjes), further exacerbating the differential weathering and subsequent shelter formation. Together these characteristics are the important contributors to differential weathering, resulting in shelter formation in the GGHNP (Groenewald, 1986). However, evidence of moisture outlets on the sandstone surfaces within the shelters indicates that internal factors could play an equal, or more important, role in the formation of the shelters. The seepage of water from within the rock enables a rich variety of microbiological colonies to sustain themselves, such as epillithic algal growth (Venter *et al*, 2010).



Figure 7.1: Location of GGHNP. Source: Modified from Bodleian Map Collection, University of Oxford

Field observations showed there is little evidence of permanent significant moisture movement along the sediment-covered slopes, and it appears that most moisture infiltrates directly into the slopes rather than gathering in run-off channels. There is, however, a stream which runs along the bottom of the valley and functions as a drainage system for the slopes.

7.2.1. Clarens sandstone

As Sumner *et* al (2009) describe, the Clarens sandstone is the uppermost section of the Karoo Sequence, a sedimentary sequence deposited between 200 and 160 MA ago. This medium- to fine-grained sandstone was deposited when aridity reached a maximum (Visser, 1984). A number of studies have investigated the properties of Clarens sandstone. Due to the large area covered by this particular type of sandstone, there is a large variation in the properties of the sandstone, as a number of studies have confirmed (see for example Castro and Bell, 1995 and Wessels *et al*, 1995). Case hardening is widespread and was recorded at almost every site surveyed. Büdel *et al* (2004) conducted a study into the microbiological activity within the upper subsurface of the sandstone and found that the cryptoendolithic cyanobacterial layer is often associated with the loosening of rock flakes with a thickness of about 2 mm. Kurtz and Netoff (2001) introduced the notion that the bacterial colonies found of friable sandstones, such as Clarens sandstone, can contribute to surface stability which appears to be applicable to the sites investigated in the GGHNP as the thicker flakes were often associated with bacterial colonies at subsurface level (see figure 7.2).

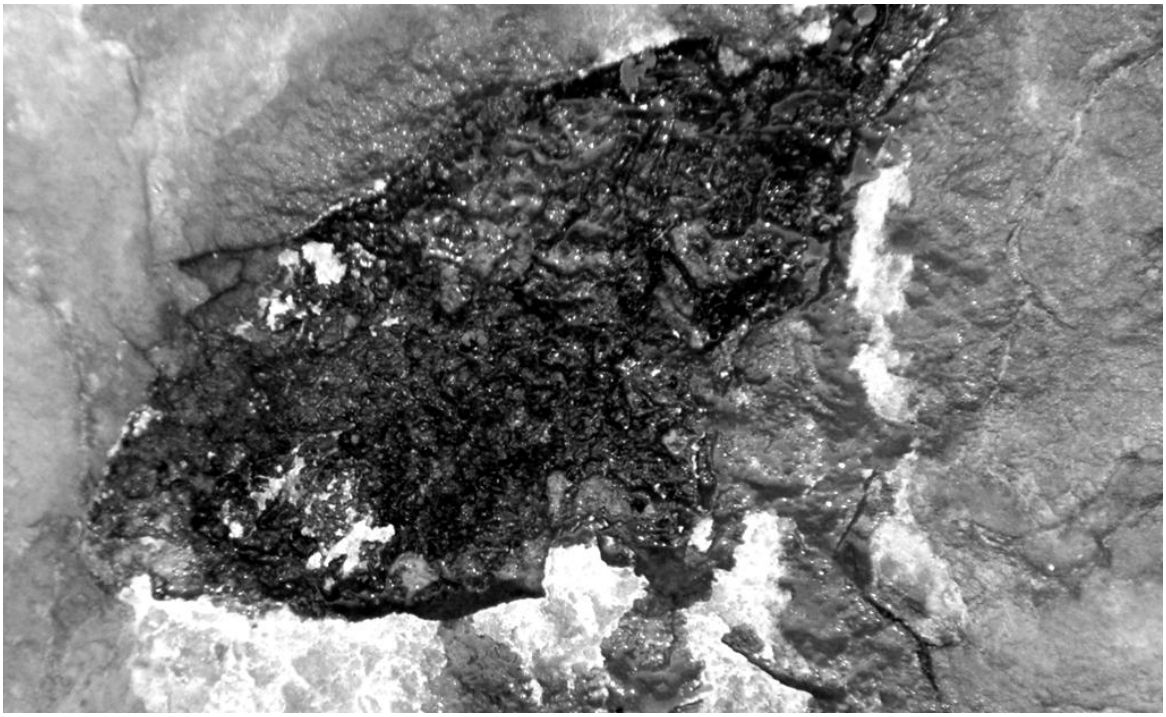


Figure 7.2: Algal colony exposed after removal of a flake as well as evidence of presence of soluble salt in the subsurface (white streaks), site 1.

The case hardening of the surface appears to play a significant role in the internal moisture regimes of the Clarens sandstone and its associated weathering. Mol and Viles (2010) found that there is a correlation between surface hardness, internal moisture and weathering. An absence of case hardening allows for increased moisture evaporation through the surface, leading to initially high moisture levels in the subsurface, followed by severe weakening of the surface and increased removal of material from the rock face. However, the presence of bacteria or soluble salts (Mellor *et al*; 1997) can aid cementation of the surface, thereby facilitating the development of protective case hardening. In addition, case hardening can influence internal moisture flow as flow paths of moisture migrating upward by for example capillarity will be deflected around areas underlying a coated surface (or any area of lesser permeability) (Conca and Astor, 1987)

7.2.2. Individual sites

A total of seven sites was assessed during a field visit in April 2009. These covered a range of shelter sizes, development, aspects and heights. We selected these sites to obtain an overview of the weathering processes found throughout the park and to test whether or not these processes were restricted to specific sites (see table 7.1).

Site	Photo	Size (m)	Aspect	Temp. °C	Notes
1		H: 4.5 W: 45 D: 1-8	WSW	Max: 35.5 Min: 13 Av: 19.1	Substantial overhang within larger scale of large-scale rock falls. Well-shielded from direct impacts of sun, precipitation and wind. Overhang approximately 4m thick, heavily calcified
2		H: 18 W: 32 D: 4.8	NNE	Max: 40 Min:13.5 Av:21.9	Very exposed site Relatively shallow overhang on top of convex hillside Multiple shelters within the same complex Clear evidence of moisture outlets Fragile surface
3		H: 4.1 W: 5.3 D: 0.75	NEN	Max: 42.5 Min:13.5 Av: 21.2	Small shelter, highly active weathering Very shallow overhang Crumbling of surface, removal of grains Site located at bottom of exposed rock face, near sediment cover
4		H: 4.2 W: 23 D: 4.2	WNW	Max: 31.5 Min:12.5 Av:18.3	Very crumbly and dusty surface No weathering crust visible on the rock face No direct evidence of moisture outlets visible on rock surface
5		H: 12 W: 18 D: 4.3	NE	Max: 43 Min: 12.5 Av:20.8	Significant discolouration of the surface; grey and red sandstone boundary ERT did not work on this site, for unknown reasons, only Equotip, infiltration and temperature data available for this site

6		H: 8 W:12 D: 13	W	Max: 25.5 Min: 10.5 Av: 15.6	Evidence of active weathering visible on all sites of cavern Moisture outlets visible on walls within the cavern Tafoni formation visible near entrance to the cavern but not further towards the back of the cavern
7		H: 12 W: 30 D: 11.34	S	N/A	Largest shelter of the sites investigated Significant calcification of overhang. Established shelter, clear evidence of weathering crust build-up

Table 7.1: Overview of sites

This site selection illustrates the diversity of sandstone shelters found within the GGHNP. To understand the weathering processes that are the drivers behind the formation of these shelters we use the development of the shelter as an indication of its relative age (i.e. young, developing, and established). We have identified shelters 3, 4 and 5 as 'young', shelter 2 as 'developing' and shelters 1 and 7 as 'established' (see table 7.2). As rock weathering rates are generally too low to yield significant results from observations at shelter scale within the span of a few years, we have substituted space for time assuming that the development of the surface, such as a transition from granular disintegration to larger scale flaking and case hardening, and depth of the overhang are indicators of the age of the shelter; the more established the case hardening and the deeper the overhang, the older the shelter.

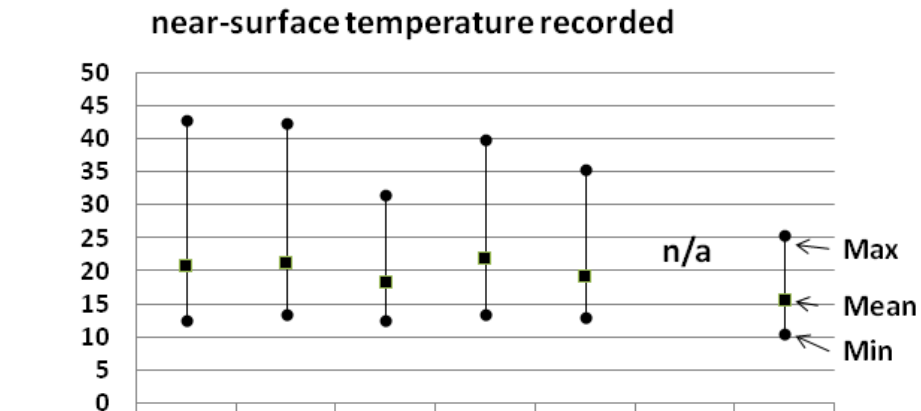
Development	Young → Established					
Site no	5	3	4	2	1	7	6

Table 7.2: Establishment of shelters as identified by overhang size and surface development

The overall size and shape of site 6 is very different from the other sites; the site appears to be a large hollow within the rock body with a relatively small entrance way rather than a shelter. We have classified it here as 'cave' due to its width to depth ratio, which differs substantially from the other shelters surveyed. However, weathering patterns at the back wall of this site are identical to weathering found in the more shallow shelters, indicating that the weathering processes operating on the cavern wall are the same.

7.2.3 Microclimatic conditions

Near-surface temperature was monitored at all sites surveyed using iButtons to record temperature every 10 mins. The duration of the temperature recording at sites varied from 18 days (sites 1, 2 and 3), to 10 days (sites 4, 5 and 6) and only temperature recordings of the 10 days when all iButtons were active were used to avoid bias in the data due to varying weather conditions. Site 7 was not monitored due to time and equipment constraints. The microclimatic conditions in the shelters varies to some extent; there is some fluctuation in near-surface temperatures recorded at the shelters varying between. Most noticeable there is a larger difference between mean-maximum than mean-minimum, indicating that these shelters receive intense sunlight during a limited part of the day, followed by lower temperatures during the early and late parts of the day, as well as the night (see figure 7.3). There is a significant difference in maximum temperatures recorded, but relatively little difference in the mean and minimum temperatures. Temperature data was not available for site 7.



	S5	S3	S4	S2	S1	S7	S6
Maximum	43	42.5	31.5	40	35.5		25.5
Minimum	12.5	13.5	12.5	13.5	13		10.5
Mean	20.8	21.2	18.3	21.9	19.1		15.6

Figure 7.3: Near-surface temperatures recorded at all sites

Unfortunately it was not possible to record internal temperature data as the metal sensors of the logging equipment would have interfered with the resistivity equipment. However, a number of studies have discussed internal temperature gradients. Smith (1977) emphasised the importance of internal temperature gradients especially when combined with moisture as a mechanism for insolation weathering. Smith and McGreevy (1988) found that there is a slight delay in temperature distribution through the subsurface of the stone blocks. More recent work has shown that that internal temperature gradient profiles are considerably more complex in space and time than the smooth exponential decrease in temperature that was previously assumed (Smith *et al*, 2011). In addition, due to the complex topology of the sites it is unwise to make any predictions on potential internal temperature gradients within the rock face without the availability of reliable data.

7.3 Methods and materials

A number of surveying techniques were used to investigate the dynamics of the shelters. We briefly describe each method used in this section.

7.3.1 Weathering surveys and petrology

A semi-quantitative survey was carried out during the site visits to establish which weathering features were most commonly found in the GGHNP. Weathering features were assessed on a scale of 1 (hardly present) to 5 (abundant and severe) at each 10th electrode at all transects, providing 5 datasets per transect. We adopted the decay mapping approach of Fitzner *et al* (2003) to suit the range of weathering processes in the GGHNP by restricting the categories to the features observed during the previous 2008 study (Mol and Viles, 2010).

In addition, thin sections were prepared using two samples from site 1; one with a developing weathering crust (which, based on field observations, is likely to evolve into case hardening) and one sample with a fresh surface, presumably recently exposed due to flaking of the top surface as no weathering rind was visible at the time of sampling.

7.3.2 Karsten tube –measurements of infiltration rates

A Karsten tube is a small open-ended glass vial which can be attached to the rock face to measure water absorption capacity and infiltration rates (Galán *et al*, 1999). By measuring the decrease in water content over a set period of time within the tube the water absorption per square centimetre can be calculated. The tube was attached to the horizontal rock face, usually on the floor of the shelter, with Blue-tack to seal any openings and then left for 90 minutes to ensure full absorption was reached (Nwaubani *et al*, 2000). Measurements were taken every 10 mins for the duration of the 90 min infiltration time. The measurements were calculated to ml/3cm^{2}min (infiltration surface

of the Karsten tube, manufacturer's specifications) which were then transferred into w-values, as specified by Snethlage (2005), to aid comparison with infiltration tests conducted on different types of stone (see section 7.4.1.2).

7.3.2. Electrical Resistivity Tomography (ERT)

Electrical Resistivity Tomography (ERT) uses low voltage (12V) electric currents to measure resistivity of a porous body between pairs of points. In this case, GeoTom equipment (Geolog2000) was used to obtain the ERT readings. By sending voltages through different combinations of electrodes attached in a profile along the rock face, a 2D pseudo-transect is built up. This method was first used in the medical sciences to monitor for example bone fatigue (Leng *et al*, 2008), but has been adapted to suit geological and more recently geomorphological needs (Abu-Zeid *et al*, 2006; Sass and Viles, 2006 and 2010; Mol and Preston, 2010).

The GeoTom was used to obtain three ERT transects at each site. The electrodes were attached to the rock surface with ECG electrode pads, at a spacing of 5 centimetres, producing a 2.45 meter long transect. Using the Wenner configuration, the set of 50 electrodes produced a 16 row 2D pseudo-section. An inversion programme (RES2Dinv) was used to produce the pseudo-sections, based on most likely distribution using an adapted version of Loke and Barker's (1996) algorithm, and incorporated into a smoothness-constrained least-squares method (see Mol and Preston (2010) for more details). This method assumes that high resistivity is indicative of low moisture content and vice versa. We also used this programme to evaluate the estimated errors, which are similar to errors reported in the previous studies (Mol and Viles, 2010; *under review*) ranging between 0.33 and 22.1%. These errors are an indication of the quality of the measurements as the errors are based on variability within the transect and geological probability. Because of the way the 2D ERT survey

technique works, the outer 2.5 cm of the rock is not measured, but instead the Wenner configuration measured from 2.5 to 40 cm depth.

It was not possible to obtain valid ERT readings at site 5, because technical difficulties meant unacceptably high errors.

7.3.3 Equotip

We used a rock surface hardness rebound device (Equotip) in this field study to assess the variability in rock surface hardness and its relation to surface weathering. This device is based on the same principles as the Schmidt Hammer (Aoki and Matsukura, 2004; 2007a). It can be used to trace fractures and irregularities in rock masses (Hack *et al,* 1993), giving the research a method for quantifying rock hardness and by implication the degree and spatial variability of weathering. It is suitable for application across a wider range of hardness than the Schmidt Hammer, and is especially useful for relatively soft rock surfaces. This makes this method extremely suitable for working on fragile sites such as historic buildings and Rock Art areas as the low and small impact causes no damage (Hack et al, 1993; Verwaal and Mulder, 1993; Van de Wall and Ajake, 1997). A 3 mm dia. spherical shaped tungsten carbide test tip is mounted in an impact body and impacts under spring force against the test surface from which it rebounds (Verwaal and Mulder, 1993). The velocity before impact (V,) and after impact (V2) are measured automatically and displayed as a ratio *(V2/V,* x 1000) which is denoted by the unit "L" (Hack *et al*, 1993). Measurements were taken (without any surface pre-treatment) along each ERT transect at every tenth electrode, with ten measurements on each measuring area. The average of these ten measurements was then taken as an indicative measurement of the hardness of the surface area and thus, by implication, the degree of weathering.

7.3.4 Conductivity measurements – field and laboratory based

Salt contents are known to influence ERT readings, where high salinity leads to lower ERT readings and vice versa (Abu-Zeid *et al*, 2006). Beauvais *et al* (2004) suggest that to accurately interpret ERT readings, all data should be compared against borehole data, which would record the salinity of the pore waters. This is not an option when investigating rock surfaces as drilling and retrieving a core is not as easy with a solid rock mass as it is in soil, in addition limitations set by to the restrictions on sampling in national parks. However, to address this problem a water conductivity kit was used to test pore water running out from the rock face as compared to the water from the stream running through part of the GGHNP, which is used here as a background data to gauge salinity levels in the wider hydrological system of the GGHNP. Calibration immediately before measurements showed a margin of error of ±0.5%. At site 1, 12 different pools at the floor of the shelter were tested all of which showed evidence of flow paths that led straight from the rock face to the collection pools. The stream running through the GGHNP was tested near the Gladstone Environmental Centre, where the stream has increased in size to a width of 3.5 m and up to 50cm depth, using a Hanna Instruments HI 9034 TDS meter. In addition, we also carried out a simple laboratory analysis of conductivity of rock samples from each site, using TDS as an indicator of soluble salts. At each site 9 samples were collected, from the top, middle and bottom of each transect. The sample was taken from the surface, either from a section where a flake was detaching or disintegration of the surface made sample possible. We used 2 grams of pulverized sample, which was then diluted in 5 ml of deionized water, placed in a Decon FS200b Ultrasonic bath for 10 mins and left to settle for 15 mins. The solution was then analysed using an Orion 150 conductivity meter.

7.4 Results

7.4.1 Weathering survey, petrology and infiltration characteristics

We first assessed the overall weathering features of all the transects analysed in this study to identify which features are most prevalent throughout. Using the semi-quantitative approach suggested by Fitzner *et al* (2003) we found that discolouration and flaking are most commonly found in the GGHNP, both showing average values of 2.4 out of 5 overall, followed by crust formation and detachment of crusts, both of which measured 1.9 out of 5 on average. Fissures and honeycombing, on the contrary, are much less commonly found (respectively 0.3 and 0.2 out of 5 overall). Significant granular disintegration was only found on sites 3 and 4 where average values were 3.1 and 2.9 respectively, against an average assessment of 1.4 out of 5 for all sites.

Our observations showed that smaller shelters such as Site 3 and Site 4 show considerably more active weathering of the surface, mostly consisting of crumbling and small flake removal, whereas larger and more established (here interpreted as older) shelters such as Site 1 and Site 7 show an established weathering crust which detaches only sporadically and exhibits a far greater coherence and strength of surface than sites 3 and 4. Figure 7.4A and B show the difference in surface structure and weathering between a young, active site (site 3) and a more established shelter (site 1).

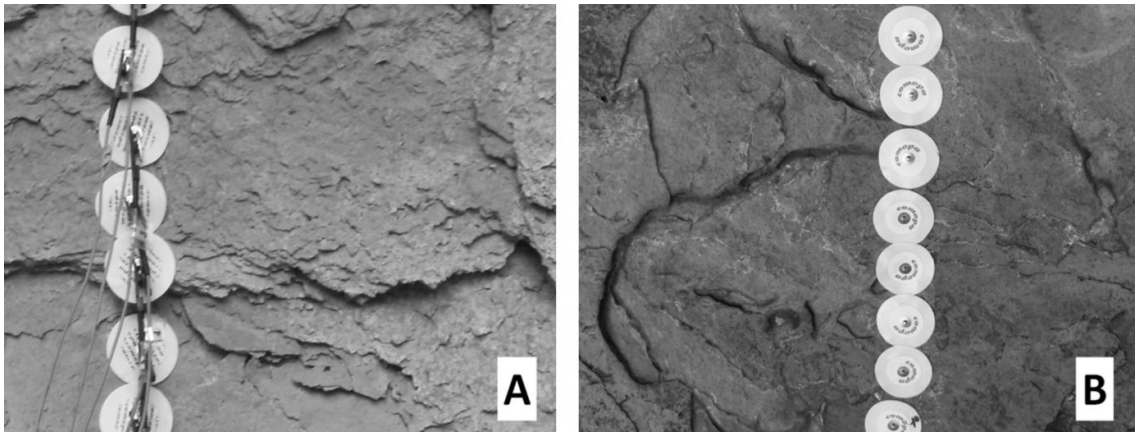


Figure 7.4: showing a close up of the crumbling surface of site 3 (A) and the more established weathering crust of site 1 (B) Both sites show flaking but the style of removal of material is entirely different

Moropoulou *et al* (1995) stated that crust formation appears wherever favourable micro-climatic conditions prevail, like low temperature and humidity fluctuations. This does hold up to a certain degree at the GGHNP, as the larger and more established shelters show smaller temperature fluctuations than the smaller and more active sites. However, site 6 (cave), used here as a control site, has significantly smaller temperature fluctuations over 10 days in April 2009 (see figure 9.3) but does not show a great increase in rock hardness compared to for example site 1. In fact, the rock surface at site 6 seems to show an interesting mixture of weathering behaviour, where the floor of the cave and the lower part of the wall are covered by a well-established weathering crust (figure 7.5A) but large areas are also crumbling (figure 7.5B)

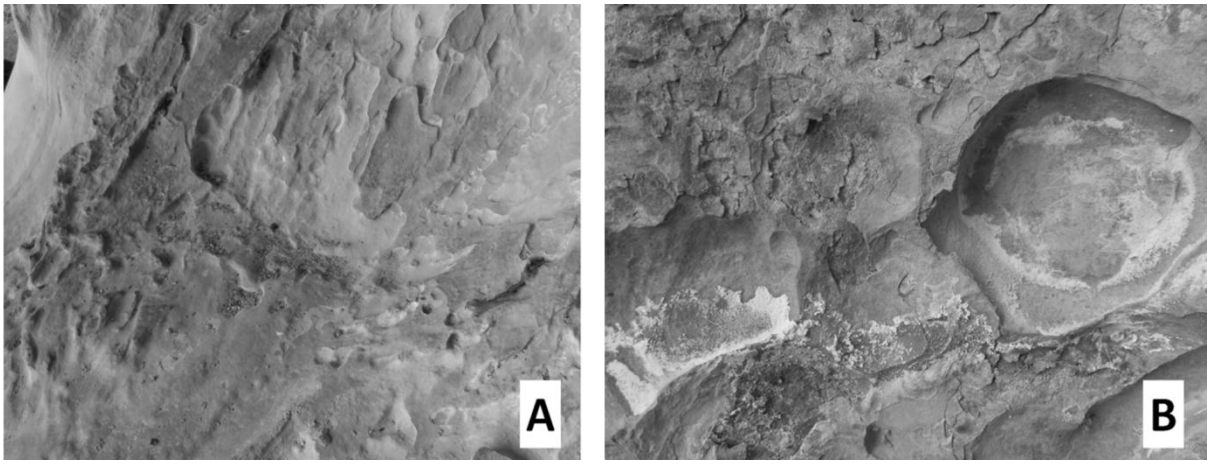


Figure 7.5: Showing the contrasting weathering behaviour found at site 6 where both surface hardening and flaking (A) as well as crumbling and cavernous weathering (B) are visible.

7.4.1.1 Thin sections

To further our understanding of Clarens sandstone, its properties and the weathering rinds found on large areas of the exposed surface we examined petrological thin sections of two contrasting samples from site 1. The first shows the typical weathering crust found on many surfaces of the shelters surveyed, the second is taken from a sample of an area with a non-weathered surface due to recent removal of the surface crust (presumably through flaking). Figure 7.6A, shows a thin weathering crust, whereas in figure 7.6B no such crust is visible. These two photos show that when the crust is present, the grains towards the surface still appear to be very coherent and show little sign of crumbling. When the weathering crust is removed the grains at the surface lose their coherence and start to crumble (see figure 7.6B). This function of weathering crusts has been discussed by McAlister *et* al (2003), who show that cementation of the surface of porous stone such as sandstone aids the stability of the subsurface. Field observations showed that in the GGHNP thin weathering crusts as shown in figure 7.6A function as stabilizing layers which enable further case hardening.

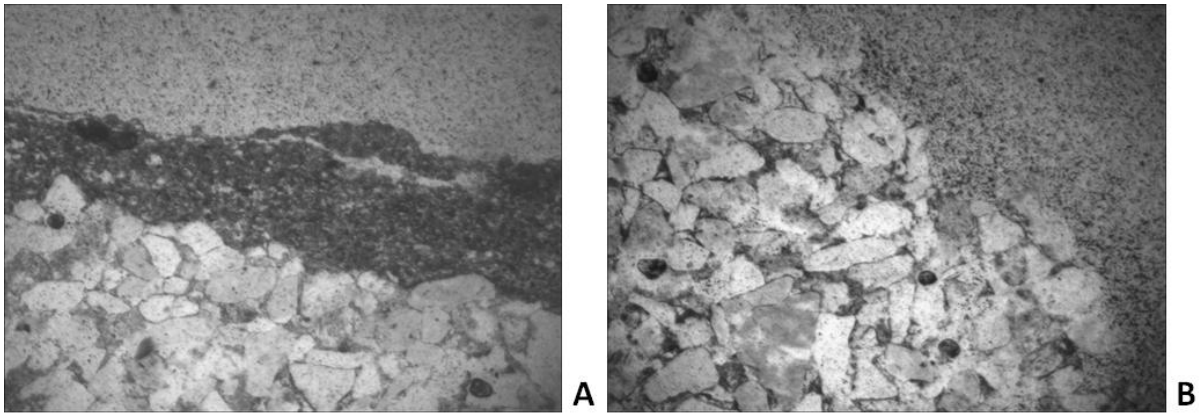


Figure 7.6: Showing thin sections of Clarens sandstone in the GGHNP. A and B show the surface of a sample which was partially covered by a weathering crust (10x magnification)

However, field observations also showed that these weathering crusts are connected to flaking of the surface as they allow accumulation of moisture and associated bacterial and fungal activity at subsurface level, leading to increasing pressure beneath the flake until it reaches critical point and is removed from the surface (also recorded by Büdel *et al*, 2004), thereby acting as a negative feedback process in addition to positive feedback in the form of surface stabilization.

7.4.1.2. Infiltration and permeability

Karsten tube tests in the GGHNP showed that the Clarens sandstone found locally is somewhat permeable, more so in areas where a weathering crust was recently present but was removed to measure permeability. We successfully measured three sites which represent different environmental circumstances. At Site 1 we used an area which has recently flaked off in the shadow of the shelter. This site yielded infiltration rates of 0.013 ml/3cm^{2}min (or w = 2.6kg/m^{2}h when using the w-values as set by Snethlage (2005), classifying Clarens sandstone as 'medium absorbing'). Site 5 is a fully exposed rock surface which is covered by a thin weathering crust which yielded infiltration

rates of 0.011 ml/3cm^{2}min (w = 2.2kg/m^{2}h). We then took a measurement at site 6, which is within a cave, at a comparable rock surface (thin weathering crust) to compare to the site 5 measurements to measure the effect of evaporation from the tube. The infiltration rates recorded at this site were 0.007 ml/3cm^{2}min (w = 1.4kg/m^{2}h). All other measurements which did not reach at least 90 minutes due to leaks were discarded. Site 1 showed the highest infiltration rates but tapered off as soon as the immediate surface was saturated. Site 5 showed consistent infiltration rates, but as these measurements were taken in full sunshine there could be a significant influence of evaporation of the water in the tube rather than infiltration. Site 6 gives the most representative measurement of infiltration, as it was affected by neither sunshine nor thick weathering crusts. All these measurements show that Clarens sandstone has a low permeability, when compared to other sedimentary rocks such as limestone w-values reported in the literature (7.78-14.96 kg/m^{2}h on Globigerina limestone, Siegesmund and Dürrast (2011, p. 125); 1 kg/m^2 'in seconds' Tinnye limestone, Török (2003; 2006); and 1.2 – 51.2 kg/m^{2}h Almayate limestone, Galán *et al* (1999)). It is however, comparable to the w-value of Cerro Coronado sandstone, Spain (0.6 – 1 kg/m^{2}h, Galán *et al*, 1999). Despite the relatively low permeability of Clarens sandstone recorded here, previous work by Mol and Viles (2010) indicates that internal moisture can plan an important role in weathering in GGHNP.

7.4.2 Field data

We have summarized the most important data in table 7.3 in an attempt to establish critical factors for sandstone surface weathering and subsequent shelter formation. This table shows that there is no clear correlation between exposure, temperature or aspect and rock surface hardness. What it does show, however, is that there is a correlation between shelter size and rock surface hardness. It also shows a relationship between level of exposure and ERT measurements, where the higher the exposure of the site the lower the resistivity values. This brings to light two very interesting

hypotheses; firstly, that rock surface hardness is directly related to the development of the shelter, the larger and more established the shelter the more resilient the rock surface becomes as surface crusts develop (see figure 7.7A). Secondly, high exposure to sunshine, wind and precipitation leads to an increase in moisture within the rock surface (see figure 7.7B). The question therefore is; how do these two factors relate and interact to determine shelter development?

Site	**Equo Max**	**Equo Min**	**Equo. Mean**	**Temp Max**	**Temp Min**	**Temp Mean**	**Exp.**	**Shelter aspect**	**Shelter size**	**ERT Res.**
1	757	28	390	35.5°C	13°C	19.1°C	Low	WSW	large	high
2	759	28	392	40°C	13.5°C	21.9°C	High	NNE	large	var.
3	568	144	365	42.5°C	13.5°C	21.2°C	High	NEN	small	var.
4	571	137	367	31.5°C	12.5°C	18.3°C	Low	WNW	small	var.
5	559	136	353	43°C	12.5°C	20.8°C	High	NE	small	n/a
6	608	107	451	25.5°C	10.5°C	15.6°C	Cave	W	Cave	low
7	762	117	518	n/a	n/a	n/a	Low	S	large	high

Table 7.3: Showing an overview of all results namely Equotip (Equo), temperature (Temp.), exposure (Exp.), shelter aspect, shelter size and resistivity as measured through ERT (ERT Res.). For Equotip n=150, temperature n=1964

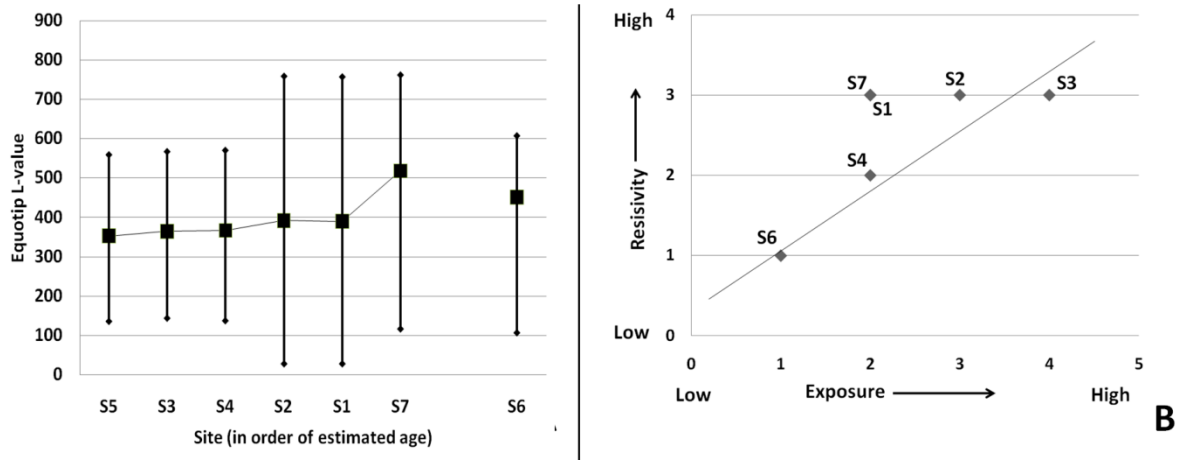


Figure 7.7A and B: (A) shows the relationship between the estimated relative age of the site (starting with S7 as the 'oldest' site and S5 as the 'youngest' site, whereas (B) shows the correlation between exposure and resistivity (here interpreted as internal moisture). Exposure is defined by the amount of direct sunlight and precipitation a site receives, whereas resistivity was ranked on a scale of 1 (almost exclusively values near 0 ohm. m) to 3 (almost exclusively values over 1000 ohm. m). A value of 2 should be interpreted as 'variable', showing pockets of low and high resistivity.

It is likely that exposure is heavily dependent on shelter development; as the size of the overhang determines to a large extend the amount of sunlight and precipitation a site receives. To simplify the complexities of cavernous weathering we interpret exposure as a direct consequence of development and therefore conclude from figure 7.7B that there is a relationship between development of the shelter and internal moisture. To test this problem statement, we will examine the internal moisture (ERT) rock surface hardness (Equotip) data sets in more detail to establish what role internal moisture plays in rock surface hardness and weathering within these shelters.

7.4.2.1. ERT measurements

Mol and Viles (2010; *under review*) concluded in previous studies on weathering of Clarens sandstone in the GGHNP that spatial variations within transects can be used to further our understanding of the relationship between rock surface hardness and internal moisture. However, this study shows that there appears to be a relationship between the stage of development of a shelter and the rock surface hardness. We therefore use the ERT data collected in April 2009 to investigate if internal moisture regimes are an important factor in cavern surface development and behaviour. We have selected one transect from each site which is representative of all the transects measured per site, to compare the general trends in moisture regimes. Figure 7.8 shows this overview of sites in the same order as set in table 7.2.

The selection of ERT transects show that there are substantial differences in internal moisture regimes between the sites. There appears to be a progression from very variable moisture content with very high resistivity areas located next to very low resistivity areas with no apparent transition zone (site 3), followed by a lowering of resistivity (site 4) and a gradual increase of resistivity in the subsurface but a layer of very low resistivity in the near-surface (site 2). Sites 1 and 7 appear to have similar internal moisture patterns, where the resistivity is generally quite high with the exception of what appear to be internal 'flow paths' where resistivity is lower.

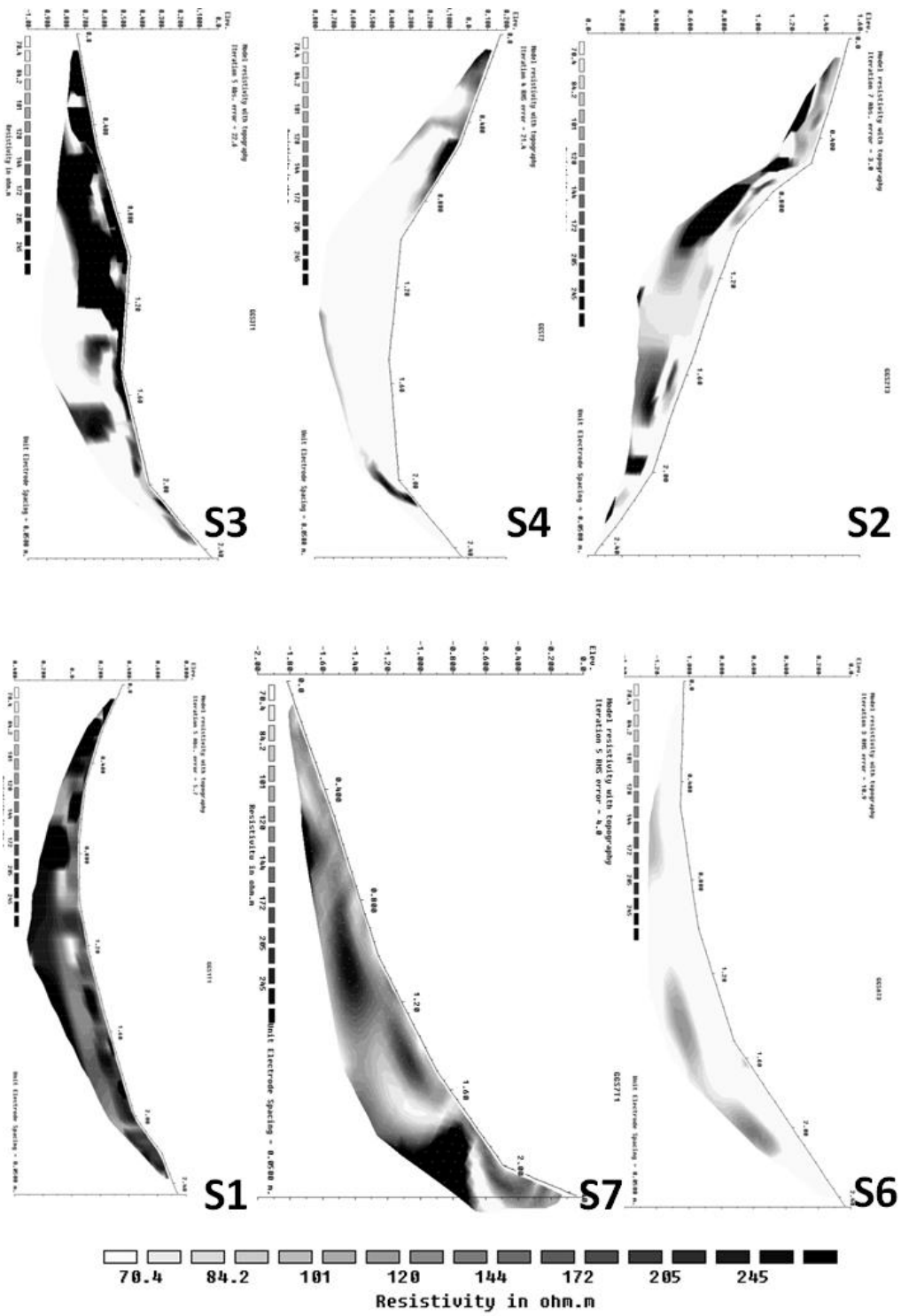


Figure 7.8: Overview of representative transects of all sites measured by ERT

7.4.2.2 Equotip measurements

To further our understanding of rock surface hardness within the GGHNP shelters we collected Equotip data at each transect. The results of the individual transect measurements can be seen in figure 9.9, where the mean, maximum and minimum values are shown. In addition, the average values for each site are plotted in grey.

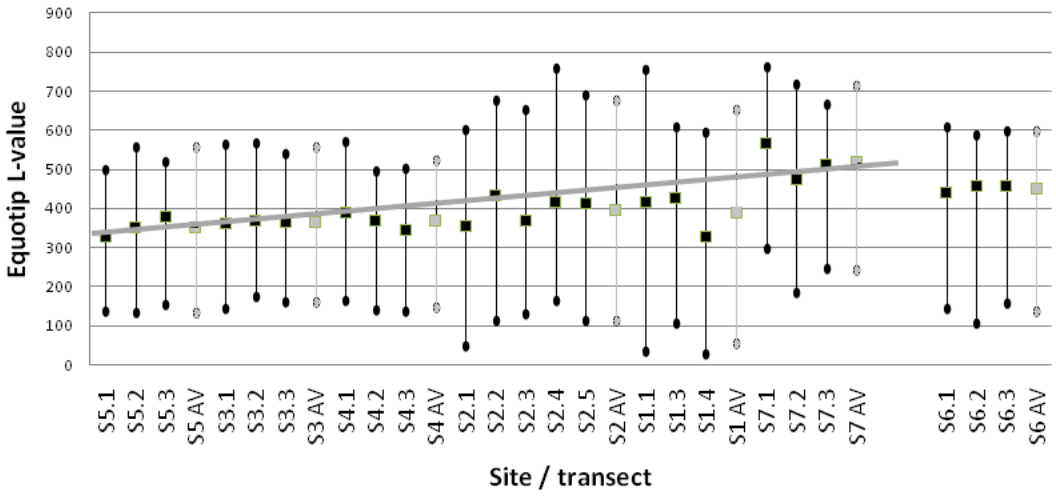


Figure 7.9: Equotip minimum, maximum and mean values as plotted per transect and mean per site

There are two trends visible in this data set. The first shows that there is a broad increase in rock surface hardness with the development of the site, supporting the observation that case hardening develops as shelters develop. Site 3, 4 and 5 show on average lower values than sites 1, 2 and 7 as the trend line indicates. The second trends shows that the younger sites (sites 3, 4 and 5) show a smaller degree of variation within the measurements than the more established sites, where variability of rock surface hardness increases (sites 1, 2 and 7).

7.4.2.3 Case studies

Both the ERT and the Equotip data set show a gradual change in internal moisture regime and rock surface hardness between the young sites and the established sites. To determine to which extent these two factors are related we will examine a number of case studies in more detail. In addition, as Mellor *et al* (1997) concluded, there is evidence that different processes are operating on different parts of the cavernous feature. In particular, Mellor et al (1997) show that case hardening is restricted to the outer roof surfaces whereas core-softening is thought to be dominant on the inner cavern surfaces. Core softening is the process of weakening of the surface and underlying subsurface, leading to cavern enlargement (Mellor *et al*, 1997). During core softening the absolute hardness of the exterior actually decreases with time but to a lesser degree than the interior, resulting in a differential hardness similar to that developed during case hardening (Comca and Astor, 1987). Therefore, we will investigate if there are variations in rock surface hardness within the transects and if these are related to internal moisture processes. To this end, we have selected three case studies which represent the different stages of shelter development. Case study 1 is site 3, a very young shelter, showing very active surface weathering, erratic moisture patterns and only marginally sheltered by a shallow overhang. Case study 2 is site 2, a moderately well established shelter which stills shows signs of active surface weathering but appears to be in a transient stage from developing to established shelter. The final case study is site 7, which is an established shelter.

7.4.2.3.1 Case study 1: Site 3

As mentioned previously, this is a relatively small site which is in the first stages of development. The shallow depth indicates its relatively short development period, while the crumbling and small-scale flaking surface shows the high weathering rates of this shelter (see figure 7.4A). The surface is crumbling as well as flaking and was relatively difficult to measure because of this fragility. We

therefore need to examine the condition of the surface of the shelter when assessing the ERT values. To highlight the resistivity variability within the transects we have changed the colour scale used in figure 9.9 to suit the range of resistivity measured within this site. We have highlighted a number of areas within each transect (see circled areas in figure 7.10) which have interesting correlations between the ERT and Equotip values. At transect 1 the top, middle and bottom of the transect show good similarities; the top shows relatively high Equotip values, which are connected to the high resistivity values in the ERT transect. There is also relatively little variation in the values here, with the exception of the pockets of high resistivity towards the surface. Field observations have shown that the surface is extremely loose with a very weak cohesion with the subsurface. The surface, where the weathering is most active, shows higher resistivity measurements. The lower surface shows much lower resistivity values, indicating higher moisture content.

Based on the ERT data and field observations it is probable that the surface, unprotected by a weathering crust or case hardening, allows for rapid evaporation of moisture, a process which was also noted by Rodriguez-Navarro *et al* (1999). The relatively large proportion of air, due to space available underneath and between the flakes in the near-surface, allows for rapid evaporation resulting in low resistivity values further into the rock but high resistivity values at the surface (see figure 7.10). The Equotip values are low compared to the more established sites (see figure 7.9), once again reflecting the highly weathered and fractured nature of the rock surface. This is reflected well in transect 2, where the high resistivity pockets near the surface also influence rock hardness measurements between 1.2 and 1.6 meters, while at 2 meters the absence of such pockets is reflected in higher Equotip values. Transect 3 shows similar patterns, with the exception of the bottom of the transect (2.4 meters) where high resistivity values together with high and consistent Equotip values appear to indicate a less weathered surface, possibly reflecting solid rock mass with low moisture content.

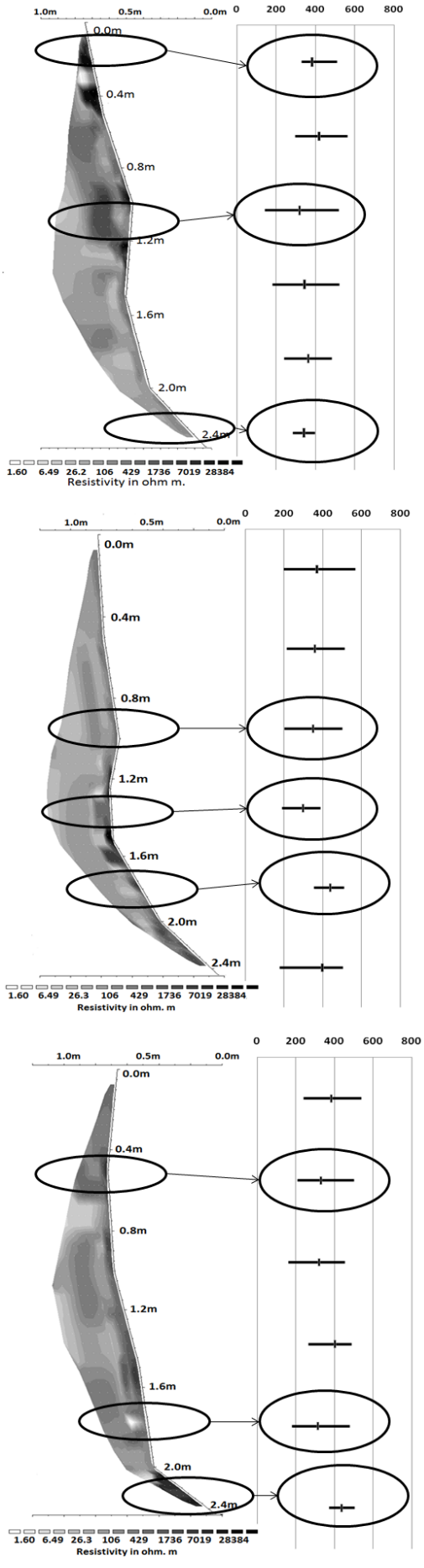


Figure 7.10: Overview of Site 3 ERT and Equotip measurements. The scale of resistivity values has been extended to 28384 ohm. m to reflect the high resistivity values near the surface. Equotip values are very low compared to sites 2 and 7.

7.4.2.3.2. Case study 2: Site 2

Site 2 is a larger and more established site which still shows signs of active weathering. We have therefore selected it as a case study for an 'intermediate' site, a site which is still in the process of development but has weathered substantially and shows signs of moving into a more established stage. Figure 7.11 shows the transects of the main shelter at site 1. The resistivity scale has been lowered to a maximum of 611 ohm. m to reflect the overall low resistivity values of this site. One of the most noticeable ways in which the internal moisture behaviour differs from the behaviour observed at site 3 is the absence of high resistivity pockets which were visible in the near-surface of site 3. Instead the surface of site 2 appears to have higher moisture content than site 3 (note the different scale used). In addition, Equotip values are higher than those recorded at site 3 (see figures 7.9 and 7.11). This could be an indication of developing case hardening of the surface. This allows for moisture build-up at near-surface level, as the moisture does not evaporate as easily as it does at site 3 where no such case hardening was visible. Transect 2, for example, shows this correlation at 2.0 and 2.4 meters where the near-surface shows lower resistivity levels and the Equotip measurements indicate higher rock surface hardness. The top of transect 2 does appear to still weather actively, as the high resistivity values show similarities to those found at site 3, while the low Equotip values show that this area is relatively friable. Transect 3 shows a very interesting case study at 0.8 meters of an area of significant near-surface moisture built up which is retained by case hardening of the surface, as indicated by the higher Equotip measurements. This site is still weathering actively but the rate of weathering is altered by the development of case hardening which is changing the internal moisture regime from a relatively high moisture content within the rock mass and rapid surface evaporation, to near-surface pocket formation and direction of moisture flows underneath the case hardening towards weaker areas in the rock surface, as can be seen at transect 1 (2.0 meters). The most noticeable way in which this manifests itself on the surface is the

shift from a crumbling surface (site 3) to flake formation resulting in a very different type of material removal from the surface.

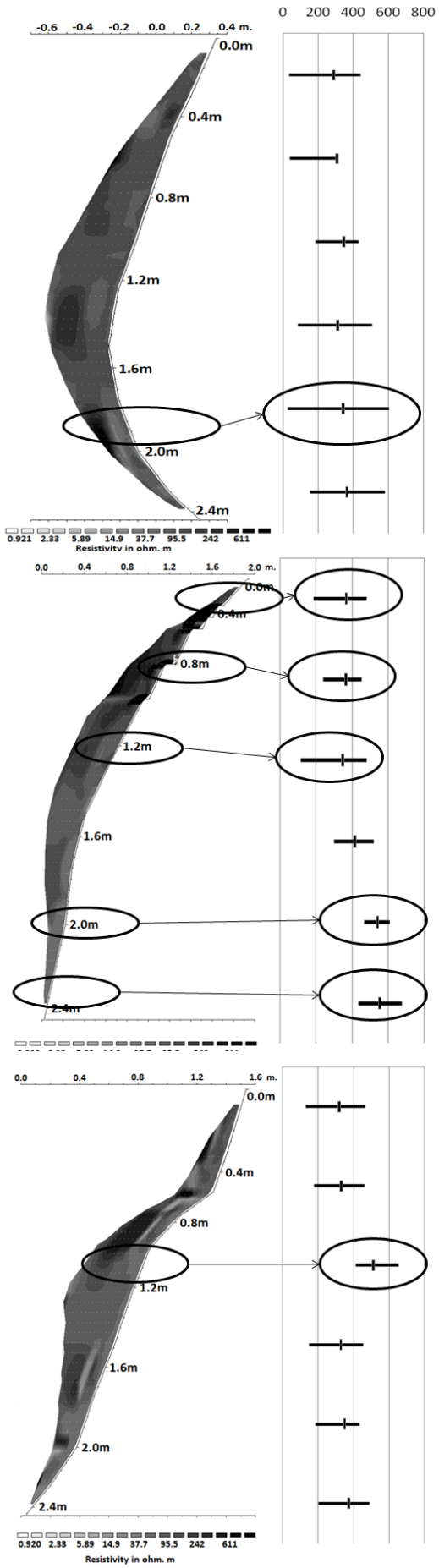


Figure 7.11: ERT and Equotip values of site 2, showing the correlation between subsurface moisture pockets and rock surface hardness variability

7.4.2.3.3. Case study 3: Site 7

Site 7 is an example of an established site; it is a very large shelter with a relatively deep overhang. The rock surface of this site is still weathering but this appears to be mostly through large flake formation. Field observations show that exfoliation of these flakes takes place when moisture builds up underneath the flake, increasing the pressure until the flake breaks away and the moisture can evaporate freely. The evaporation rate here is possibly less rapid than that found at site 3 due to the lower exposure of site 7 to wind and sunlight. ERT measurements indicate that internal moisture behaves differently at this established site, as clear moisture flows are visible and there seem to be directed flows through weaker areas of the rock (see figure 7.12). This is especially visible at transects 1 (1.4 and 2.0 meters) and 2 (1.2 meters) where moisture appears to flow from deeper within the rock mass towards the surface through set pathways. The outlets of these pathways are directly coupled with lower rock surface hardness values.

The Equotip measurements are also remarkably variable; each set of measurements spans a wider range of values than found at for example site 2. However, increased variability in Equotip values correlated to the degree of weathering and flake formation (Aoki and Matsukura, 2007b), as case hardening can decrease the rebound value (Viles *et al*, 2011) through the cushioning effect of air in a cavity underneath the hard surface layer.

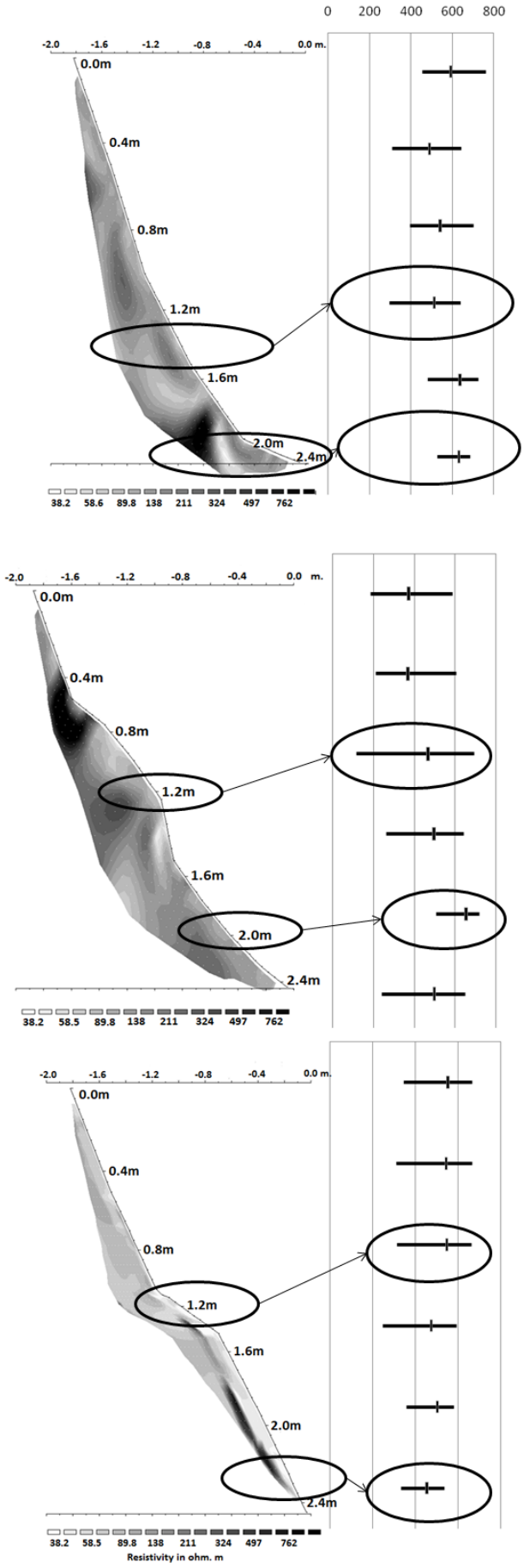
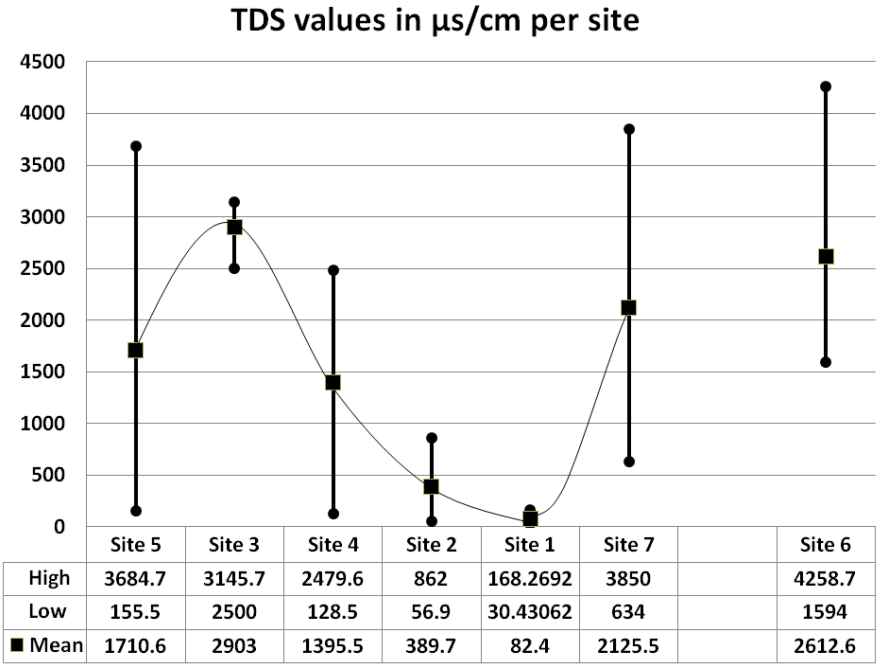


Figure 7.12: Showing ERT and Equotip values at site 7. The resistivity scale has been marginally increased compared to site 2 to 762 ohm. m.

7.4.2.4. Salinity and conductivity

As salt weathering is widely regarded to be an important process in cavern formation, we performed a simple conductivity test to compare fluctuating levels of salinity within and between sites. Firstly, we conducted water conductivity tests at both the run-off water at the rock face and the stream which runs through the park, using Total Dissolved Solids (TDS) as an indication of soluble salt content. The stream yielded conductivities of 223, 223 and 227 µs/cm, whereas 11 water samples found in puddles at site 1 yielded a large range of conductivities from 57.4 µs/cm in the main channel on the floor of the shelter where sediment accumulated, to 652 µs/cm near the back of the shelter at the rock wall surface, averaging to 177.6 µs/cm. These values are relatively low, especially when compared to for instance sea water (Gros *et al*, 2008), indicating that within the moisture that leaves the rock face there is little soluble salt. This could instead have accumulated at the rock surface and subsurface, lowering ERT and Protimeter values. We therefore compare these with the conductivity values of the rock samples obtained in the laboratory. The results are summarized in figure 7.13.



	Site 5	Site 3	Site 4	Site 2	Site 1	Site 7		Site 6
High	3684.7	3145.7	2479.6	862	168.2692	3850		4258.7
Low	155.5	2500	128.5	56.9	30.43062	634		1594
Mean	1710.6	2903	1395.5	389.7	82.4	2125.5		2612.6

Figure 7.13: TDS values of samples from all sites

These results show that there is a very high variability within the conductivity of the rock surface. In addition, when plotting the TDS values in the same order as shelter development (see table 2), there appears to be a trend of rising salinity levels at the very young sites (sites 3 and 5), followed by a decrease in salinity at the developing sites (sites 1, 2 and 4) after which the salinity in the surface rapidly increases. Even though these measurements show TDS rather than specific soluble salts and measurements were taken using solutions derived from crushed rock rather than directly from pore waters, the trends observed give an indication of potential transports of salts to the surface through capillary moisture movement and surface evaporation. Although soluble salts have been shown to produce rapid salt weathering under some circumstances, Mellor *et al* (1997) show that high evaporation rates can also draw soluble salts to the surface where they can aid surface cementation and hardening. We established earlier that due to the friable surface and high exposure of site 3 evaporation rates are likely to be high. In contrast, sites 1 and 2 show very low TDS values indicating that any soluble salts present in the surface, through previous capillary moisture flow, may have reacted with the surface to form the case hardening observed there. At site 7 an influx of soluble salts from within the rock face may have accumulated behind the case hardened surface through the directed flow paths as observed in the ERT measurements.

However, this data set is very limited and is used here to illustrate the changing nature of internal moisture rather than providing a conclusive answer on the role and behaviour of soluble salts within cavernous weathering.

7.5 Discussion

7.5.1 The relationship between internal moisture and case hardening

Based on the Equotip and ERT results, we have found that in the GGNHP, rock surface hardness and internal moisture are highly interrelated. According to our findings, there is a shift from core

softening behaviour (as reported by Conca and Rossman (1985) and modelled by Huinink *et al* (2004) and seen at for example site 3) to case hardening (as reported by Mottershead and Pyes (1994) and seen at sites 1 and 7).

Moisture passing through the surface of the rock is instrumental in the development of case hardening, as the cementation of silicate minerals and quartz minerals which is evident within the case hardened crust of the Clarens sandstone is facilitated by the presence of moisture (Büdel *et al*, 2004), creating a situation where at first case hardening is dependent on internal moisture. We hypothesise that once case hardening is established internal moisture regimes are dependent on the degree of case hardening but also vulnerable due to near-surface moisture build-up. This is followed by a phase where internal moisture finds alternative pathways, alleviating the pressure from the near-surface and progressing into a steady state where case hardening and internal moisture operate alongside each other.

7.5.2 Cavernous weathering development – the role of internal moisture

We have assessed the development of cavernous weathering at the GGHNP using a space for time substitution method. By combining data on rock surface hardness and internal moisture regimes we have found that there is a non-linear dynamic between these two data sets. This was previously suggested (Mol and Viles, *under review*) and incorporated into a small-scale model of surface strength and moisture fluctuations, but we now look at it on a shelter-scale. To reflect the changing nature of sandstone weathering over time, and its relation to rock surface hardness and internal moisture, we propose that to understand shelter development and its associated rock surface weathering it is necessary to look at the long-term interaction between these two factors. We have summarized the interaction in figure 7.14 with examples of sites in the GGHNP which illustrate the particular stage of shelter development.

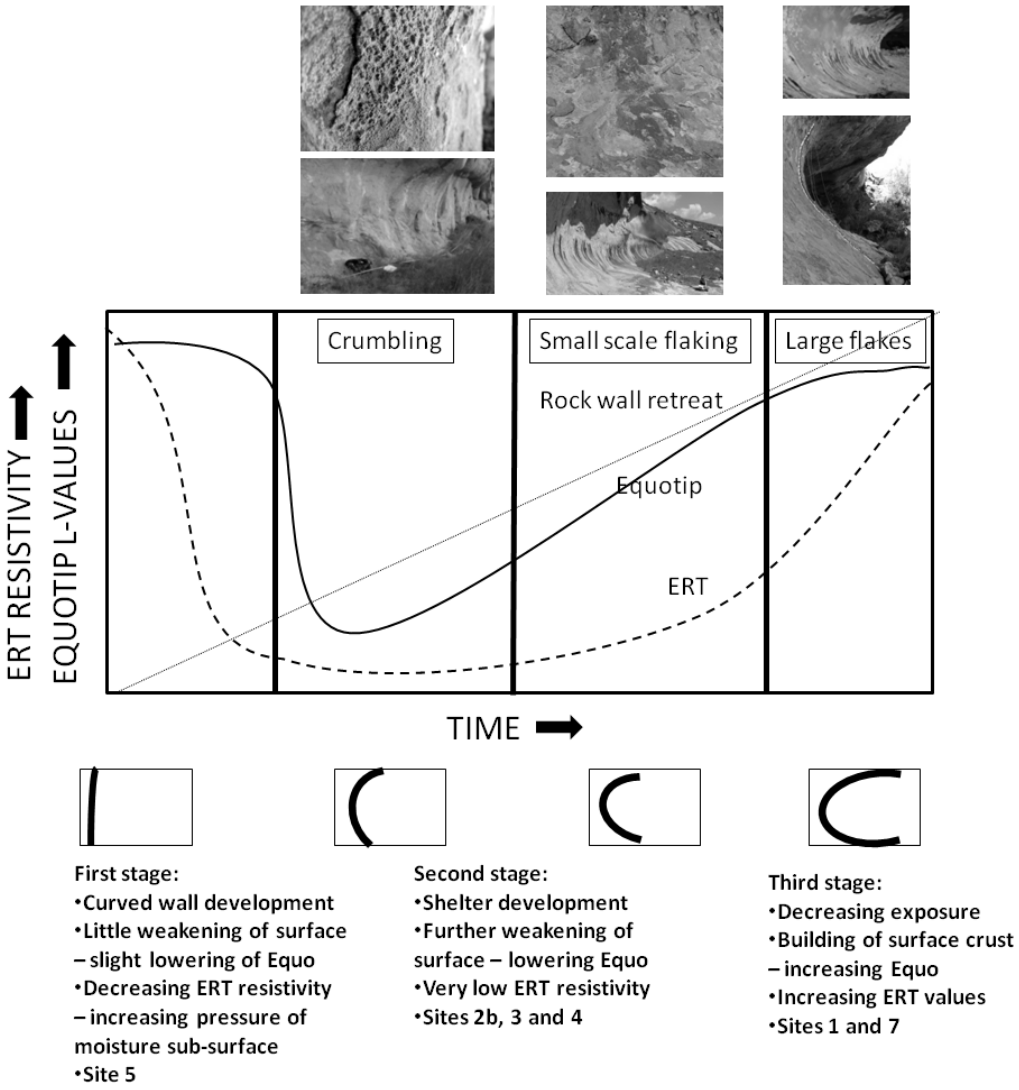


Figure 7.14: Interaction between rock surface hardness, ERT values, weathering type and shelter development over time.

Stage 1 is the starting phase where an exposed rock face starts experience differential weathering, such as found often along bedding planes. This is reflected in the weakening of the surface and the first indications of cavernous weathering feature development such as the appearance of shallow hollows in the rock face. The second stage is the development of the larger cavernous weathering feature where the shelter grows relatively rapidly through surface weakening and material removal.

The third stage is the developed stage of the shelter where case hardening has taken place and the growth of the shelter has slowed down.

This model covers one cycle of shelter development. However, this process is ongoing, as established sites can suffer from catastrophic collapse of the overhang. There is evidence that this happens with regular occurrence in the GGHNP due to the high number of large boulders strewn on the slopes beneath areas of active and ancient rock wall retreat. We therefore propose that this cycle will be reset once this collapse has taken place, effectively changing the rock wall shape from a shelter to a curved exposed surface.

This new interpretation of rock surface hardness values in correspondence with surface weathering also indicates that the general statement “weathering alters the inherent properties of the material [the rock] and reduces its strength” (Aoki and Matsukura, 2007a) needs to be revisited. We have found that weathering processes can lead to case hardening which strengthens rather than weakens the rock. This research shows that there is a curve of weakening of the sandstone surface followed by strengthening as weathering crusts develop and the internal moisture regime adjusts. It is in fact the interplay of these two factors which determines the strength of the rock surface within the Clarens sandstone, not merely the external factors which have been correlated to degree of rock surface weathering. This was also confirmed by the thin section results, as the surface with weathering crust showed a much stronger cohesion than the surface without weathering crust (see figure 7.2). As Turkington and Phillips (2004) argue, the case hardening of the surface and weakening of the underlying rock are fundamental factors in cavernous weathering. In addition, we have now shown how this process evolves over time to establish the shelters seen in the GGHNP as we follow the development of shelters from the shallow, high weathering rates exposed surfaces of the young sites to the large, low weathering rate sites of the established shelter.

The complexity of this dynamic system shown in this research incorporates a number of different theories of tafoni development, as discussed in the introduction. This fits in with Viles' (2005)

discussion of cavernous weathering research to date which, rather than providing any consensus viewpoint, gives the overall message that 'mine are different than yours' (p. 1472). Our research shows that, by comparing hardness, weathering and internal moisture regimes in caverns at different stages of development, plausible evolutionary models can be developed which link together a range of different processes and theories. This conceptual model could provide the basis for future numerical modelling as well as testing in different field settings.

7.6 Conclusions

Using a selection of shelters at the GGHNP, we have shown that the development of cavernous weathering is influenced by the interaction of surface hardness and internal moisture. This dynamic changes over time, and we therefore propose that cavernous weathering of sandstone should be regarded as a highly dynamic and ever-changing processes that adjusts itself to changing circumstances, not only of environmental conditions, but more importantly internal conditions. We suggest that internal moisture plays a substantial role in the weathering of Clarens sandstone and that changing internal moisture regimes determine type of weathering to a large extend. We therefore propose a new model which incorporates the dynamic nature of internal moisture into shelter development. We therefore propose a new model which incorporates the dynamic nature of internal moisture into the evolution of rock shelters. However, we have not been able to establish the exact role of salts in this cycle, which requires further research.

Acknowledgements

We thank South Africa National Parks Service for granting us permission to work at GGHNP, as well as all the staff at the Gladstone Offices (GGHNP), in particular Sandra and Johan Taljaard and the

guides, Sam, Moses and Joseph. We thank Matt Telfer, Andrew Goudie (Oxford University) and Stefan Grab and Jennifer Lalley (University of the Witwatersrand) for their excellent comments, suggestions and company. We would also like to thank the staff at the OxRBL for all their help in preparing for this fieldwork as well at John Meneely at Queen's University, Belfast, for his help with thin section preparation. In addition, Lisa Mol is very grateful for the Dudley Stamp Memorial Award which she received from the Dudley Stamp Memorial Trust in collaboration with the Royal Geographical Society / IBG and the Bill Bishop Award, received from the Quaternary Research Association. In addition, we would like to thank St Cross College, Oxford University, as well as the Oppenheimer Fund, Oxford University, for their generous financial contribution towards the research.

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CHAPTER 8: USING ERT TO ASSESS THE INFLUENCE OF EXPOSURE TO ELEVATED NEAR-SURFACE TEMPERATURES ON CAPILLARY RISE AND DRYING BEHAVIOUR

This chapter has been submitted as a publication for *Environmental Earth Sciences* and reports on a series of laboratory tests which were performed using both the PSR-device and ECG-electrodes. The fieldwork in South Africa provided an insight in to the role of internal moisture in cavernous weathering. However, it was difficult to determine the role of temperature in the movement of internal moisture due to a lack of internal temperature gradient data. A new laboratory test was therefore designed to investigate the response of moisture to altered near-surface temperatures. The two main aims of these tests were 1. To determine which method of electrode attachment to the stone surface was most effective and how they perform using a variety of semi-controlled environmental circumstances and 2. How changing near-surface temperatures affects the internal moisture regimes, focussing specifically on capillary rise.

Again, it was not possible to collect internal temperature gradient data as the resistivity equipment was installed on both the front and the back of the block and the metal temperature sensors would have interfered with the resistivity measurements. However, the data provided by the iButtons recorded detailed information on the temperature fluctuations provided by the heating device. The results of this study are of wider importance to this thesis as it shows that higher near-surface temperatures do not necessarily result in lower internal moisture content – on the contrary, the capillary rise seemed to increase with increasing near-surface temperatures. This is a new phenomenon that needs to be taken into account when interpreting fieldwork results.

Submitted: 04/03/2011. Reviewing process started: 07/07/2011 (with editor)

EXPOSING DRYING PATTERNS: USING ELECTRICAL RESISTIVITY TOMOGRAPHY TO MONITOR CAPILLARY RISE UNDER DRYING CONDITIONS IN SANDSTONE

L. Mol*, H. Viles

Abstract

Rising damp and other moisture movements through porous stone and rock are known to cause weathering and deterioration, as noted in a range of recent field, and laboratory studies. Mathematical models have also been developed which provide a simple conceptual picture of moisture distributions under various conditions. However, there remains a gap in our knowledge between the complex moisture regimes observed in the field and the simplified modelling results. This paper has two main aims: firstly, to evaluate different resistivity methods to monitor subsurface and surface moisture regimes and, secondly, to use these methods to monitor the movement of water by capillary rise in a sandstone block under (a) conditions of constant moisture ingress at the base and (b) an enhanced drying regime with and without constant moisture ingress at the base. Our results indicate that, for ERT measurements on a sandstone block, medical electrodes provide more reliable contact with the stone than spring-loaded pointed metal electrodes, and that the combination of ERT and handheld moisture meters gives a realistic picture of moisture movements within the block. The capillary rise and drying experiments reveal complex moisture movement over time and space. Accelerated drying with constant moisture ingress at the base of the stone block results in maintained or even increased capillary rise. These findings bridge the gap between the

complex internal moisture regimes found in the field and moisture behaviour predicted in mathematical models.

8.1 Introduction and aims

Capillary moisture movement is a well-known phenomenon in many built structures in a large array of environments (Moreno *et al*, 2006; Huinink *et al*, 2004; Pender 2004), as well as natural rock outcrops (Mol and Viles, 2010). Wherever ground water is present, there is a risk of moisture ingress via capillary rise which can cause deterioration of the structural stability of the stone or rock outcrop through surface weathering, often in the form of cavernous weathering such as honeycombing and tafoni formation.

Moisture is known to move within porous materials, such as rocks and building stone, through capillary transfer along interconnected networks of pores. For example, rock in contact with groundwater is known to experience capillary rise, which can often be seen to be associated with deterioration (with the zone of maximum deterioration occurring towards the top of the capillary fringe, see for example McKinley and McCabe, 2010). Water is a key agent in many weathering processes, such as salt weathering, freeze-thaw and dissolution weathering. Recent advances in moisture research show that moisture does not behave in a uniform way throughout the stone mass, and could be heavily influenced by temperature changes at surface level. Hall *et* al (2010) found that potential evaporation rates are subject to daily, annual and secular variations in the microenvironment, adding to the complexity of moisture regimes. In addition, porous stone such as sandstone is often situated in areas where it is exposed to a number of moisture sources (i.e. rainfall, Sass and Viles, 2010 or groundwater infiltration due to capillary rise, La Iglesia *et al*, 1997). Recently, the use of Electrical Resistivity Tomography (ERT) methods, over generally large scale transects of the order of meters to 10s of meters, has allowed visualisation of the moisture regimes

within such porous rocks without the need for invasive probes, which take only spot readings of moisture levels (McKinley *et al*, 2006). For example, Mol and Viles (2010) found complex moisture regimes in two contrasting rock shelters within Clarens sandstone at the Golden Gate Highlands National Park, South Africa, allied to surface exhibiting a range of active weathering features. The use of handheld moisture meters has also increased in recent years, and such simple tools may provide additional data on near-surface moisture regimes to add to ERT datasets. In order to enhance our confidence in ERT and moisture meter techniques it is helpful to test their performance under controlled conditions which might simulate the wetting and drying regimes found in natural situations.

In this paper we report on a two part laboratory experiment of intermediate complexity. The aims of this experiment were (a) to evaluate the reliability of two different ERT electrode arrays, and of two handheld moisture meters (FMW and Protimeter) and (b) to investigate the moisture regime within a large block of sandstone subjected to capillary rise with constant water source at the base and then capillary rise under accelerated drying (both with and without the water source at the base)

8.2 Materials and methods

8.2.1. Stone block

For these tests, a block of carboniferous Millstone Grit medium grained sandstone was obtained from the Stoke Hall Quarry in Derbyshire (dimensions: 55 x 32 x 25.5 cm). Laboratory tests show a very even distribution of quartz minerals, with visible pores and no evidence of weathering rind build-up as the block was freshly cut. Microscope observations confirmed that this type of sandstone consists almost exclusively of quartz minerals. Pore volume tests on three smaller samples, using the standard ADOP EN1925 (water absorption capacity, WAC) and EN1936 (porosity, Po) methods,

showed that WAC measured 3.2% at an average Po of 11.2%, which is in the same range as the standards provided by the supplier (3.3% WAC, Po 12.6%).

8.2.2 Resistivity equipment

A number of different devices are available to measure resistivity across 2D profiles, involving an array of equally spaced electrodes. Such methods are often summarized as ERT methods, and can be used to build up a picture of the internal characteristics of porous bodies in a non-destructive and non-invasive way. We use GeoTom (Geolog2000) ERT equipment, which can measure profiles involving up to 100 electrodes. The basic principle of ERT is to pass an electrical 12V current between two designated potential electrodes. By increasing the spacing between the two designated electrodes the current penetrates the stone further, building up a 2D transect of point specific resistivity which can then be recalculated into a most probable resistivity distribution using the inversion programme RES2DInv (see Sass and Viles, 2006 and Mol and Preston, 2010 for more information). A range of different methods can be used to establish a good connection between electrodes and the underlying porous material – with nails, screws or metal pegs commonly used in soils and other materials into which drilling is acceptable. For most heritage buildings and rock art panels, such partially destructive electrode connections are not allowed and thus non-invasive methods have been proposed. Medical electrodes are known to provide a good connection (e.g. Sass and Viles, 2006; 2010) but may leave a sticky residue which can be hard to remove. A more recent design utilises spring-loaded metal pins mounted on a rigid array, which allow fixed spacing of electrodes and should permit good contact on rough surfaces without the need for adhesive pads. In this paper we use transects composed of 25 ECG medical electrodes stuck at 2cm intervals, in comparison with a spring-loaded permanent spacing device (PSR device, see figure 8.1) with 25 pins set a 2cm intervals, giving total transect lengths of 48 cm in both cases. In order to get good contact

between the stone and the PSR device, conductive gel was applied to the head of each pin before each reading.

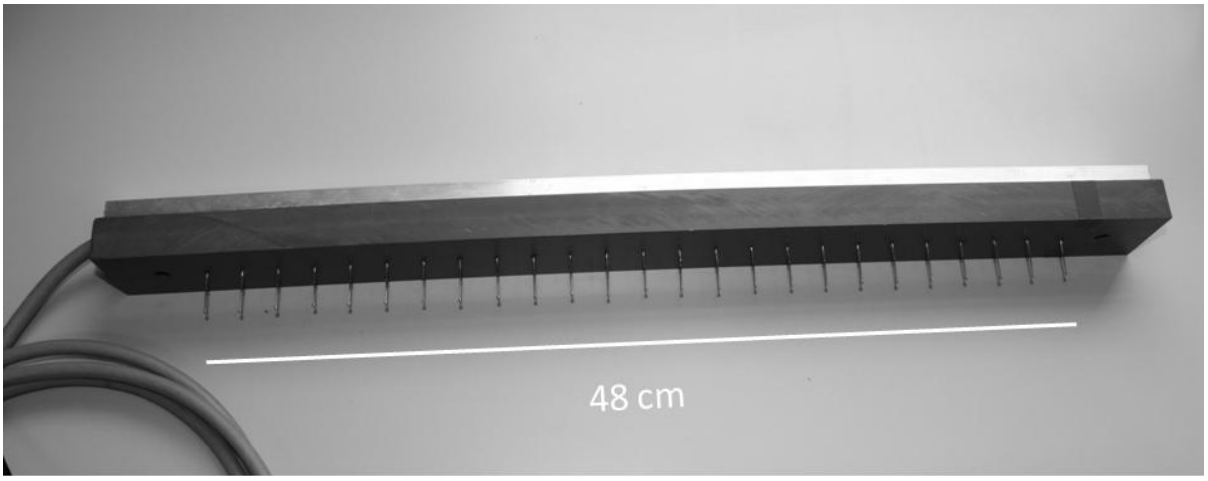


Figure 8.1: PSR device

A Wenner array was used for each measurement, as pilot studies found this to be the most effective in tracing the moisture movement. Wenner arrays sample resistivity in parallel transects which builds up to an 8 layer, 92 point dataset which is inverted into a 2D transect using a forward modelling subroutine in the RES2Inv programme. This programme calculates the most likely distribution of resistivity values based on a K-nearest neighbour system, building a pseudo-section of the measured material. Because of the set-up of the electrodes there is a 0.5cm gap between the surface and the measurements, effectively measuring the resistivity between 0.5cm and 10.5cm from the surface.

8.2.3 FMW, Protimeter

The Protimeter (Surveymaster BLD5360) is a low-cost 2 pronged resistivity device commonly used in building surveys to detect damp in walls. It is calibrated for wood, and gives values expressed as %WME (wood moisture equivalent) which are non-linearly related to absolute moisture contents in stone. According to the manufacturer's specification the Protimeter measures percentage saturation over the range 6-100% at a depth of c. 25.4 mm. In contrast, the FMW (Brookhuis T-model) is a capacitance based moisture meter, also often used to survey damp problems in walls. Capacitance-based devices are known to be less sensitivity to complicating factors such as the salinity of the water (which has a strong influence on resistivity-based measurements). The FMW reads over a range of 5-99%, with an error margin of 0.5%, can be calibrated for a range of different materials, and can be set to measure at a depth of 10 to 20mm within the surface of a porous material.

8.2.4 iButton temperature monitoring

In order to monitor the near-surface temperature conditions whilst the drying phase of the experiment was being run, a series of iButton (Thermochron DS1921G) were installed on all sides of the block (see figure 8.2), with four on the front and back vertical face (one towards the top and one towards the base at each transect) and a further two per vertical face on the sides of the block. The iButtons were programmed to record data every 10 mins and the manufacturers quote and accuracy of ± 1°C.

8.3. Experimental design

This experiment consisted of two distinct phases, as summarized in table 8.1. Experiment 1 was a straightforward capillary rise experiment under laboratory temperature and humidity conditions, which ran for 28 days with a constant moisture source at the base of the block. Experiment 2 was more complex, consisting of 24 hours of accelerated drying using a heater whilst retaining the

constant source of moisture at the base, followed by 7 days of accelerated drying with no moisture source at the base, and finally involving 28 days of drying under laboratory temperature and humidity conditions. Repeat measurements using the ERT, Protimeter and FMW were taken at intervals, which decreased in frequency over the course of the experiments and conditions stabilised.

Phase	Part	Heat	Moisture	Duration
1		No	Yes	28 days
2	1	Yes	Yes	24 hours
	2	Yes	No	7 days
	3	No	No	28 days

Table 8.1: Overview of experiment phases

8.3.1. Experiment 1: Capillary rise under constant conditions

The sandstone block was placed in a tray and water was added to a depth of 5 cm. Because of the weight of the block, water ingress was likely to have been concentrated around the outer margins of the block. Two vertical transects were marked out starting just above the water line next to each other on the front of the block (T1 and T2, see figure 8.2). The ERT electrodes were attached to the stone surface using ECG medical electrodes at transect 1 (T1), transect 2 (T2) was measured using the new PSR device. Both transects extended 48 cm. Through the duration of this experiment the iButtons were not yet attached to the surface as we monitored capillary moisture behaviour under steady conditions. The water supply was replenished regularly to maintain an equal water pressure throughout the experiment.

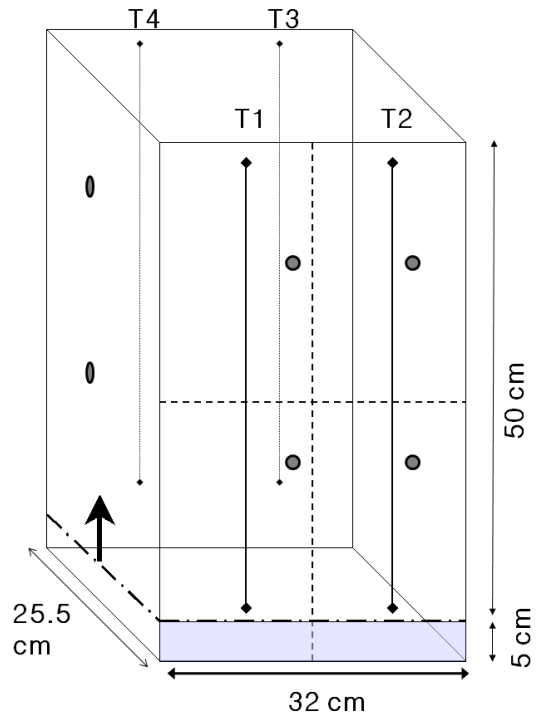


Figure 8.2: Showing the set-up of the all the transects and iButtons (dots) used within the series of experiments. T1 and T2 are placed at the front of the stone, where eventually the heating element was placed. Transects 3 and 4 (T3 and T4) were used in the drying experiments and were not exposed to direct heating.

8.3.2. Experiment 2: Capillary rise under accelerated drying

For the second experiment, two additional transects were installed on the rear face of the block and iButtons installed on all vertical faces to monitor temperature regimes across all sides of the block. In order to create accelerated drying, a fan heater was placed 50cm from the front of the block directly in front of transects 1 and 2. Figure 8.3 shows the temperatures measured on the four vertical faces during the experiment, and illustrates the difference between the front and right side (hotter) and the back and left side (cooler).

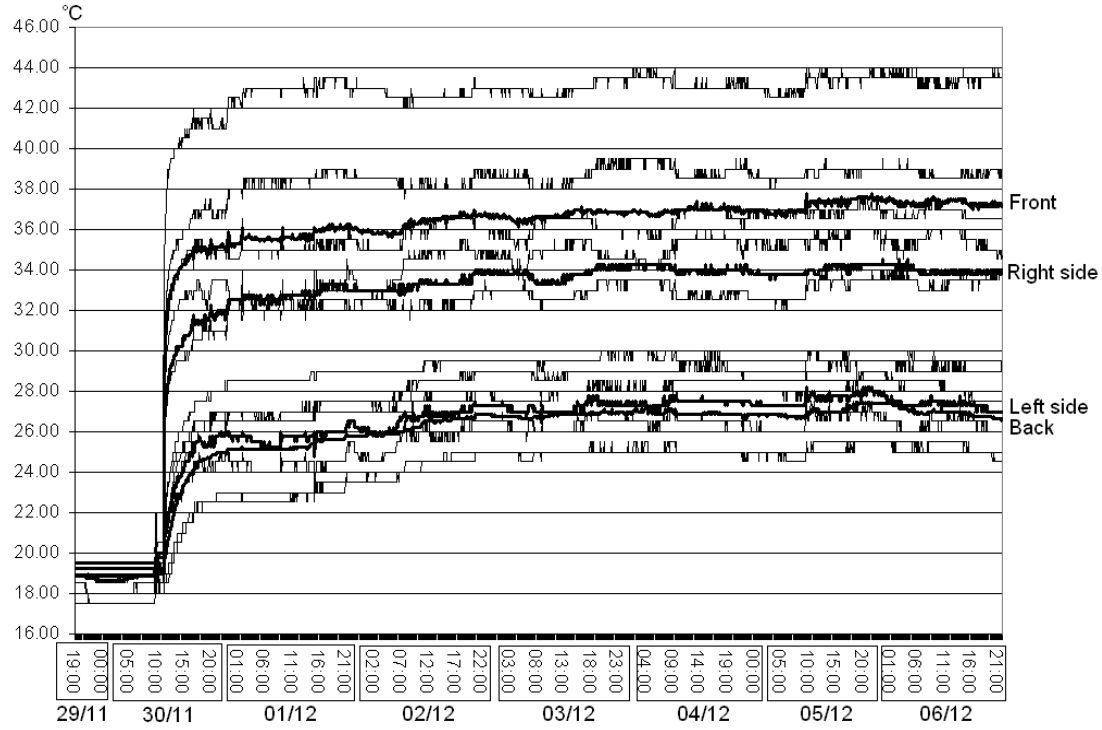


Figure 8.3: Temperature log for all sides, consisting of four iButtons for both front and back and two iButtons for each of the sides. Temperature increase around the block is evident at 10:00am on 30/11.

However, the airflow generated was almost negligible as the exposed front measured wind speeds of an average of 1.8 ms^{-1} and 0.4 ms^{-1} along the sides, using a Kestrell 1000 anemometer. No reading was possible at the back of the block as there was no measurable air movement.

Protimeter and FMW measurements were taken along both front and back faces in a transect between the two ERT transects, following the layout in figure 8.4. These measurements were taken at the same time as the ERT measurements.

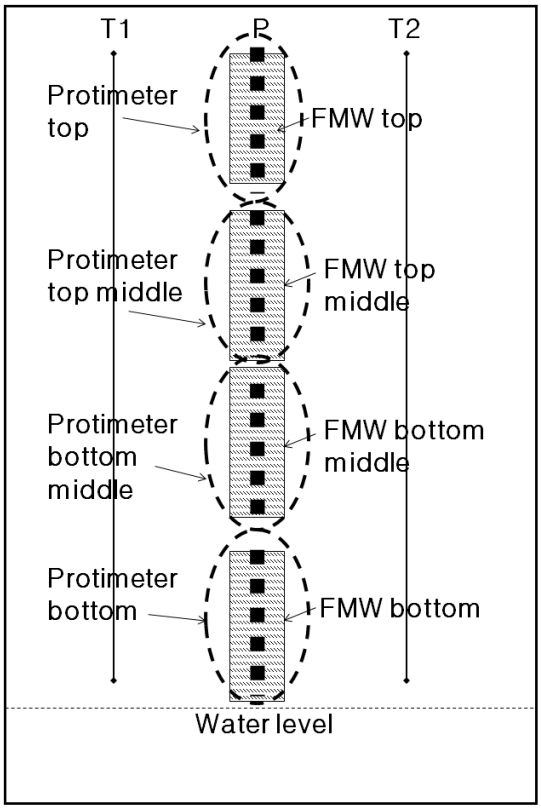


Figure 8.4: ERT (T1 and T2), Protimeter (P) and FMW measurements as related to the block. Note that the gap between FMW-top and FMW-top middle as well as the gap between FMW-bottom middle and FMW-bottom is caused by the placement of iButtons in that position. It also shows the large measurement surface area of the FMW compared to the point-specific Protimeter.

8.4 Results

The ERT data from each measurement have been transformed into 2D pseudo-sections through the RES2DInv software using a standard algorithm (see Mol and Preston, 2010 for further details). The Protimeter and FMW data have not been calibrated specifically for sandstone, and raw values are only presented here to observe corresponding, or a lack of corresponding, trends between the data sets rather than a direct comparison.

8.4.1 Experiment 1: Capillary rise under constant conditions

As illustrated in figure 8.5, capillary rise proceeded as might be expected with moister conditions at the base towards the outer faces of the block within the first 4 days of capillary rise, because of the weight of the block slowing water ingress towards the centre. Figure 8.6 indicates that the medical (ECG) electrodes in transect 1 provide a more consistently reliable assessment of moisture regimes than the PSR device (transect 2). The PSR device gave quite erratic moisture patterns on days 5, 6, 8 and 12 – illustrating difficulties in making good connections between the spring-loaded pins and the stone surface. Care needs to be taken using this device in the future, although it performed well in the early and later measurement periods. Despite these complexities, both transects record a progressive rise of water around the outer edges of the block over the 28 days of monitoring, with a noticeably wet outer zone stretching up to around 20cm up the transect (i.e. 25cm above the base of the block, as the transect starts above the water line at 5cm above the base). After the first 12 days the interior of the block also became wetter to the same height as the outer zone. After 28 days under constant laboratory conditions equilibrium was reached and no further moisture rise occurred.

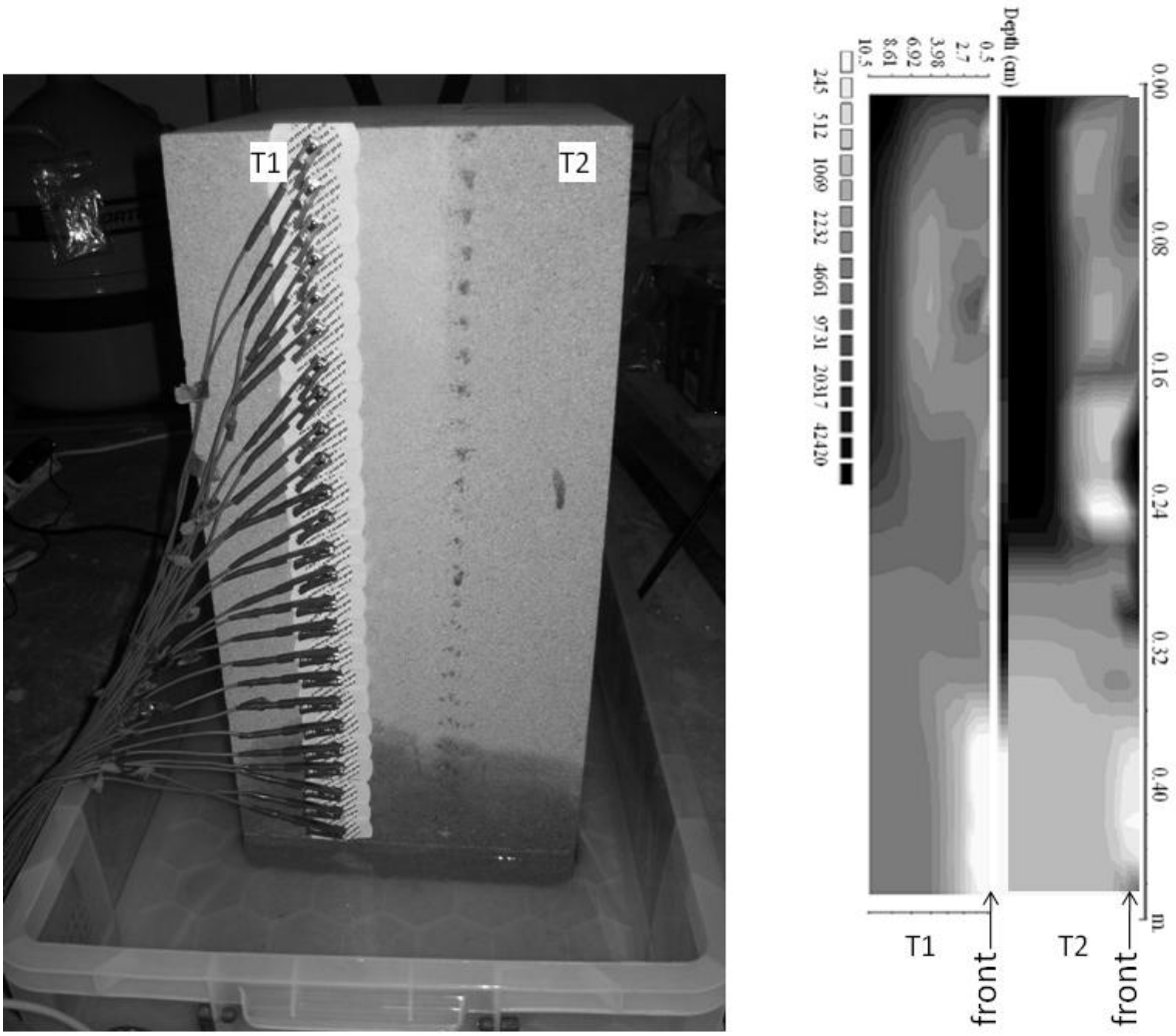


Figure 8.5: stone sample after 4 days of capillary rise, showing an agreement of the data of both the electrodes and the permanent spacing resistivity device, as well as a correlation between the visibly wet surface at the base of the stone block and the lowest resistivity area of in the ERT transects. The ERT ohm m. scale will be maintained throughout this article, with the exception of the differential inversions.

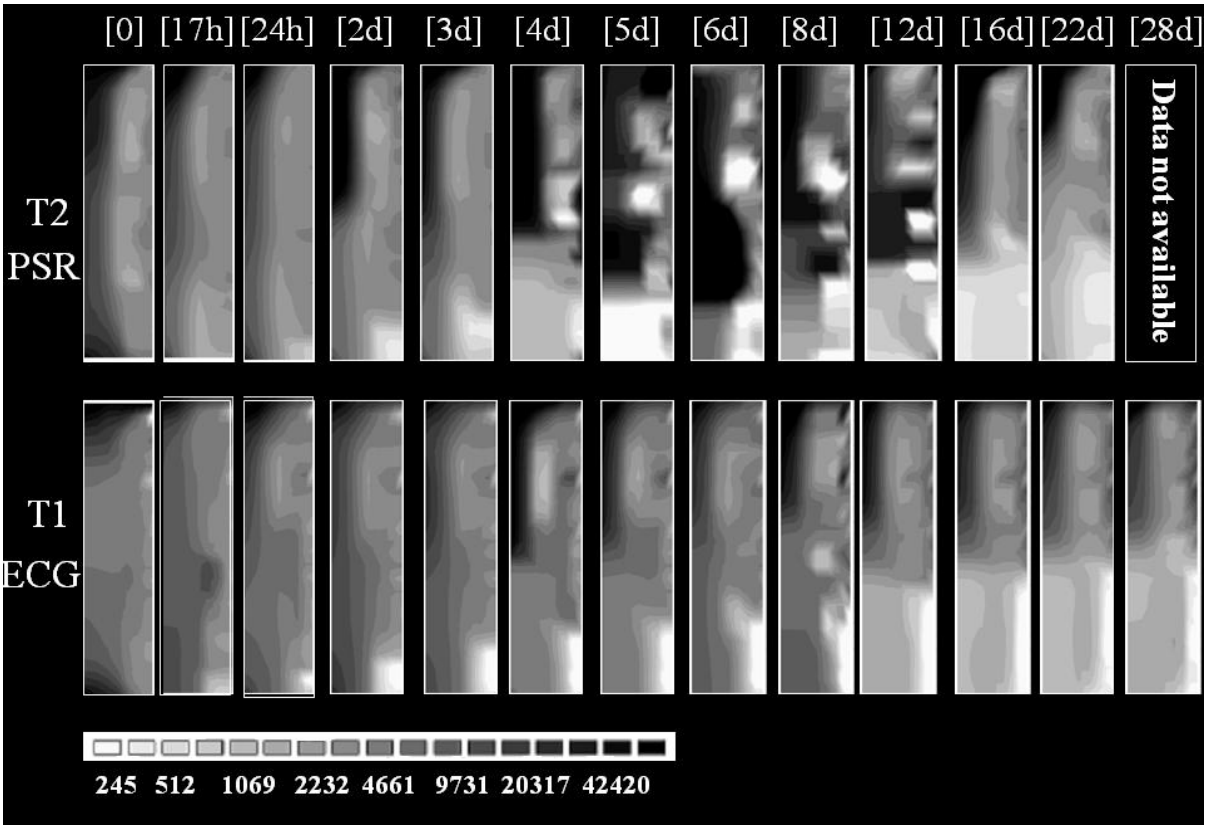


Figure 8.6: Resistivity arrays results showing the permanent spacing device (T2) and electrodes attached with ECG pads (T1) at an array of times. [0] is base data just before wetting.

After evaluating the performance of the PSR at the end of this part of the experiment we concluded that even though it shows promise in terms of performance it needs to be further developed to increase the conductivity between the electrodes and the stone surface to ensure reliable results. We therefore from now on only use ECG electrodes to attach the ERT electrodes to the stone surface.

8.4.2 Capillary rise under accelerated drying

Figure 8.7 summarises the main trends in drying over the first 8 days of this experiment. During the first 24 hours, the block was still in contact with a constant water source at the base, but for the

remaining 7 days there was no further water ingress. Because four ERT transects were monitored (two at the front and two at the back) during this experiment, each set of images in figure 8.7 records a profile from the front to the back of the block (one on the right side and one on the left). Interestingly, despite the accelerated drying regime on the front of the block, there is still a wet zone towards the front of both profiles extending up to about half-way up the block. In contrast, both cross profiles through the stone show a lower, less distinctive near-surface wet zone on the back face. Some drying does appear to have occurred towards the top of the front parts of both profiles after about 2.5 days, and this is also evident on the back face by day 8.

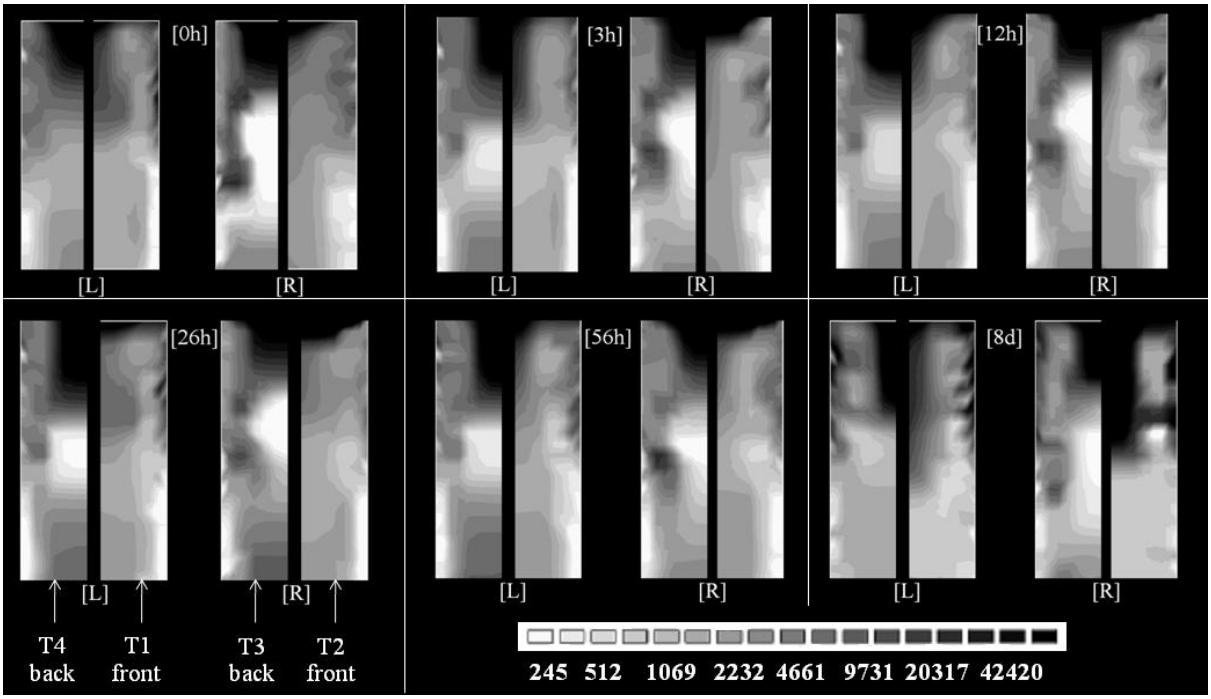


Figure 8.7: Overview of selected measurements taken during the drying processes. [L] indicates transects 4 (back) and 1(front), which are at the left side of the block, [R] indicates transects 2 (front) and 3 (back) which are situated on the right hand side of the block (see figure 8.3 for a schematic representation). Note that the heat was switched on after the baseline measurement [0h], the water supply at the base of the block was removed after 26 hours [26h] and the heat switched off after 8 days [8d].

It is remarkable how quickly the water spreads along the subsurface of the stone, especially at the start of the heating and drying experiment. Almost immediately after wetting, changes in the moisture content are seen towards the top of the block. This is shown more clearly in figure 8.8, which shows the differential inversions of [0h] and [2h], [0h] and [12h] of transect 1. These inversions were obtained by directly subtracting the raw data of [0h] from [2h] and [12h] from [0h]. This new dataset was then used to obtain a new inversion through RES2DInv. Note that 0.08 on the horizontal scale is near the top of the block, and 0.40 near the base (the submerged) part of the block. The base data used is the moisture content measured at the end of the capillary experiment, and just before the heat was switched on.

As is clear from these two difference pseudo-sections, the block does dry over 12 hours, but only at depth whereas the immediate subsurface continues to get wetter and at the base of the block.

To understand this wetting mechanism better, the results have been split out by experiment phase (with or without moisture source at the base of the block) in which they were taken.

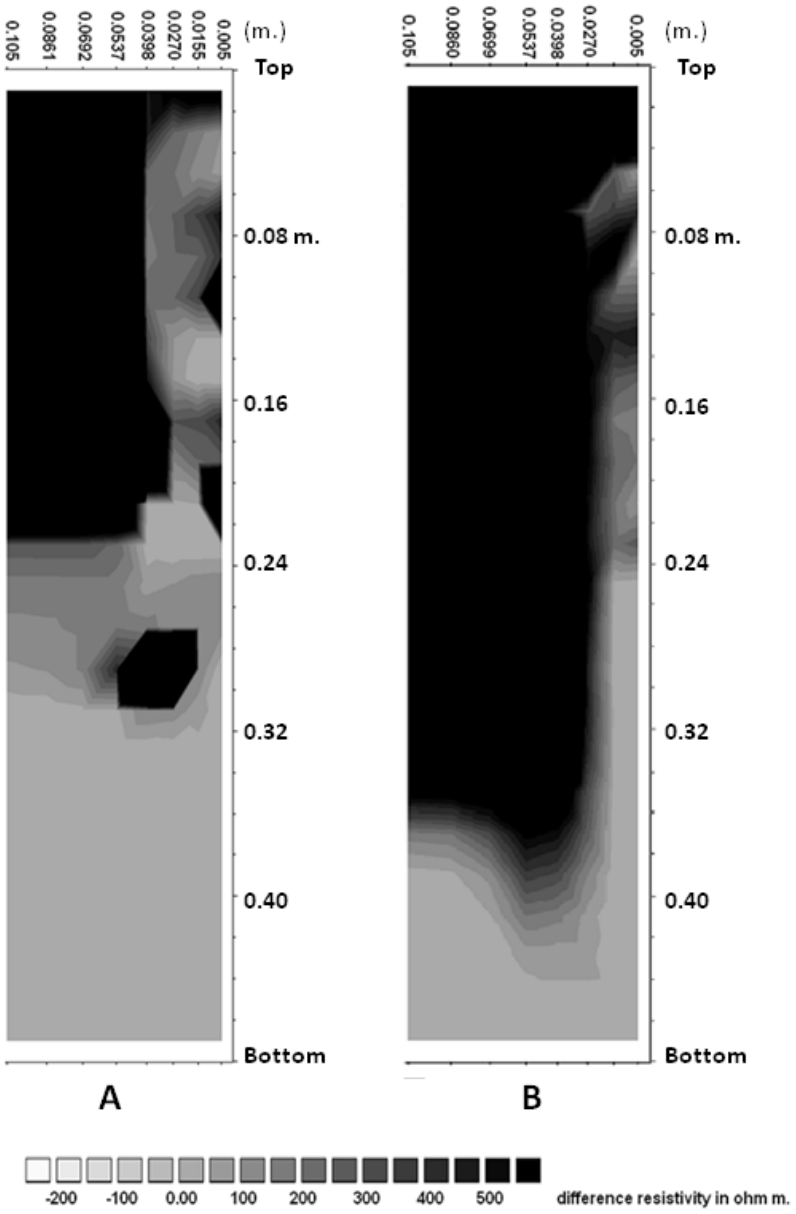


Figure 8.8: (A) Differential inversion of [0h] minus [2h] (2 hours of heating) at transect 1, front of the block. (B) Differential inversion of [0] minus [12h] (12 hours of heating) at transect 1, front of the block. White and light greys indicate wetting (decrease in resistivity), whereas black and dark greys indicate drying (increase in resistivity).

8.4.2.1. Accelerated drying with constant moisture supply

Figure 8.9 provides more detail on the first 24 hours of experiment two, showing how each ERT transect behaves over time (at 0, 4, 10, 16, and 24 hours into the experiment). Transect 1 and transect 2 are located at the front of the block and are characterized by similar stability in height of the capillary rise within the near-surface zone (around half way up the block). Higher up the block, the surface is wetter than the inner portion of the block. Conversely, T3 and T4 at the back of the block show an increasing trend in the near-surface capillary rise zone (from about a quarter to half way up the block between 4 and 24 hours). Transect 4 and to a limited extent transect 3 show evidence of deep seated wetness to a higher level, with very dry conditions above.

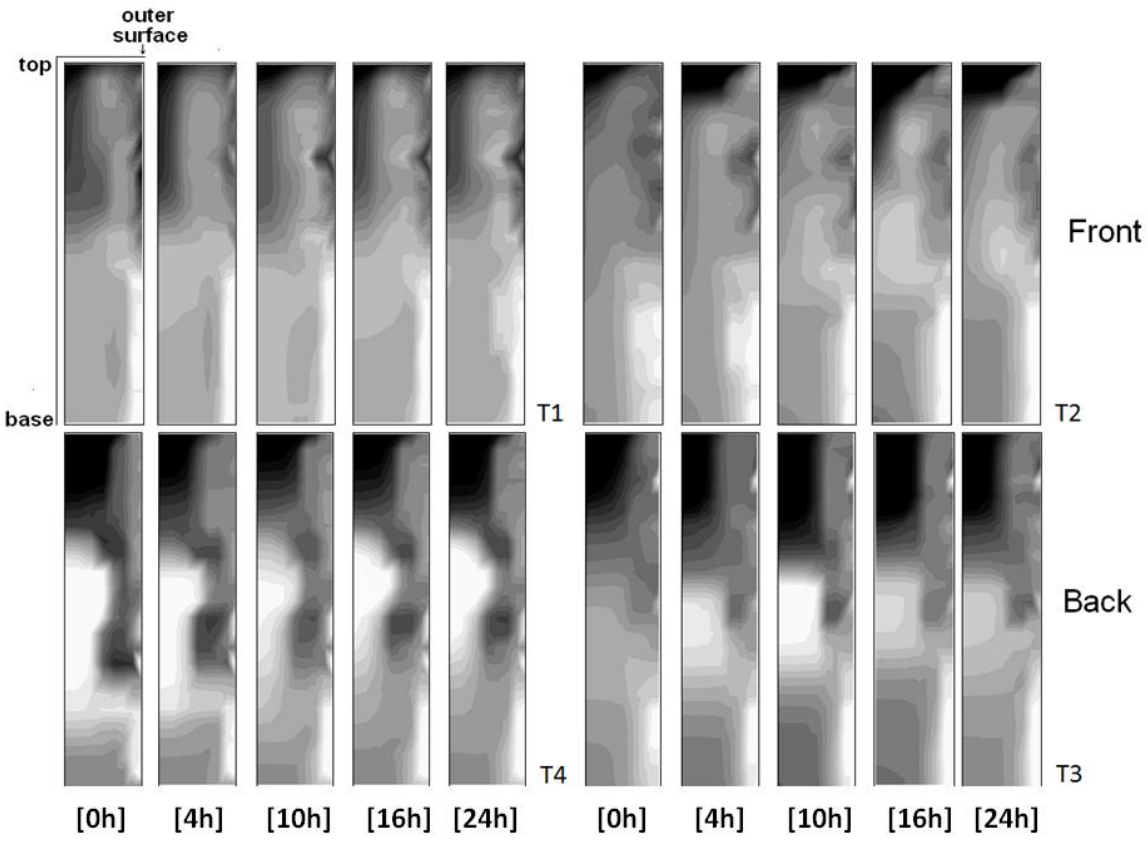


Figure 8.9: Drying measurements at baseline measurement, 4 hrs, 10 hrs, 16 hrs and 24 hrs, before moisture was removed from the base of the stone.

Looking in more detail at the upper parts of transect 1 in figure 5.10 we can see the differences between measurements taken at 16 and 24 hours after the beginning of the experiment. The circles indicate areas where the change in moisture content is particularly visible, and shows the moisture rising through the block at point 2 and concentrating in a particular area towards the top of the block at point 1. Thus the stone is becoming wetter rather than drier in this part of the block, with only a slight drying trend in the near-surface zone (forming a wedge-shaped drying front). Figure 8.11 portrays similar behaviour in transect 2, but more extreme as this transect was exposed to higher temperatures than transect 1. There is the same upwards movement of water, the formation of concentrated pockets of moisture and minimal drying of the near-surface zone.

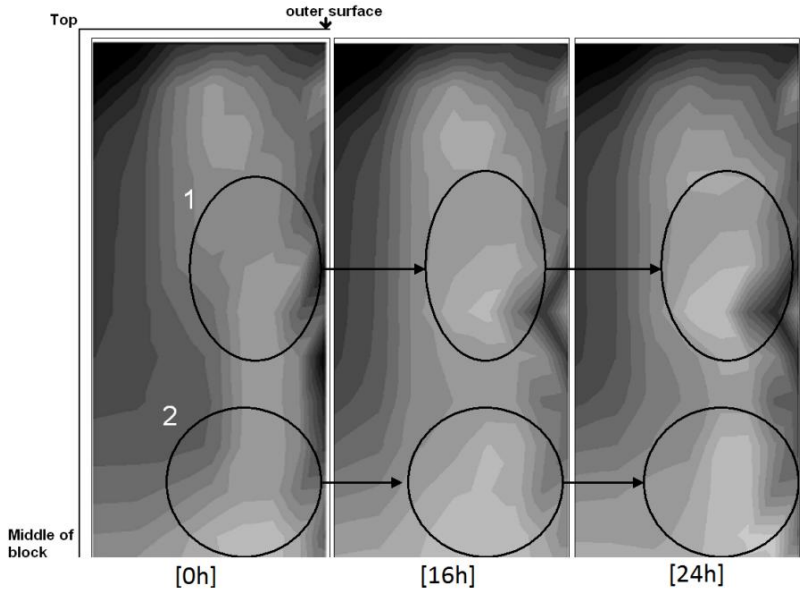


Figure 8.10: Top half of transect 1 pseudo-sections at baseline measurement, 16 hours and 24 hours showing the increased moisture at the top of the block, as well as the continued rise of moisture from the bottom half of the block.

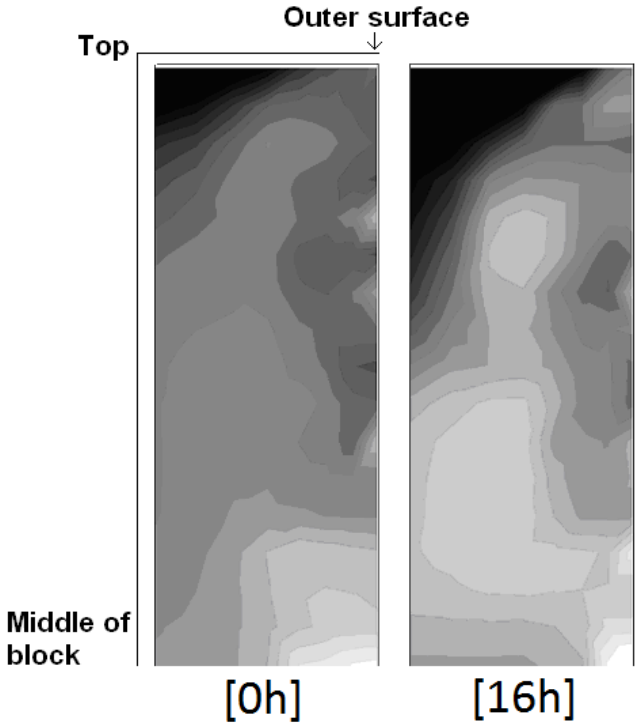


Figure 8.11: pseudo-sections of the top half of transect 2 using measurements [0] and [6] to illustrate the increased moisture movement and concentration of moisture in pockets as well as the movement of moisture towards the surface of the block.

8.4.2.2. Accelerated drying with no moisture supply

When the moisture source for the capillary rise was removed after 24 hours a distinctive change in the internal moisture regime can be seen. Figure 5.12 shows how each ERT transect starts to dry out from the outer surface zone after the moisture source at the base is removed. After 8 days from the start of the experiment the accelerated drying regime was stopped and the final 28 days were run under normal controlled laboratory temperature and humidity conditions. Even under these conditions, drying has occurred, both at the front and the back of the block.

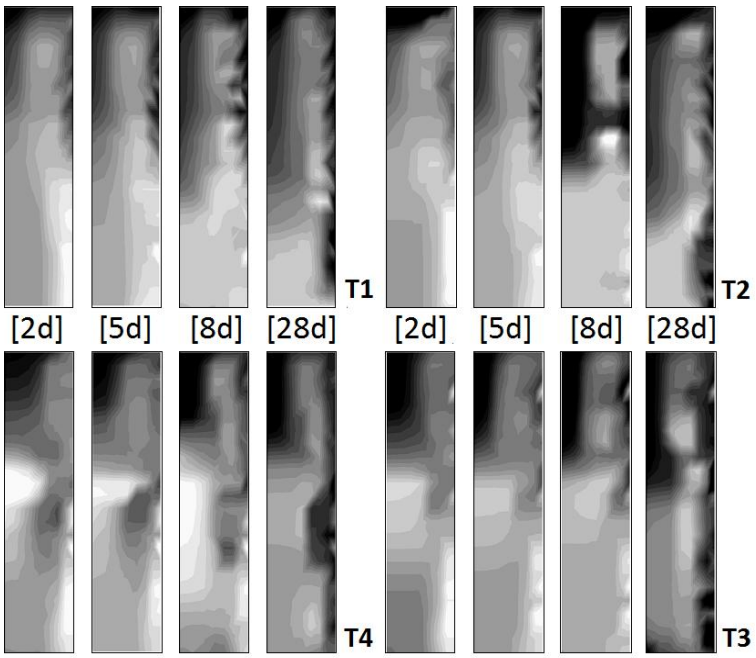


Figure 8.12: Showing the transects of both the front (A and B) and back (C and D) of the block, at 2 days, 5 days and 8 days of heating and a final measurement at 28 days after the heat was switched off.

8.4.3 FMW and Protimeter measurements of near-surface moisture regimes

At the beginning of experiment 2, surface moisture measurements were taken in a central transect between the two ERT transects on both front and back faces of the stone block. Figure 8.13 plots the Protimeter vales as recorded between day 1 and day 6 of the experiment from four zones of the transect (top, top-middle, bottom-middle and bottom). Drying in all zones was obvious right from the start, despite the fact that constant moisture ingress from the reservoir at the base occurred during the first 24 hours. The upper parts of the profile were drier and experienced very little change, whereas the bottom section dried rapidly from an initially wet state. No clear differences emerge between the front and back of the block.

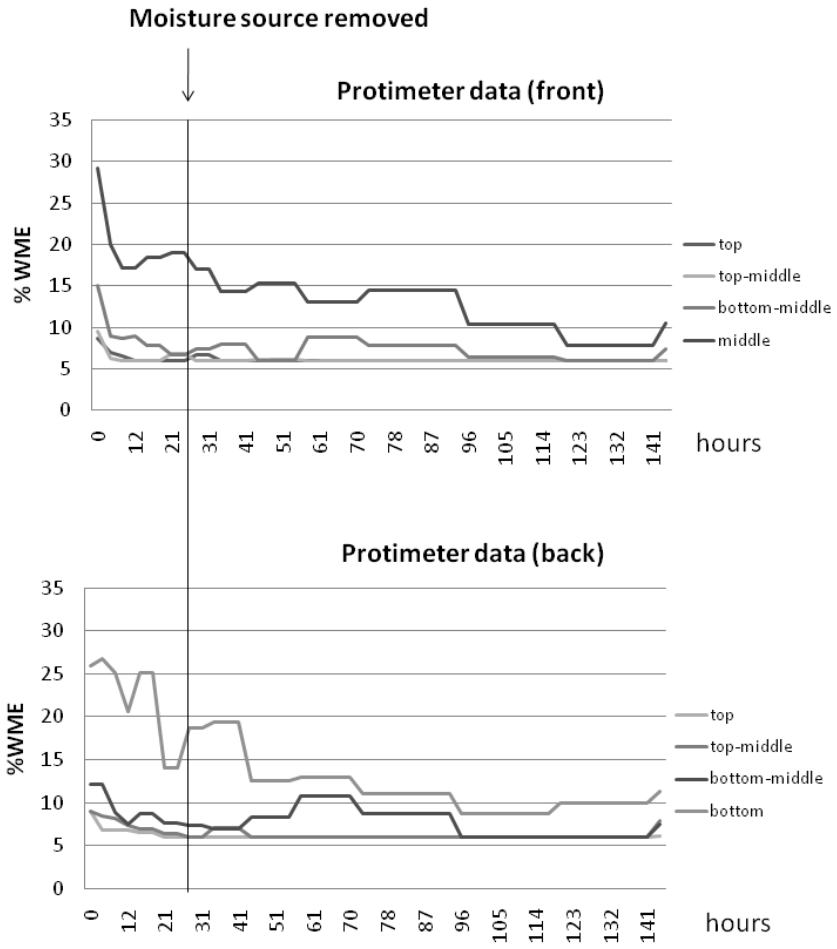


Figure 8.13: Protimeter measurements from the front and the back of the stone, x axis shows % saturation, as calibrated for wood and therefore here used as a relative measurement

To further investigate the near-surface moisture content we also measured relative moisture content using a FMW, a capacitance based moisture meter, at both 10 and 20 mm depth 34 hours after the start of the drying stage when the moisture source was no longer present. The FMW results show a good overall correlation with the Protimeter measurements, as illustrated in figure 8.14. Over 6 days of monitoring the top and middle-top of the sections showed very little change, although there were clear differences between the behaviour when the FMW was set to measure the outer 20mm of the stone in comparison with the outer 10mm alone. The lower part of the profile shows ordered swings swings from wet to drier, as also seen in the Protimeter data.

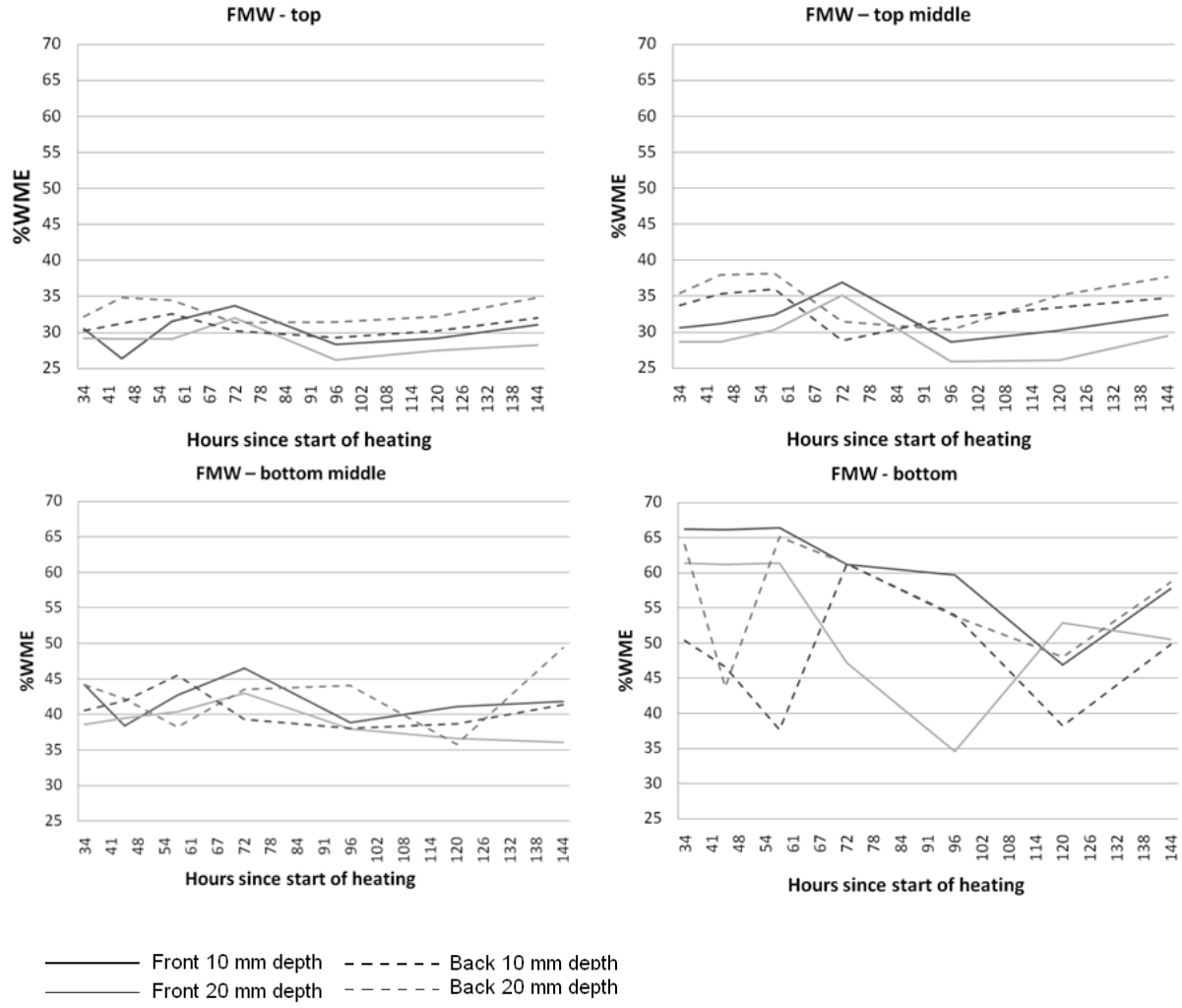


Figure 8.14: FMW-T measurements sorted by height placement on stone surface.

Similar patterns can also be found in the bottom-middle measurements. The bottom measurements show a much more extreme but still similar drying and wetting trend. Similar patterns were found in the ERT data, as figure 8.15 shows, where relatively rapid drying can be seen at the bottom of all transects, whereas the moisture content in top section of the block remains far more constant. However, the wave-like behaviour cannot be seen in the ERT data, possibly because the relative differences in moisture content that suggest the wave-like curve in the FMW data are too small to translate to significant changes in the ERT readings.

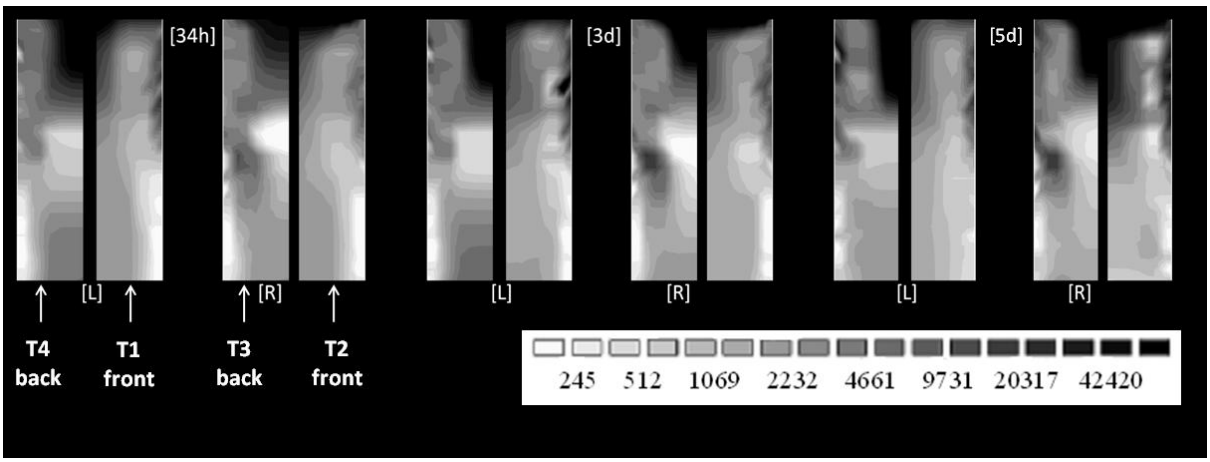


Figure 8.15: ERT measurements of the no-moisture source drying stage correlating to the FMW measurements.

Hall and Hoff (2002) describe drying behaviour that is somewhat similar to the drying observed in the FWM data. They propose that drying under constant external conditions occurs in two distinct stages, the constant drying rate period (stage I, which occurs when the rate of evaporation is limited or controlled by external conditions rather than the rate of transport within the material) and the falling drying rate period (stage II, where surface water contents fall rapidly and steeper gradients of water content develop behind the drying surface). However, while the data shows behaviour that is overall similar to Hall and Hoff's observations, they show a recurrent cycle which is not just a two-stage system but an interplay between drying and wetting.

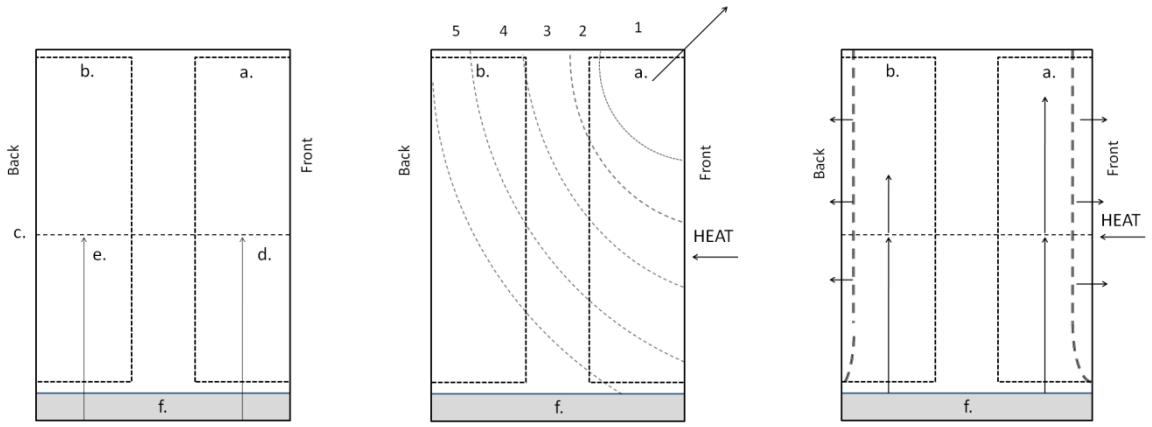
Neither the FMW nor the ERT conclusively confirms the behaviour described by Hall and Hoff, instead the drying behaviour observed underlines the complexities of moisture behaviour under semi-controlled circumstances. In the case of the FMW measurements, there is a discrepancy between the front and the back of the block, especially within the bottom section measurements where no linear drying curve can be established. The ERT shows that the complexities of moisture movement extend towards the middle of the stone block, where movement of moisture can be seen throughout all experiments especially at the back of the block where a fluctuating area of low

resistivity is present in both the middle section of T3 and T4. Smith *et al* (2010) conducted a similar intermediate complexity experiment recording surface and near-surface temperatures under changing heating regimes and found that the temperature profiles were considerably more complex in space and time than the smooth exponential decrease in temperature they initially assumed. This type of experiment opens up the possibility that there are previously unconsidered complexities within internal moisture behaviour and its relationship with fluctuating temperatures.

8.5. Discussion and conclusions

The ERT measurements obtained in the course of these experiments show that internal moisture behaviour is rather complex. However, the visualisation of resistivity, as shown in the 2D transects, can aid our understanding of moisture behaviour on a spatial and temporal scale. During the capillary rise experiment without heating, moisture ingress commenced at the surface rather than the centre of the block because of the weight of the stone sample, which pressed the bottom surface down onto the tray rendering it relatively inaccessible for the surrounding water. Under constant laboratory conditions the capillary rise stabilised after 28 days. Under accelerated drying conditions, with constant moisture ingress at the base, the capillary rise height of the wetting front was maintained and even increased. When the moisture source was removed, the height of the capillary rise declined from the surface inwards and dried faster at the front of the block than at the back (see figure 16). The surface and near-surface moisture measurements illustrate similar trends – with the bottom parts of the block remaining wet even while the top of the block dried out. The Protimeter, which measures to a depth of 25.4mm, shows more variable moisture trends than the FMW, capturing drying on the outer 10 and 20mm.

Figure 8.16 shows a schematic representation of the initial capillary rise within the block (A), the theoretical model of drying as would have been expected based on exposure of both the top and the sides of the block (B) and the moisture movement observed in the ERT readings (C).



A. B. C.

Figure 8.16: A. Capillary rise within the block with a = area covered by front transect, b = area covered by back transect, c = middle of block to which moisture rose before decelerating, d = movement of moisture at front of the block, e = movement of moisture at back of the block and f = line to which block was submerged in water. B. Theoretical drying of the block, dotted lines indicate stages of drying, order identified by numbers at the top of the block. C. Observed moisture behaviour showing drying of the surface of both the front and the back of the block and the height of capillary rise during heating.

The reason drying would be expected to occur in a semi-circular way starting at the top of the block on the heated side is because in that part of the block there are several sides which are open to the air and therefore can provide numerous outlets for moisture stored, which aids the rise of hot air containing evaporated moisture. In addition, this would be stronger at the heated side of the block due to higher evaporation rates from these heated and exposed surfaces (figure 8.16B). However,

what we instead found is that there is a strong drying curve at the surface of the block but an increase in moisture content further into the stone block (figure 8.16C). When looking at the correlation between the handheld moisture devices and the ERT measurements, the Protimeter showed a very limited image of the moisture movement, and in fact did not detect the rising moisture within the block but instead gave readings of decreasing moisture content at surface and subsurface level. The FMW, on the contrary, showed somewhat different trends at subsurface (10 millimetre) and lower subsurface (20 millimetre) level, especially at the bottom section of the block. The inverted behaviour of the front and the back of the block during the drying stage indicate the difference in moisture movement and the way the sides are affected by the presence or absence of increased temperatures by direct heat.

Based on the results presented, we have drawn the following conclusions. 1. Increased temperatures in a semi-controlled environment appear to increase capillary rise in porous material, where a constant moisture source is present. 2. Handheld moisture devices can be used to monitor the near-surface of a porous stone, but do not necessarily accurately reflect the complexity of the lower sub-surface processes. 3. At a near-surface level, as measured by the Protimeter and FMW, moisture shows erratic behaviour at the bottom of the block and more stable drying towards the top of the block.

This study seeks to increase our understanding of moisture behaviour in sandstone by simulating exposure of a porous stone surface to heating and drying in an intermediate complexity experiment under semi-controlled circumstances. We have shown that ERT can be used as a tool for furthering our understanding of moisture behaviour. We have illustrated the complex nature of moisture response to increased heating. In addition, we have highlighted the need for these intermediary experiments to further our understanding of moisture in field settings, which can be highly complex

and of direct influence on surface weathering and deterioration (Mol and Viles, 2010), where often moisture sources are of influence on the building stone or natural rock outcrop as well as heating and drying cycles through exposure to, or absence of, direct sunlight. The combination of ERT, FMW and Protimeter reading show, however, that despite these complexities we can monitor changes over time and space and increase our awareness of these issues in internal moisture behaviour and associated weathering.

8.6 References

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CHAPTER 9: SYNTHESIS AND CONCLUDING REMARKS

This research has tied together a number of different techniques and approaches to further our understanding of cavernous weathering of sandstone in semi-arid environments, through the further development and understanding of Electrical Resistivity Tomography as a geomorphological tool. The overall conclusion drawn is that internal moisture plays a significant role in determining the type of weathering of sandstone surfaces and changes in its nature over time. However, to examine this rather sweeping statement in more detail the themes brought up in the literature review will be discussed in relation to the findings.

9.1 Sandstone weathering and internal moisture

The literature review (chapter 2) showed that the role of internal moisture is largely still undetermined as surface measurements do not always indicate accurately the movement of moisture within the inner parts of the rock. The debates regarding case hardening and core softening are an illustration of this. However, ERT has provided a new geomorphological tool for investigating the distribution of moisture within the rock. This has become evident in chapters 5 and 6, which discussed the influence of near-surface moisture on flaking of the surface.

The investigations into internal moisture presented in chapters 5 and 6 have shown a number of complexities in which the moisture regimes interacts with surface weathering processes. The initial pilot study, as described in chapter 5, showed through ERT measurements that on the Clarens Sandstone internal moisture transport is a major contributor to the formation of surface weathering features. Initially, the conclusion was drawn that site 2, which has lower resistivity values throughout the ERT profiles, is the site with more severe weathering. Honeycombing at the bedding plane as well as flaking caused by sub-surface moisture accumulations where no outlet is present occurs

actively at both sites, as shown by the ERT profiles and field observations. This led to the development of a feedback model (see figure 9.1, reproduced from chapter 5), which summarizes the interaction between internal moisture and exposure and how these relate to surface-level weathering.

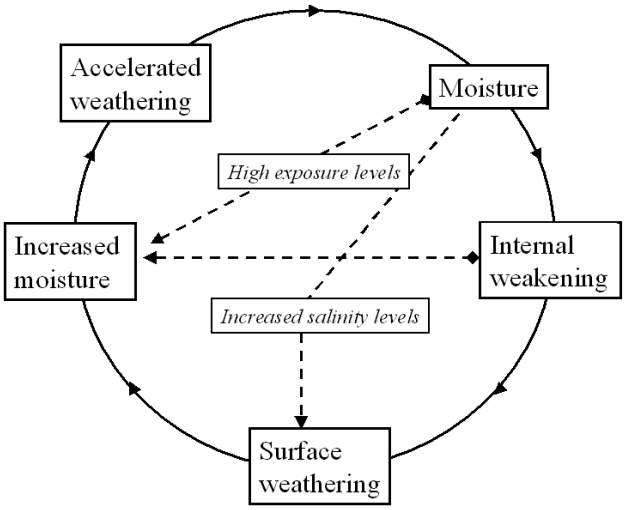


Figure 9.1: Internal moisture and surface weathering feedback model (replicated from chapter 5)

This model shows that high exposure levels lead to weakening of the rock surface which allows for increased moisture transport through the surface, unless the development of case hardening is more rapid, which leads to a higher internal moisture content. A change in any of the factors in this model could cause an acceleration or deceleration of weathering rates of the sandstone. The follow up research (see chapter 6) confirms this notion, as it proposed a non-linear relationship between international moisture regimes and surface weakening. In addition, moisture was found to be structurally beneficial to sandstone surfaces, as a completely dry surface looses part of its cohesion, while a saturated surface is also prone to disintegration of the mineral structure. A model was therefore developed based on slope stability, which works on the same 'optimum moisture content' principle to illustrate how moisture content affects surface strength (see figure 9.2, reproduced from chapter 6).

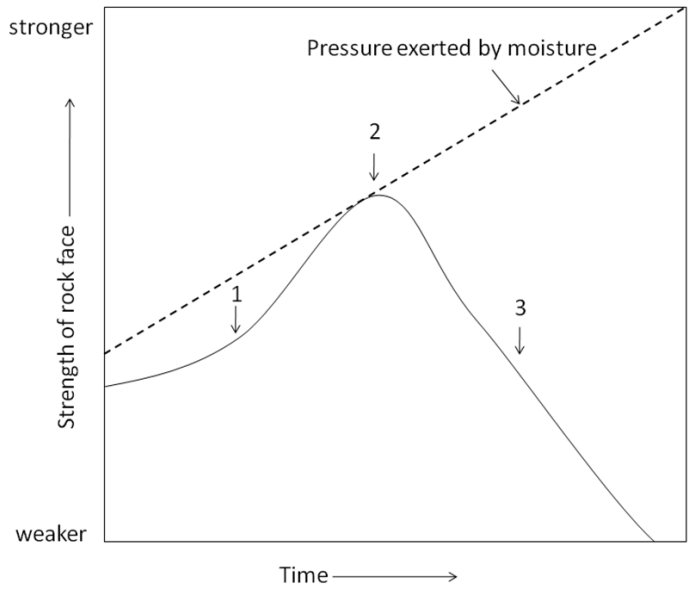


Figure 9.2: Model of optimum moisture content in relation to strength of rock face (replicated from chapter 6)

Combining these finding, the conclusion is drawn that internal moisture heavily influences sandstone surface strength but in a non-linear manner as it functions both as a facilitator of weathering processes and as an aid to surface cementation. The other factor to examine is to what extent moisture regimes are dictated by external factors such as exposure and temperature, and if these external factors are more influential in surface weathering than internal moisture.

9.2 Internal moisture and cavernous weathering

The second theme discussed in the literature review is the influence of internal moisture in particular on cavernous weathering, as discussed in chapter 7. There is still a division within the literature on the development of these features, whether case hardening or core softening is dominant. The extended number of sites surveyed in April 2009 sheds more light on this question.

Using a wider variety of shelters and assuming that the better developed and larger the shelter, the older the shelter, there were a number of complexities that arose both in the rock surface hardness database and the ERT measurements. There appeared to be no linear correlation between internal moisture regime and rock surface hardness across the sites. At individual transect level there are a number of correlations that can be identified. As demonstrated in section 4.4 of chapter 7, on a number of occasions there is a clear correlation between subsurface moisture accumulation and weakening of the surface. However, these correlations do not hold up on a larger scale when comparing ERT and Equotip across all sites surveyed. Looking at the broader scale, a model is proposed (see figure 9.3) which relates weathering, hardness and internal moisture regimes over the evolution of cavernous weathering features. The model covers one cycle of shelter development (see figure 9.3), which is thought to be repeated over time (Pope, 2011 pers. comm.). This model shows that there is a curve of weakening of the sandstone surface followed by strengthening as weathering crusts develop and the internal moisture regime adjusts. It is in fact the interplay of these two factors which determines the strength of the rock surface within the Clarens sandstone, not merely the external factors which have been correlated to degree of rock surface weathering.

The combination of all field results shows that there is a dynamic relationship between the development of the rock surface, such as case hardening, and internal moisture regimes. The interplay between case hardening and changes in internal moisture distribution appears to play a significant role in the formation of shelters, confirming that it is not just the presence of internal moisture but the distribution and changes therein that are of importance in sandstone surface weathering.

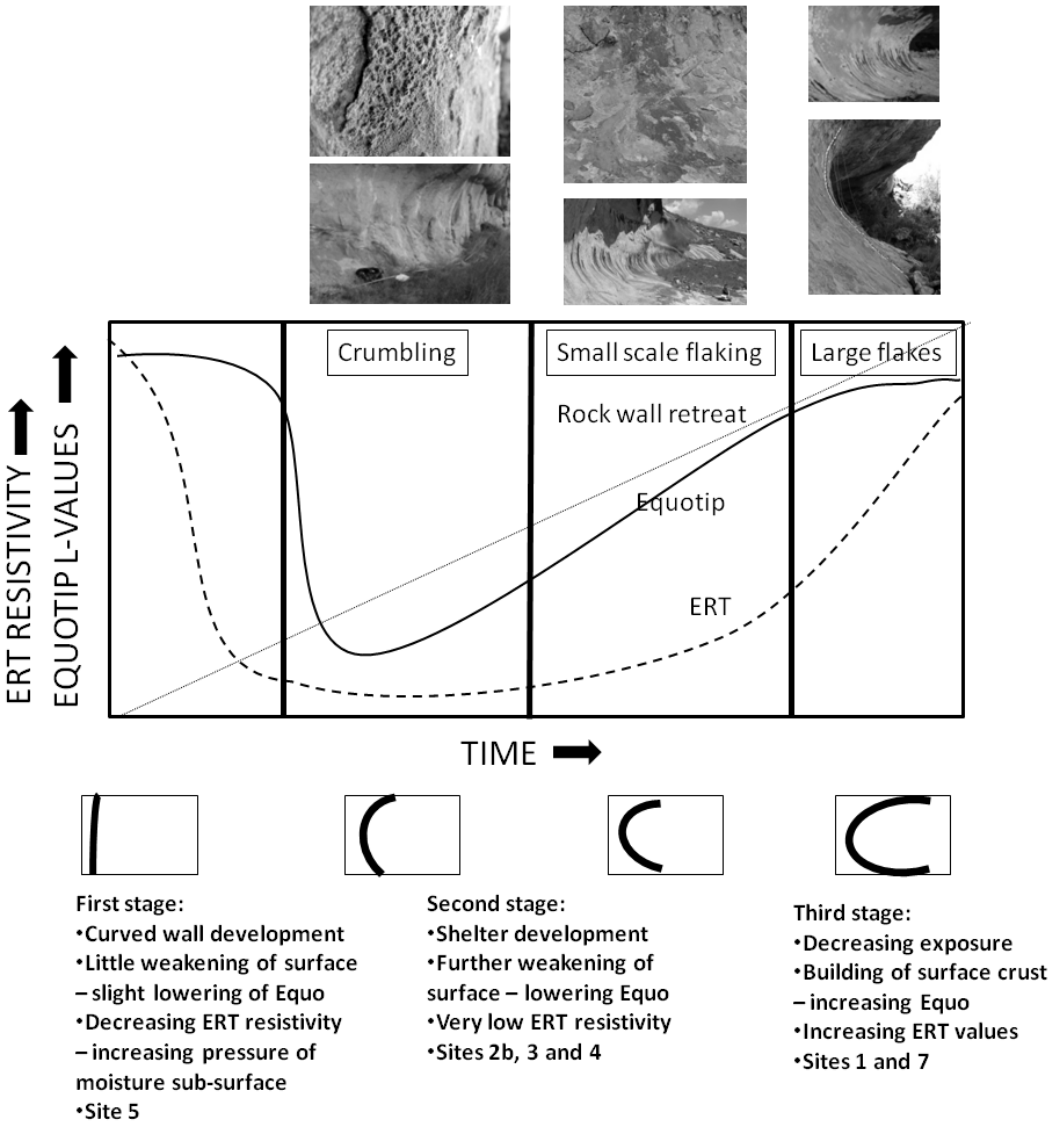
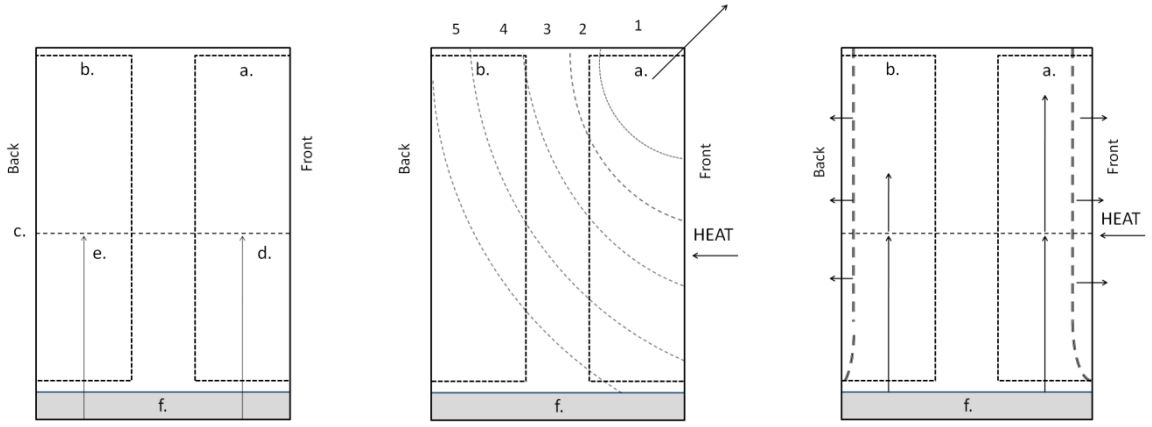


Figure 9.3: Model of the dynamic relationship between rock surface hardness, weathering and internal moisture set within the development of a rock shelter (replicated from chapter 7)

9.3 Internal moisture movement and temperature; lessons learned

One of the underlying issues of the fieldwork which was not resolved was the influence of temperature on internal moisture behaviour. As installing internal temperature logging equipment was impossible in the GGHNP, a semi-controlled experiment was conducted in the laboratory to

simulate the influence of temperature on internal moisture. Monitoring capillary moisture behaviour under both ambient and increased temperatures showed how moisture moves through a porous material and confirms the non-linearity of moisture regimes under realistic conditions. Accelerated drying produced enhanced capillary rise, until the moisture source at the base of the stone block was removed, when surface drying occurred although much of the internal portions of the block remained wet. These laboratory findings have implications for natural situations where groundwater enters a rock wall, and capillary rise is influenced both by groundwater ingress and the drying rate on one or more external surfaces. Deep-seated wetness may remain, and be important for subsequent surface weathering, even when the surface is dry. This is confirmed by the measurements of the handheld moisture meters, as they showed that the internal moisture behaviour does not correlate with the % moisture readings at surface level; both the FMW and Protimeter reported a drying of the stone which is contradictory to the moisture behaviour found within the ERT readings. This was confirmed by my findings, summarized in figure 9.4 (reproduced from chapter 8).



A. B. C.

Figure 9.4: Schematic representations of (A) capillary rise, (B) predicted drying behaviour and (C) observed drying behaviour (replicated from chapter 5)

These findings support the conclusion that even though there are a number of handheld devices available for investigating internal moisture, ERT has a significant advantage over these as it measures moisture distribution rather than only its manifestation at surface level which may not be representative of the internal moisture regime. This research also successfully showed that ERT can be used to monitor complex field observations to predict moisture movement by using it to monitor moisture behaviour under semi-controlled conditions.

On the other hand, the laboratory test also revealed the origins of a number of complexities within internal moisture; it shows that the interaction between a moisture source, such as groundwater, capillary ingress of moisture and the ensuing interaction with the stone surface is connected and responds to changes in environmental conditions such as temperature. This in itself is not a groundbreaking discovery, but these new measurements with ERT can pinpoint the nature of these interactions and show that the distribution of internal moisture cannot necessarily be understood by only using surface and subsurface measurements. They also show the importance of capillary movement of moisture, which is a process often encountered in field situations, but still poorly understood in terms of its place within the complexities of internal moisture behaviour.

9.4 ERT as a geomorphological tool

Based on the results obtained both in the laboratory and field a number of successful applications of ERT within weathering research have been shown that ERT can be instrumental in understanding weathering processes and rock wall retreat. The field research showed that internal moisture distribution and intensities varied significantly not only between sites but also between site transects. The rock surface hardness measurements, in this thesis used as an indication of surface weathering as previously reported in various studies (see chapter 2 for more details), showed a link

with subsurface moisture accumulations and changes therein. This indicates that the combination of the Equotip and ERT can be a very valuable contribution to investigations into weathering.

In addition to contributing to weathering research, the results of this series of studies can also be used to further our understanding of Rock Art deterioration and the role ERT can play in conservation and management. The results show that ERT is a valid method for identifying subsurface moisture accumulations, which were shown to affect rock surface hardness and weathering. It can thus also be used to identify the Rock Art areas at risk of further deterioration or future deterioration.

9.5 Contributions and broader implications of this research

This research deals with a number of aspects of weathering research, technological advances and its wider implications for both geomorphology and heritage research. It shows that the advances made in using and understanding ERT as a geomorphological tool can significantly contribute to our understanding of internal moisture and our subsequent understanding of rock surface weathering. This research has shown that internal moisture is a very complex and dynamic system, responsive to change in environmental circumstances (see chapter 8) and has a direct influence on surface weathering (see chapter 7). The monitoring approach taken in this research has illustrated the small scale complexities of drying and capillary behaviour of internal moisture.

9.5.1. Implications for sandstone weathering research

As noted previously, moisture has been acknowledged to be a key factor involved in weathering (Hall, 1986; Hall and Hoff, 2002; Sass, 2005; Warke *et al*, 2005). A number of laboratory and field tests have confirmed that moisture exerts dynamic influence on the rate and nature of weathering,

and can also be involved in surface cementation and hardening (Pel *et al*, 1996; Theoulakis and Moropoulou, 1997; Sass and Viles, 2006). ERT provides a new insight into the mechanisms of weathering processes, as it enables mapping and monitoring of internal moisture at a resolution which cannot be obtained by point-specific moisture probes for example. It can be used in the laboratory for experiments under fully- of semi-controlled circumstances, but can then be transferred into the field for 'real life' observations and experiments. As Smith (1994) notes: *There is a need, therefore, for more precise and consistent methods of assessing surface and internal changes in rock properties consequent upon weathering. Ideally, such methods should be applicable under both field and laboratory conditions to permit work to be integrated between the two situations* (p.55). This bridging of laboratory and field measurements is one of the greatest strengths of ERT as a geomorphological tool, as it is applicable both in a laboratory setting and in the field on a number of scales. The understanding of capillary moisture movement found in the laboratory (see chapter 5) have been applied directly to the findings at Site 3 (GGHNP, see chapter 9) where high exposure to sunshine and wind lead to an extremely dry surface but a relatively wet subsurface, which would not have been detected by moisture meters that penetrate only the near-surface.

This thesis shows that using ERT in combination with Equotip gives a new insight into weathering; the relationship between rock surface hardness and internal moisture is a central theme to the argument presented in this research. As chapter 9 argues, the dynamic relationship between rock surface hardness and internal moisture is integral within shelter formation. Chapter 8 shows that the relationship between moisture and rock surface hardness is non-linear as moisture can have both a weakening and strengthening role through its complex relationship with weathering and hardening processes. In a comparison with 'optimal moisture content' such as is found in slope stability research, the results of the GGHNP fieldwork showed that the non-linear correlation between surface strength and moisture content could be founded on the same principle; too little moisture causes a loss of cohesion between the sandstone grains, too much moisture causes high

pressure between the grains, resulting in loss of cohesion and subsequent weathering. However, when an 'exactly right' amount of moisture is available it could result in an increase in surface strength. This new insight into weathering was carried into the further research of development of cavernous weathering over time.

9.5.2. Implications for landscape development research

This research shows that internal moisture plays a substantial role in weathering of sandstone surfaces. It has shown that ERT is a very valuable tool for increasing our understanding of internal moisture as the influence of this moisture is not based merely in the subsurface but instead the accumulations and pathways it forms further into the rock mass appear to be of more importance than previously acknowledged. This has a larger implication for landscape development research as the differential and cavernous weathering of sandstone is responsible for a wide range of landforms in semi-arid areas around the world. As Wells *et al* (2008) state: [There is a] *renewed demand for more quantitative rock weathering data, which include not only the cumulative levels of debris produced over time, but also information about the manner in which weathering rates change over time. This information is of particular importance in weathering-limited erosion scenarios in which landform evolution is dictated by the rate at which fine transportable sediment is generated from the breakdown of surface rock material* (p.1047). This thesis shows that based on the measurements taken in the GGHNP the type of material removal from the surface in cavernous weathering is noticeably dependent on the internal moisture regime and its interaction with the surface. When applying this model to other research areas it of course needs to be adjusted for rock material and environmental regimes in the particular area investigated but it does show that this new understanding of the role of internal moisture can be used to increase our understanding of sandstone weathering, weathering rates and surface material removal.

9.5.3. Implications for heritage conservation research

As mentioned in chapter 2, weathering of rock and building stone is a wide-spread problem that can be identified in virtually any environment. A wide variety of approaches is available to investigate sandstone heritage deterioration, but one of the factors often mentioned in research results is the influence of drying behaviour on surface weathering (see for example Zhang *et al*, 2010), where uncertainty over internal moisture regimes and drying of the subsurface prevents decisive exclusion or inclusion of this process as an important factor in surface deterioration. ERT can provide a far more detailed insight into the drying regimes of these sites,

In addition, the consequences of surface weathering are perhaps greatest for heritage that is directly placed on the surface such as rock engravings and paintings, or decorative features on buildings. Once the surface deteriorates the overall structure may still be standing but the detail is irrevocably lost. In the case of San Rock Art, once the surface has detached the painting cannot be restored. This loss of San Rock Art was recorded in the GGHNP, and shows the importance of understanding surface weathering processes in conservation of especially *in situ* heritage.

9.6 Future research

A number of further questions have arisen from this research. Chapter 5, for example, showed the influence of temperature changes on capillary rise. The further implication of this is that with future climate change and its associated changes in temperatures and rainfall regimes over the next 50 to 100 years, a significant change in internal moisture regimes could potentially be detected in sandstone, both in natural outcrops and as a building material. The consequences for our built heritage could be significant, especially in light of the evidence presented in this thesis that internal moisture plays a significant role in weathering of sandstone. However, to make confident statements on the influence of changing climate regimes on internal moisture a number of longer

term laboratory tests need to be performed, most noticeably a monitoring and climate simulation experiment, linked to specific places and sandstone types. In addition, fluctuation in groundwater levels and precipitation provide additional complicating factors, which need to be investigated in more detail. Modifying internal moisture regimes might make a contribution to the conservation of fragile rock art, and certainly knowledge of internal moisture regimes should be taken into account when designing conservation strategies.

There are also a number of conceptual models proposed in this thesis which need to be investigated further. First of all, the 'optimum moisture' model needs to be quantitatively investigated to determine what the optimal moisture content is for the stability of a sandstone surface, and at which point moisture content, or lack therefore, is detrimental to the surface. Similarly, a model of weathering changes over times has been proposed in chapter 7, which needs to be investigated in more detail to understand the rate of these processes and how much material is lost. A combination of laser-scanning, to determine surface material loss, and ERT would be beneficial for our further understanding of the influence of internal moisture on sandstone.

Additional factors such as temperature, silicate content and salt content changes are known to affect resistivity measurements (Cassiani *et al*, 2006; de Franco *et al*, 2009; Kemna *et al*, 2002) need to be considered when interpreting ERT measurements. Future work therefore needs to be undertaken which measures the quantitative influence of these factors on ERT measurements, providing calibration curves for known saline content, temperature and silicate content.

These are just two examples of future research that could be undertaken, to build on the observations made in this research that ERT is a very effective tool for weathering research, and geomorphological research as a wider discipline, and the array of rock types, scales (micro-, meso- and macro rock surface scale), as well as monitoring on a longer time scale, can be extended to further our insight into weathering mechanisms.

9.7 References

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