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THE GEOLOGY OF MONTSERRAT, BRITISH WEST INDIES.

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ABSTRACT.

The island of Montserrat lies towards the northern end of the Lesser Antilles. It is made up of the products of five major and three smaller, parasitic volcanic centres. The four oldest volcanoes occur in the northern half of the island. Products of these volcanoes include andesitic lavas and pyroclastics but there is a lack of unreworked fragmental deposits and primary volcanic structures so that it is difficult to reconstruct the volcanic history of these centres. It appears however that the Harris-Bugby Centre, where a two-pyroxene andesite lava gave a K-Ar age of 4.1 m.y. is the oldest volcano on Montserrat. Silver Hill where a late-stage (?) lava has a K-Ar age of 1.5 m.y. is older than the Centre Hills and Carabald Hill should probably be regarded as a parasitic centre of the Centre Hills in view of the similarity of the products and state of erosion of the two volcanoes.

The oldest volcano in the south of Montserrat is South Soufriere Hill, where eruptions may have begun as much as 1.6 m.y. ago. The products of this volcano include basaltic lava flows and a well-exposed sequence of andesitic and basaltic pyroclast falls, known as the White River Pyroclast Fall Series. Ultrabasic cumulate blocks occur within an andesite block fall of the White River Pyroclast Fall Series. It is thought that the lava flows and pyroclast falls built up a cone-shaped strato-volcano with a large central crater. Late in the history of South Soufriere Hill two basic domes were extruded within the crater and their extrusion destroyed most of the crater wall and much of the eastern flank of the strato-volcano. The intrusion at Roche's of a body of basic two-pyroxene andesite of similar composition to the domes at South Soufriere Hill may also have occurred about this time. Among deposits disturbed by this intrusion are a group of tuffaceous limestones which on palaeontological grounds are thought to be about 40,000 yrs. old. Because of the compositional similarity of the Roche's Intrusion and the South Soufriere Hill domes and because the intrusion has affected deposits which are similar to South Soufriere Hill pyroclast falls the Roche's Centre is probably a subsidiary centre of South Soufriere Hill.

The earliest events at the Soufriere Hills included the extrusion of two domes of two-pyroxene andesite and associated pyroclast flow eruptions. These were followed by the extrusion of at least two domes of hornblende-hypersthene andesite and charcoal from a pyroclast flow believed to have been associated with one of these domes gave an age of $23,568 \pm 736$ yrs. St. George's Hill which erupted large quantities of hornblende-hypersthene andesite pumice falls may have been active as a subsidiary centre on the north west flank of the Soufriere Hills about this time. Sometime after the extrusion of the hornblende-hypersthene andesite domes violent pumice flow eruptions gave rise to the formation of English's Crater. Charcoal from one of the pumice flows has given an age of $18,390 \pm 360$ yrs. Late stage events at the Soufriere Hills include the extrusion of the Castle Peak hornblende-hypersthene andesite dome within the crater and this may be related to the breaching of the east wall of the crater. Minor eruptions of pyroclast flows and pyroclast falls have occurred since the formation of Castle Peak and charcoal from the most recent of these has been dated at A.D. 1646 ± 54 yrs. Although there have been no recorded eruptions at the Soufriere Hills solfataric activity has been continuous in historic time and three periods of unusually intense seismic and solfataric activity have occurred within the last 70 years.

An estimate of the relative volumes of rock types on Montserrat shows that andesite (96.5%) greatly predominates over basalt (3.3%) and dacite (0.2%). Basalts occur only at South Soufriere Hill where they account for about 35% of the total volume. South Soufriere Hill with its ultrabasic cumulates, basalts, basaltic andesites and andesites resembles Mt. Misery, St. Kitts or the Soufriere, St. Vincent. The other Montserranian volcanoes and most volcanoes in the Lesser Antilles have erupted nothing but andesite.

The Montserrat basalts and andesites have many petrographical features in common with other calc-alkaline lavas. Plagioclase which is the most abundant phenocryst mineral has highly calcic cores ($\sim \text{An}_{85}$) which may reflect initial crystallisation under high water vapour pressures. Olivine ($\sim \text{Fo}_{75}$) was apparently the first phenocryst to

form in the basalts. There is some evidence of a reaction relation between olivine and liquid to produce hypersthene but olivine is more often surrounded by clinopyroxene coronas than by hypersthene rims. Magnetite which is more abundant in the basalts than the andesites may also have been an early phase to separate. Pyroxene phenocrysts in the basalts and andesites show complex interrelationships. There is, however, no evidence to suggest a reaction relationship between augite and liquid to give hypersthene. Instead clinopyroxene probably reacts with liquid to give hornblende, which will account for the antipathetic relationship between these minerals in the Montserrat lavas.

Microphenocrysts in the lavas have different compositions and properties to the phenocrysts and are believed to have crystallised at higher levels in the crust probably close to the surface. Phenocrysts which initially formed deeper in the crust may undergo additional crystallisation at this stage.

A notable feature of the groundmasses of the Montserrat lavas is the abundance of tridymite and cristobalite, which appear to have crystallised at a very late stage, perhaps from fluids trapped in lavas at the time of their eruption. A few lavas contain quartz rich mica-bearing aggregates which have a similar mode of occurrence to tridymite and cristobalite in the other rocks. The mica is probably phlogopite.

Disequilibrium petrographic features are common in the Montserrat lavas. Lowering of water vapour pressure may account for the resorption of quartz, hornblende and calcic plagioclase at shallow depths. Oscillatory zoning in plagioclase might reflect small fluctuations in water vapour pressure but is probably best explained in terms of a diffusion-supersaturation theory.

Four groups of xenoliths were recognised on Montserrat. Ultrabasic cumulates composed of unzoned crystals of sodic anorthite ($\sim \text{An}_{90}$), aluminous amphibole, olivine ($\sim \text{Fo}_{75}$) and magnetite occur within andesitic pyroclastics of the White River Pyroclast Fall Series. They have probably formed by the crystallisation of basaltic magma under high water vapour pressures at depths of 76-8 km. Rare doleritic blocks also occur in andesitic horizons of the White River Pyroclast Fall Series. Cognate xenoliths of

basaltic composition are found in andesitic lavas and represent accumulations of minerals which occur as microphenocrysts in the host rock together with a few "older" phenocrysts. Metasedimentary and metavolcanic blocks were also found on Montserrat.

Forty-five new major element analyses together with new determinations of 13 trace elements in 13 rocks and $\text{Sr}^{87/86}$ ratios in 7 rocks are presented along with some older analytical data. These data suggest that the Montserrat lavas form a closely related series of rocks. The rocks of South Soufriere Hill however, differ from those of the other Montserranian volcanoes in that their SiO_2 range is larger and the South Soufriere Hill andesites are slightly depleted in total iron, MgO , TiO_2 and V and slightly enriched in Na_2O and Al_2O_3 relative to andesites from the other volcanoes.

Petrochemically, the Montserrat lavas resemble those from most of the other islands in the Lesser Antilles, especially St. Kitts. However they have less K_2O , Rb, Ba and Cr and more Na_2O , V, Co and Cu than lavas from St. Lucia and lower $\text{Sr}^{87/86}$ ratios and smaller amounts of radiogenic lead than lavas from St. Lucia and Dominica. The Montserrat lavas also bear an overall chemical resemblance to lavas from other calc-alkaline suites but they are somewhat depleted in TiO_2 , Rb, Sr, Ba, Ni and Cr and enriched in Al_2O_3 and CaO compared with most calc-alkaline lavas especially those from continental areas. Basalts from Montserrat contain slightly more K_2O than most high alumina basalts but the Montserrat andesites are considerably depleted in K_2O relative to most andesites.

The fundamental process in the petrogenesis of the Montserrat lavas is believed to involve the partial melting of oceanic tholeiite, or its metamorphosed equivalent along the Benioff Zone beneath the Lesser Antilles. Oceanic tholeiite is a suitable parent for the Montserrat and the Lesser Antillean lavas in terms of composition and availability. The only difficulty is that the Lesser Antillean lavas, particularly those from St. Lucia and Dominica are so enriched in the large and highly charged cation elements and radiogenic nuclides compared with oceanic tholeiite that an extra source for these appears to be required. Relatively small amounts of alkali basalt,

oceanic sediment and detritus from South America or the Lesser Antilles may be carried into the upper mantle and melted with the oceanic tholeiite and these are possible sources of the "missing" elements and also of water.

The composition of the magmas resulting from the melting of material along the Benioff Zone will vary depending on the physical conditions. Low temperatures and hydrous conditions will favour the production of andesitic liquids whereas dry melting and high temperatures will tend to produce basaltic liquids. As the arc evolves the tendency is probably towards wetter melting conditions as more material from the arc or more oceanic sediment does down the Benioff Zone.

As the magmas generated along the Benioff Zone ascend to the surface they may be modified by a number of secondary processes. These include fractional crystallisation, wallrock reaction, assimilation and gas transfer.

There is evidence in the Lesser Antillean rocks for at least two periods of fractional crystallisation. One of these occurs near the surface, at low pressures and probably has little fundamental petrogenetic effect. The other, which occurs deeper in the crust (? 6-8 km.) involves the separation of sub-silicic aggregates from basaltic magma and is probably instrumental in producing andesites at certain volcanoes in the Lesser Antilles, like South Soufriere Hill, Montserrat and Soufriere, St. Vincent.

The relative importance of the other "secondary" processes is rather difficult to assess. Wall rock reaction does not appear to be very important within the mantle but may occur within the crust. Gas transfer is likely to be quite important especially in water rich magmas and may be in some measure responsible for the erratic behaviour of certain elements notably K_2O in the Lesser Antillean lavas.

The compositional variation within the Lesser Antilles may to some extent reflect differences in the relative importance of different "secondary" petrogenetic processes at different places. The restriction of chemically "evolved" lavas to the islands of St. Lucia, Dominica, and ?Martinique in the central portion of the arc may, however, reflect the fact that these islands are the oldest in the Lesser Antilles although their position relative to the direction of underthrusting of oceanic crust might also be important.



FRONTISPIECE

English's Crater and the Castle Peak Dome from the east. Perche's Dome is in the foreground on the left of the picture.

English's Crater is horse-shoe shaped being open on the east. In this picture the crater walls are partly obscured by the Castle Peak Dome but the northern and southern walls can be seen. The south wall is made up largely of the truncated flank of Galway's Dome and ends a little to the west of Perche's Dome. The white patch on the north wall marks the site of the Cow Hill Soufrieres.

English's Crater is occupied by the Castle Peak Dome, which has a strikingly irregular morphology with two prominent lava towers forming its summit. The youthful morphology of Castle Peak contrasts sharply with the regular, more mature outline of Perche's Dome. Recent pyroclastic deposits, some of which are probably associated with the formation of the Castle Peak Dome make up most of the foreground of the picture.

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CHAPTER 1.

THE OXFORD UNIVERSITY DEPARTMENT OF GEOLOGY RESEARCH PROGRAMME IN THE WEST INDIES.

This study of the geology of Montserrat forms part of a programme of volcanological and petrological research in the Leeward and Windward Islands, initiated by the late Professor L. R. Wager and Dr. G. M. Brown of Oxford University, together with Dr. G. R. Robson of the Seismic Research Unit, University of the West Indies, Trinidad. The project began in 1960 and was financed by a special grant from D.S.I.R., which terminated in 1968.

The principal aim of the programme has been the elucidation of the geological history, petrology and geochemistry of some of the active and recently active volcanic centres in the Lesser Antilles. The information thus obtained, together with the geophysical data for the Caribbean area which has become available since the beginning of the nineteen fifties, has thrown light on problems of fundamental interest to geologists, such as the development of island arcs and the petrogenesis of andesites.

Three regional studies have been carried out by research students at the Department of Geology and Mineralogy of Oxford University. In addition to the author's work on Montserrat, Dr. P. E. Baker has described "The Geology of Mount Misery Volcano, St. Kitts" (1963) and Dr. J. F. Tomblin "The Volcanic History and Petrology of the Soufriere Region, St. Lucia" (1964). Dr. J. F. Lewis carried out a more specialised mineralogical and petrological study on the plutonic blocks of the Soufriere Volcano, St. Vincent. (Lewis, 1964).

The present study was begun in December 1966 and the author carried out field work in Montserrat from January until May 1967. Before arriving on Montserrat, the author was given a useful introduction to the problems involved in mapping recent volcanic terrain, by Drs. Robson and Tomblin on St. Vincent, by Dr. Tomblin on St. Lucia and by Dr. Baker on St. Kitts.

Although the programme of research outlined above has now ended at Oxford University, it is being continued at Durham University, under Professor G. M. Brown. Dr. Tomblin is now Head of the Seismic Unit in Trinidad and is at present engaged on geological work in Grenada and St. Vincent.

The first geological work was done in 1964 at St. Vincent, where the geology of the island was studied. This was done by Dr. Tomblin and his colleagues, who were assisted by local geologists. The results of this work are given in a report published in 1965.

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CHAPTER 2.

THE LESSER ANTILLES

2.1 BATHYMETRY OF THE EASTERN CARIBBEAN.

The Lesser Antilles (Fig. 1) are a chain of islands linking the northeast of Venezuela with Puerto Rico and the Greater Antilles. The bathymetric map of the Eastern Caribbean (Fig. 2) shows that the islands of the Lesser Antilles form the highest points on a series of arcuate ridges, convex towards the Atlantic.

Barbados, which is composed of a thick series of Eocene flysch deposits, overlain by deep water marls and Pleistocene coral limestone, lies on the outermost ridge. The Barbados Ridge, which is separated from the main arc of the Lesser Antilles by a trough over 6,000 ft. deep, dies out northwards.

The main ridge describes a smooth curve from Grenada northwards as far as Saba and the islands on it are composed of Tertiary and Quaternary volcanic material. The crest of the ridge lies at about 2,000 ft. below the islands, which rise to heights of between 3,000 ft. and 5,000 ft. above sea level, so that the individual volcanic piles rise from 5,000 to 7,000 ft. above the general level of the ridge. The slope of the ridge is considerably steeper on the western side than on the eastern.

North of Dominica the main ridge splits into two parts. The outer part of the ridge reaches the surface in a series of low-lying islands known as the "Limestone Caribbees" since they are composed mainly of limestone with some older Eocene to Miocene volcanic material. These islands (Desirade, the eastern half of Guadeloupe, Antigua, Barbuda and the Anguilla group) stand on broad submarine platforms, less than 600 ft. deep. They are separated from the volcanic islands of the Leeward Islands by relatively shallow water, not exceeding 3,000 ft. in depth. To the north and east of the limestone islands, in contrast, the sea floor slopes steeply away into a south-eastward extension of the Puerto Rico Trench and depths of over 18,000 ft. are recorded less than 50 miles from the east coast of Guadeloupe.

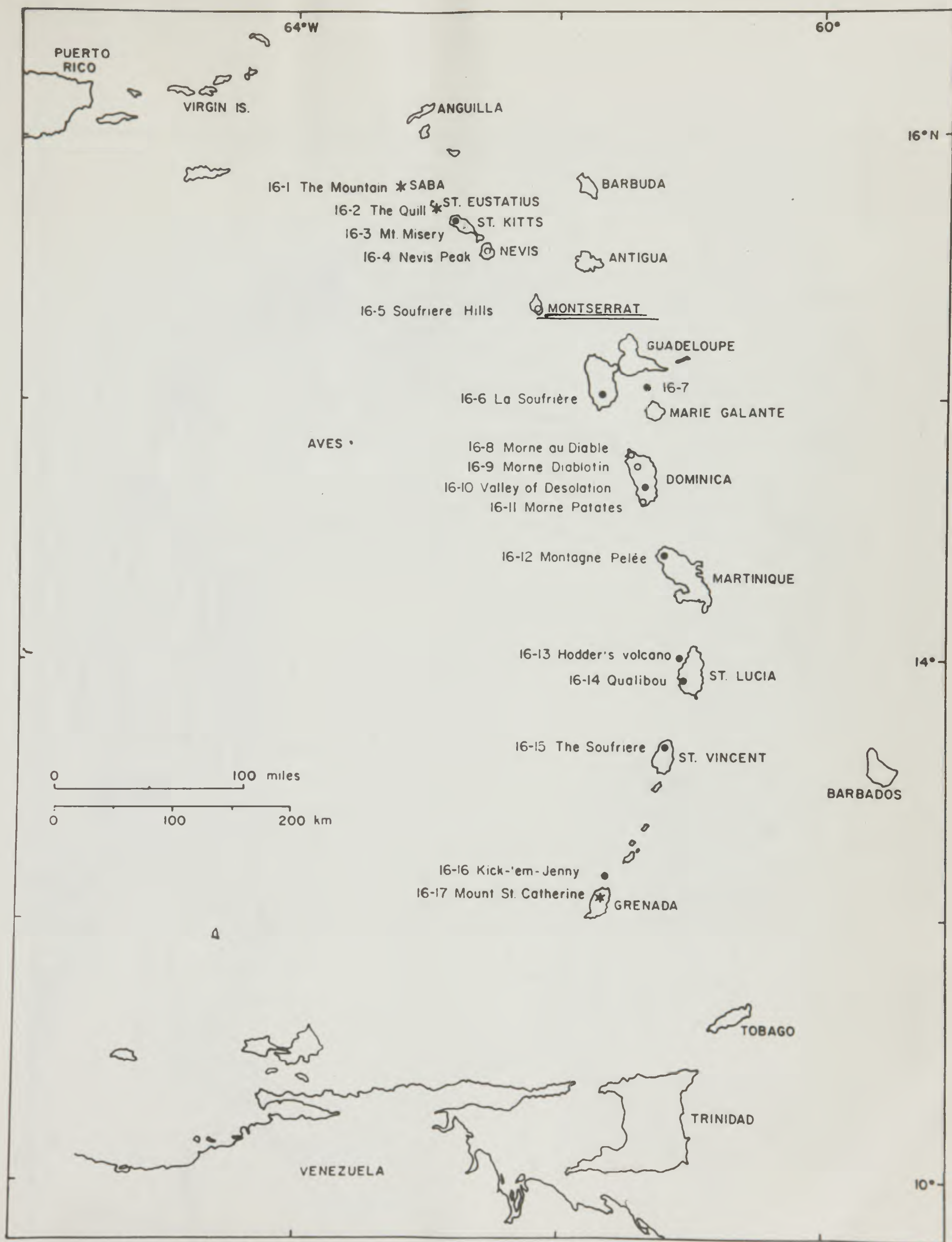


FIGURE 1.

Map of the Lesser Antilles showing the location of active and recently active volcanoes (after Robson and Tomblin, 1966).



FIGURE 2. Bathymetry of the Eastern Caribbean (after Hess, 1966).

About 150 miles west of the Lesser Antilles is another ridge which runs more or less parallel to the main volcanic arc. In general this ridge, known as the Aves Swell, lies at a depth of between 3,000 and 6,000 ft. below sea level but it reaches the surface at its northern end in the tiny island of Aves.

2.2 GEOPHYSICAL DATA.

The earliest geophysical work in the Caribbean area is that of Hess (1938). Hess made a gravity survey of the Eastern Caribbean and his work showed a belt of negative anomalies along a line connecting the Puerto Rico Trench with the Barbados Ridge and a line of positive anomalies along the volcanic island chain. More recent gravity and magnetic measurements in the Lesser Antilles (Masson Smith and Andrew, in press) confirm the general picture established by Hess but have revealed minor breaks and steps in the general level of the positive anomaly. They note that the profile along the volcanic arc is dissected by a number of E.-W. trending gravity lows. To explain the positive gravity anomaly Masson Smith and Andrew postulate the existence of a 100 km. wide arcuate slab of lower crustal material (basalt?) with its upper surface at a depth of 5 to 10 km. The thickness of the slab must be at least 10 km.

Officer et al. (1957, 1959) have reported seismic velocity data for the Caribbean crust and some of their results are shown in Fig. 3. Officer, et al. (1959) noted the general similarity between the velocity profiles of typical oceanic areas and those of the Caribbean Sea but pointed out the following differences. In oceanic sections there is an abrupt velocity change from about 6.5 to 8.1 km./sec. at the crust-mantle boundary, whereas in the Caribbean there is usually material with velocity 7.1 to 7.7 km./sec. between the mantle and the 6.5 km./sec. crustal material. The Caribbean crust also tends to be thicker, with lower velocities in the upper part than a typical oceanic section. Beneath the volcanic islands of the Lesser Antilles, the intermediate (4-5.5 km./sec.) and the high (6-6.5 km./sec.) crustal velocity layers are thicker and rise closer to the surface.

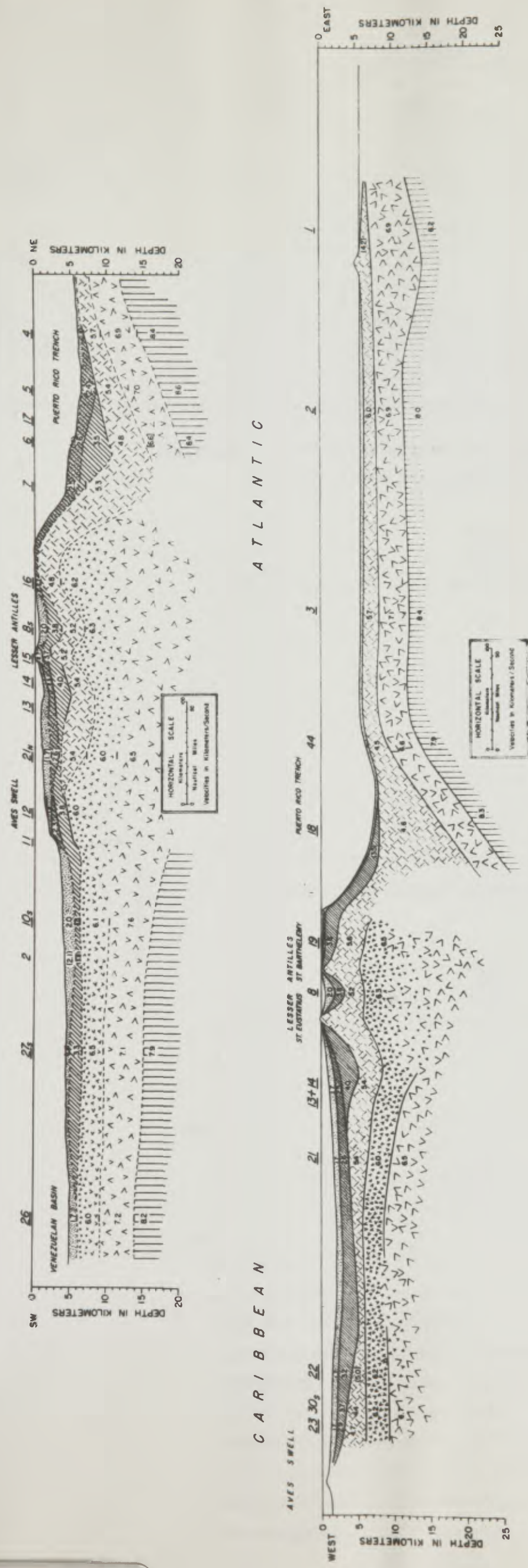


FIGURE 3. Seismic refraction profiles through the Lesser Antilles (after Officer et al., 1959). The upper section runs approximately S60°W - N60°E crossing the Lesser Antilles near the southern end of Nevis and Barbuda. The lower section runs approximately N-S. (For full details see Officer et al., 1959, FIGS. 2, 14 and 15).

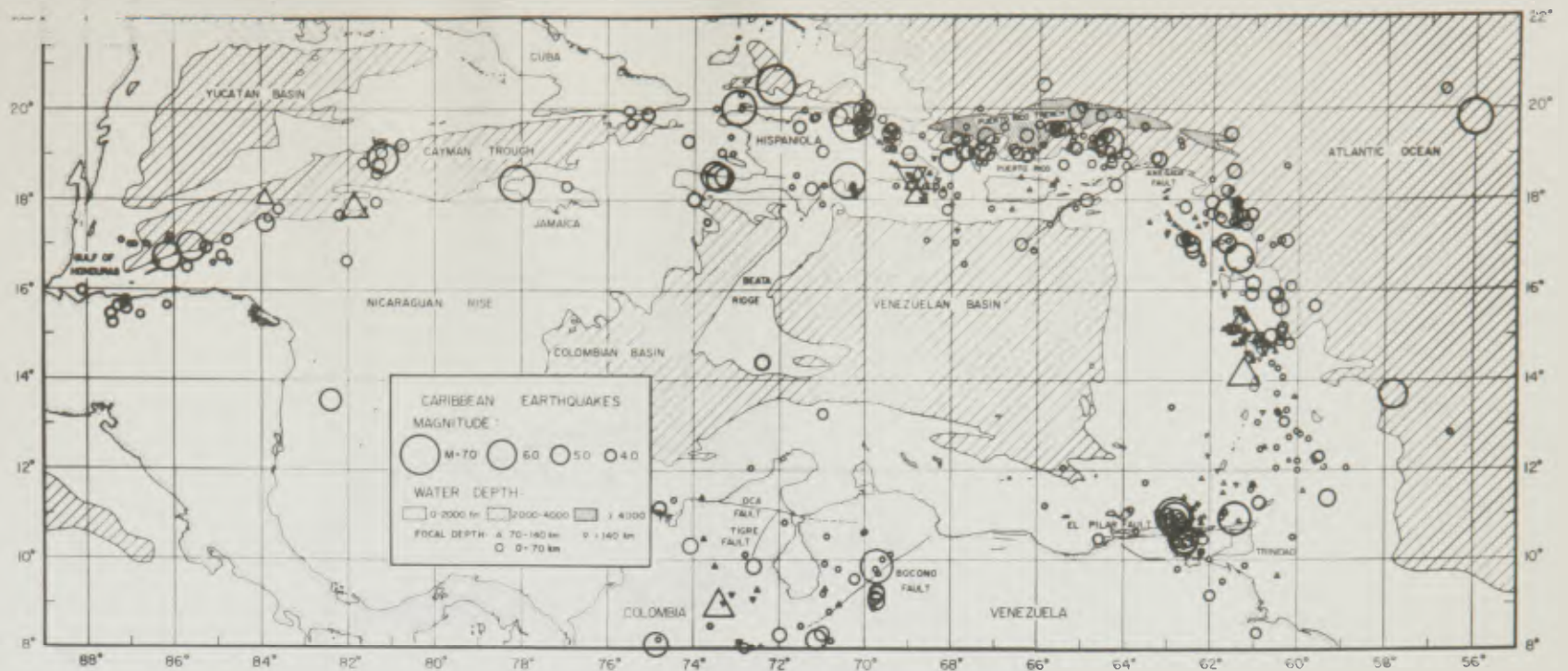
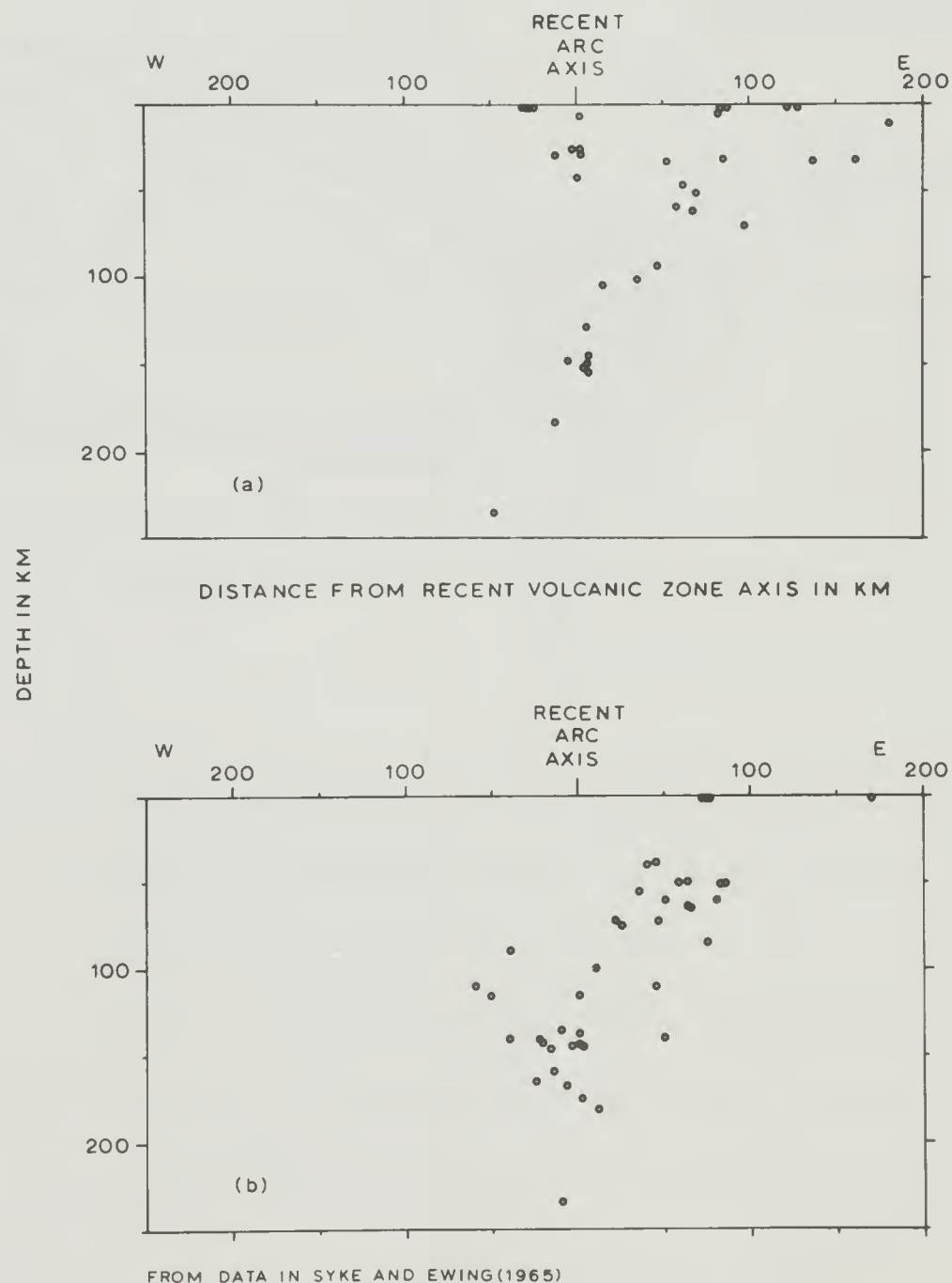


FIGURE 4A. Earthquake epicentres in the Caribbean region from 1950 through 1964 (after Sykes and Ewing, 1965).



4B East-west vertical sections of hypocentres of seismic disturbances in the vicinity of the Lesser Antilles based on data in Sykes and Ewing (1965). Upper section is for seismic disturbances north of 16°N latitude showing two classes of earthquake. Lower section for disturbances between 14° and 16°N latitude showing only a single class of earthquakes.

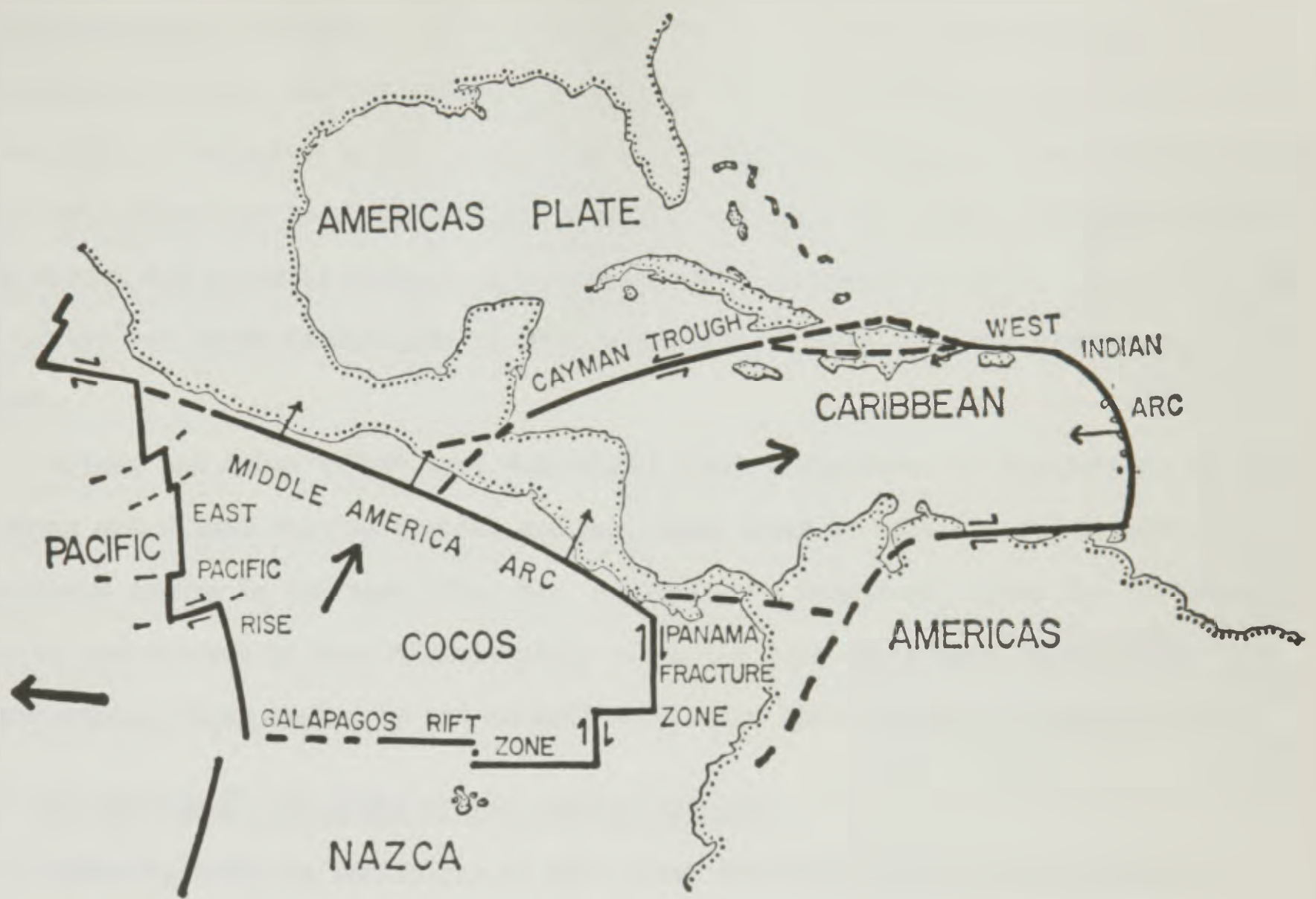


FIGURE 5.

Map showing plates of lithosphere in the Caribbean area and the relative motion of these plates (after Molnar and Sykes, 1969). The bold arrows show the directions of motion of these plates with respect to the Americas plate. The fine arrows show the direction of relative motion of plates at the boundaries.

A considerable amount of data on earthquakes in the Caribbean area is now available (Sykes and Ewing, 1965; Seismic Unit, unpublished data). This data (Fig. 4A) may be summarised as follows. A Benioff Zone exists along the entire length of the Lesser Antilles (Fig. 4B) but a number of shallow focus earthquakes occur, particularly to the north of Dominica, which do not lie within the Benioff Zone. Some of the shallow focus earthquakes may be related to the movement of magma near active volcanoes (see p. 66) while others are probably related to movements along transverse faults. In general the part of the arc north of Dominica is more seismically active than the southern part of the arc.

Molnar and Sykes (1969) have determined focal mechanisms for earthquakes in the Caribbean and Middle America regions and have used these to work out the pattern of lithosphere plates in the area (Fig. 5). According to Molnar and Sykes the Caribbean plate is underthrust by the Atlantic plate along the line of the Lesser Antilles, this underthrusting being marked by the Benioff Zone which dips westwards beneath the arc.

2.3 THE STRUCTURAL EVOLUTION OF THE LESSER ANTILLES.

Opposing views on the origin of the Lesser Antilles were expressed by two of the earliest writers on the subject. Spencer (1895) regarded the Lesser Antilles as relics of a formerly widespread land area while Hill (1905) thought that the islands were simple volcanic piles built up from the ocean floor. Woodring (1928, 1954) suggested that a submarine ridge below the present islands was formed during the Laramide (Upper Cretaceous) orogeny which affects the rocks of Venezuela and the Greater Antilles and Schuchert (1935) supported this view. Schuchert proposed (op. cit., p.393) that the islands of the Lesser Antilles grew as "young volcanic islands parasitic upon the folded formations making up the much older basement of the (Greater) Antillean and Venezuelan mountain chains."

Officer et al. (1959) however concluded that the Caribbean was not a drowned continental area but an altered oceanic region and there is a good deal of agreement at the present time that island arcs develop across oceanic crust (e.g. Hess, 1960;

(Isacks et al., 1968). Thus, Hill's views on the formation of the Lesser Antilles may be essentially correct even though the geophysical evidence indicates that the Caribbean crust is no longer strictly oceanic. The exact nature of the relationship of the Lesser Antilles to the Greater Antilles is however, still uncertain.

Spilites, keratopyres and low-grade metamorphics, which have given an unconfirmed upper Jurassic age ($142.2 \pm 9.7 \times 10^6$ yrs.) have recently been discovered on Desirade, a small island which lies to the east of Guadeloupe (Fink, 1968). The similarity of these rocks to rocks of the same age in the Greater Antilles led Fink to suggest that the Greater Antilles and the Lesser Antilles had a similar origin and once formed a continuous feature. The continuity of the negative gravity anomaly belt from Hispaniola to Trinidad supports this suggestion. However, in view of the very small outcrop of spilites and keratophyres in the Lesser Antilles compared with their great volume in the Greater Antilles and the fact that the upper Jurassic age has yet to be confirmed, this correlation should still be regarded as tentative. In addition, a continuous line of volcanicity along the Greater and Lesser Antilles in the Cretaceous implies a plate arrangement that is substantially different from the one that exists at the present time (Fig. 5).

Fink (1968) further suggests that in the Lesser Antilles the submarine spilites and keratophyres were followed by sub-aerial, calc-alkali lavas of Cretaceous to Eocene age, erupted from volcanic centres, forming an arcuate row extending from Grenada to Anguilla and probably through the Greater Antilles as well. It must be admitted, however, that whereas andesites of this age are abundant in the Greater Antilles and in the "Limestone Caribbees" the evidence for the existence of pre-Miocene volcanics on the islands south of Martinique is fairly scanty.

Evidence for the evolution of the Lesser Antilles in post-Eocene times is more substantial. During the middle Eocene to middle Oligocene, volcanic activity came to a halt in the Greater and Lesser Antilles and widespread uplift, erosion and deposition

of shallow water limestone occurred. The formation of the Barbados Ridge by the folding of a thick sedimentary succession, which had accumulated at the southern end of a deep sea trough which in Eocene times lay to the east of the Lesser Antilles, may also have occurred at this time (Chase and Bunce, 1969). When volcanic activity was renewed, during the middle to late Miocene, it was continuous from Grenada to Saba. From Dominica to Grenada the older and younger arc axes are superimposed but some eastward translation of the segment of the pre-Miocene arc north of Dominica occurred during the cessation of tectonic and volcanic activity so that the younger arc axis lies to the west of the older arc axis in this region. Fink (1968) has attributed this translation to movement along a major transverse fault, north of Dominica. He suggests that the development of this fault was accompanied by the development of other transverse structural features.

The Lesser Antilles has been the site of some famous historic volcanic activity, notably the 1902 eruption of Mont Pelé in Martinique and the 1902-03 eruptions of the Soufriere volcano, St. Vincent. Several other active or recently active volcanoes occur along the arc (Fig. 1) and details of activity at these volcanoes are summarised by Robson and Tomblin (1966).

CHAPTER 3.

MONTSERRAT - GENERAL BACKGROUND.

Montserrat (lat. $16^{\circ}45'N.$, long. $62^{\circ}10'W.$), lies towards the northern end of the Lesser Antilles, in the north-eastern Caribbean (Fig. 1).

The island, which has an area of approximately 39 sq. mls. is pear-shaped, being elongated in a N.-S. direction. It is $10\frac{1}{2}$ miles long and has a maximum width of six miles.

Montserrat was one of islands discovered by Columbus in 1493. It is thought that the rugged topography of the island reminded him of Montserrat in north-east Spain. Montserrat is also known as the Emerald Isle, not only because of its lush vegetation, but because the first European settlers were Irish. They colonised Montserrat in 1632. The French occupied the island for a short period between 1664 and 1668 and again, very briefly, in 1782. Montserrat was finally ceded to Britain by the Treaty of Versailles (1783).

The present population (12,000 in 1960) of Montserrat is largely African Negro. Of the original inhabitants of Montserrat little trace now remains of the Caribs, who inhabited the island before the European settlement, or of the Arawaks who were their predecessors. The Irish influence is more obvious. Irish placenames e.g. St. Patrick's Village, Galway's Soufriere, Cork Hill Village, Kinsale are common and many of the present inhabitants have Irish surnames e.g. Blake, Sweeney, Gibbons.

Of the total area of Montserrat only about 7,000 acres are cultivated. The coarse mudflow and pyroclast flow deposits which cover much of the island make large-scale cultivation, especially of sugar cane, very difficult. A small amount of sugar cane is, however, grown and is used mainly for distilling rum. Conditions are better suited to the production of cotton but the chief variety "Montserrat sea island" is difficult to spin and the amount of cotton grown has declined in recent years. Vegetables

are being grown on an expanding scale, and exports, to other islands in the area, are increasing.

Although agriculture on Montserrat is developing at a rather slow rate the economic growth rate has averaged over 8% p.a. since 1964. This is due, largely, to an increase in tourism and also to the development of the island as a resort for retired North Americans.

Climate.

Montserrat is the wettest of the Leeward Islands with an average annual rainfall of 62 in. The rainfall is predominantly orographic (though depressions, drifting south-eastwards from the direction of Puerto Rico and Florida give occasional cyclonic rainfall) and precipitation is considerably higher on the more elevated areas of the island (probably 120 in. on Chance's Peak). In the low-lying areas around Silver Hill and the southern part of South Soufriere Hill rainfall is less than 40 in. p.a. and semi-arid conditions prevail. The leeward (western) side of the island is wetter than the windward. September, October and November are generally the wettest months of the year (Hardy, 1922).

Montserrat lies within the Trade Winds Belt and the prevailing wind direction is from the east, with a north-easterly bias in winter and a south-easterly bias in summer. Hurricanes and cyclones sometimes occur in early autumn.

The Trades have a moderating influence on the climate. The average annual temperature is 79°F. and the monthly averages vary only from 76°F. in January to 81°F. in July. Humidity is generally about 75%.

Vegetation.

The higher slopes of Centre Hills, Soufriere Hills and South Soufriere Hill are covered by dense tropical forest, including many cabbage palms, tree ferns etc. On parts of the lower slopes of the mountains and on some of the smaller hills (Carabald Hill and Silver Hill) there is a considerable growth of scrub. Cacti and thorn of

various kinds are quite common, in the drier parts of the island and especially around the south coast.

The lower hill slopes are extensively cultivated. A law, aimed at soil conservation, prohibits cultivation above 1,500 ft.

CHAPTER 4.

MONTSERRAT - GEOLOGICAL BACKGROUND.

4.1 PREVIOUS GEOLOGICAL WORK.

By far the most important previous geological work on Montserrat is that of MacGregor (1938). MacGregor was the first geologist to carry out systematic field work and geological mapping on the island. Recorded geological work prior to MacGregor's study includes that of Nugent (1811), Waller (1883), Sapper (1903), Lacroix (1904) and Hardy (1922). The interested reader is referred to the original papers or to MacGregor's summary (MacGregor 1938, pp. 9-12).

MacGregor's work was a direct result of the organisation by a Royal Society Committee, under the chairmanship of Sir G. Lenox-Conyngham of an expedition to Montserrat in 1936. The aims of the expedition were to study the geology of Montserrat and to investigate the earthquakes and soufriere activity which had caused considerable damage and alarm during 1934 and 1935. MacGregor was accompanied on the expedition by Dr. C. F. Powell as physicist and the results of their work are to be found in MacGregor (1936, 1938), Powell (1938) and Lenox-Conyngham (1937).

MacGregor (1938) recognised the existence on Montserrat of seven separate volcanic centres and on the basis of the field relations of their products he was able to work out the relative ages of the centres. He described the products of each centre in some detail but did not attempt to make detailed reconstructions of the history of individual centres. MacGregor also classified and mapped the active soufrieres on the island.

In addition to his field work MacGregor made many important petrological observations on the Montserranian lavas. These include his descriptions of corrosion of feldspar phenocrysts; of oxidation and resorption phenomena in hornblende phenocrysts; of the nature of cognate inclusions in the lavas; and of the mode of occurrence and optical properties of tridymite and cristobalite in the groundmass of

the lavas. In addition, he presented seven chemical analyses of Montserrat rocks. Nockolds and Allen (1953) have determined trace element abundances in these analysed rocks.

Powell's report (1938) is concerned with the seismic crisis and is of less general interest to the geologist. With the somewhat primitive seismographs then available, the exact location of earthquake foci was difficult. Powell, however, found a significant concentration of foci at depths of between one and two kilometres beneath St. George's Hill, and another active belt, along a line running east-west through English's Crater and Castle Peak.

The eminent American volcanologist F. A. Perret visited Montserrat several times during the seismic crisis of 1934-36. His published account (Perret, 1939) contains much useful information on the earthquakes and activity at the soufrieres. He also made some important observations on the geology of the island. He maintained that the peaks of the Soufriere Hills (notably Gage's and Chance's Mountains) had the status of genuine pitons and he suggested that many of the fragmental deposits of the Soufriere Hills were "mud-lavas" (i.e. mudflows).

Martin-Kaye included a chapter on Montserrat in his "Reports on the Geology of the Leeward and British Virgin Islands" (1959). His account of the geology of the island is based largely on MacGregor's work and his geological map is essentially the same as MacGregor's, though modified slightly by air photograph interpretations. Martin-Kaye, however, gives a lot of new information on the active soufrieres, including temperature measurements, gas analyses of soufriere minerals and detailed maps. He quotes Robson and Willmore's (1955) measurements of heat flow at the Montserrat soufrieres.

In their account of the geology of Saba and St. Eustatius, Westermann and Kiel (1961) have included an account of the geology of the area around Roche's Bluff, Montserrat. They have described the palaeontology of the tuffaceous limestone. Westermann and Kiel consider the Roche's Bluff area to be a small centre of uplift

analogous to Brimstone Hill, St. Kitts or to the White Wall Formation of St. Kitts.

Robson and Tomblin (1966) summarised the geology of the Soufriere Hills and included a new geological map of the southern part of Montserrat, based on MacGregor's map with amendments by Robson. They suggested that the central nucleus of the Soufriere Hills represents the remnants of an early strato-volcano, the summit of which was removed to form English's Crater (see p. 49). Robson and Tomblin also gave an account of historic volcano-seismic activity at the Soufriere Hills centre. Shepherd, Tomblin and Woo (1969) have described the most recent seismic crisis, which occurred in 1966-67, in some detail.

In connection with the present study the writer has given a brief account of the geology of the southern part of Montserrat (Rea, 1968) and Shotton, Blundell and Williams (1968) have reported the date of charcoal collected by the writer from a Soufriere Hills pyroclast flow (see p. 60).

4:2 PHYSIOGRAPHY.

The island of Montserrat is made up of six distinct mountain masses, each of which is composed mainly of the products of a single volcanic centre, though it may include some pyroclastic material from neighbouring centres. The centres are from north to south, Silver Hill, Centre Hills, Carabald Hill, St. George's Hill, Soufriere Hills and South Soufriere Hill. Of these, St. George's Hill and Carabald Hill are believed on geological ground to be parasitic centres developed on the flanks of the Soufriere Hills and Centre Hills respectively but nevertheless these centres form distinct, though rather small physiographic units. On the other hand the Roche's Bluff Centre which is probably a late stage parasitic centre on the flanks of South Soufriere Hill does not form a unique physiographic unit partly because it has not completely penetrated the pre-existing cover and partly because it has been obscured by more recent deposits from the Soufriere Hills.

The six physiographic units are each characterised by their own system of consequent radial drainage with the ghauts (the local name for drainage channels) cutting back towards the summits of the hill. With the exception of the Soufriere Hills and South Soufriere Hill, the units are separated from one another by distinct hollows or areas of relatively low ground. South Soufriere Hill and the Soufriere Hills are rather indistinct units and are joined by a high col. Physiographic features of the individual volcanoes are described in the chapters on the field geology of Montserrat but one or two general points can be made here.

1. Silver Hill, Centre Hills, Soufriere Hills and South Soufriere Hill lie along an axis running approximately N.-S. This axis coincides with the axis of elongation of Montserrat and more or less follows the crest of the volcanic arc ridge.
2. In the south of the island there is a striking alignment of centres of volcanic activity along a W.N.W. - E.S.E. axis running from Carabald Hill to Roche's Bluff. Along this line are Carabald Hill, St. George's Hill, Gage's Dome, English's Crater, Castle Peak, Perche's Dome and Roche's. Chance's Dome and Galway's Dome are only slightly offset to the west of this line.

4.2.1 Submarine Features Around Montserrat.

Fink (1968) has compiled a detailed bathymetric map of the area around Guadeloupe (Fig. 6). This map shows three interesting features in the vicinity of Montserrat.

The Montserrat Sea Trough, a S.W. - N.E. trending feature to the west of Montserrat, is interpreted by Fink as the surface expression of a fault zone normal to the arc ridge crest. No obvious continuation of the Montserrat Sea Trough can be seen on or to the east of Montserrat.

The Montserrat Ridge lies just to the south of the Montserrat Sea Trough and is parallel to it. Again no obvious continuation of this feature is seen on Montserrat.

The Kahouanne Depression is an elongate depression, which runs from Basse Terre,

Guadeloupe to the S.E. corner of Montserrat. Paralleling the trend of the Kahouanne Depression and located on both sides of it are five sea knolls. Since the depression lies along the axis of the younger volcanic zone, Fink suggests that the sea knolls are volcanic in origin. Their alignment suggests extrusion along a crustal fracture between Basse Terre and Montserrat.

Fink's bathymetric map does not cover the area north of Montserrat but the Admiralty Chart of 1869 shows a gently inclined shelf around the northern part of the island (see MacGregor, 1938, p. 17). That this shelf implies submergence is indicated by the submarine extension of certain topographic features notably Bransby Point. According to MacGregor the products of the Centre Hills and Silver Hill volcanoes probably extended at one time as far as the present 35 m. submarine contour, which would mean that Silver Hill was originally a large volcano with a basal diameter of about six miles.

4:3 GENERAL GEOLOGY

MacGregor (1938) recognised the existence on Montserrat of seven volcanic centres. Of these, he considered (MacGregor, 1938, Table 1) Silver Hill to have been active in the late Miocene or early Pliocene - i.e. about ten million years ago. He believed that the other six centres were all active within Pleistocene or Recent times i.e. within the last 1.8 million years (Berggren, 1969). MacGregor suggested the following order of activity for these centres:- Roche's (oldest) - Centre Hills - Carabald Hill - South Soufriere Hill - St. George's Hill - Soufriere Hills.

Detailed field work and radiometric dating have shown that MacGregor's sequence of activity needs to be somewhat revised (see Tables 1 and 3). The oldest dated rocks on Montserrat - a series of two-pyroxene andesite lavas and agglomerates - occur in the area around Harris Village and Bugby Hole. This area apparently represents the eroded remnants of an old volcanic centre which was active over four million years ago (p. 22). Silver Hill, which is also considerably eroded is the next oldest

centre on the island and lava from Silver Hill has given a K-Ar age of around 1.5 million years. The products of Silver Hill are mainly two-pyroxene andesite lavas and agglomerates. A period of submergence may have occurred shortly after the end of activity at Silver Hill.

The Centre Hills volcano which occupies an area of about 12 sq. miles or approximately one third of the total area of Montserrat has given rise to a wide variety of products and may have been active over a longish period of time. Products of the Centre Hills include two-pyroxene andesite and hornblende-hypersthene andesite pyroclast flows, pyroclast falls, mudflows and some lava units. The products of Carabald Hill are very similar to those of the Centre Hills and it is probable that Carabald Hill was a small parasitic centre on the flanks of the Centre Hills.

Although products of the four centres mentioned above occupy over half the total area of Montserrat considerably less attention was paid to these centres than to the younger centres in the south of the island. One of the main reasons for this is that the products of the older centres have been subjected to widespread erosion and redistribution and the resultant lack of good sequences of primary deposits makes it virtually impossible to work out detailed histories for these volcanoes. In addition the Centre Hills is particularly inaccessible and there is a complete lack of recognisable large-scale volcanic structures e.g. craters or domes in the northern part of Montserrat.

The four younger centres in the south of Montserrat are more rewarding from the point of view of detailed field work and it has proved possible to reconstruct a fairly detailed history of volcanic events in this area. The oldest centre in the south of the island is South Soufriere Hill where there may have been two phases of activity the second of which probably started less than one million years ago. The early eruptions of South Soufriere Hill built up a large cone-shaped strato-volcano composed of basaltic and andesitic pyroclast falls and basalt lava flows. Activity at South Soufriere Hill ended with the extrusion of a large dome of two-pyroxene basalt lava, which destroyed the eastern flanks of the strato-volcano. The intrusion of a body of

basic two-pyroxene andesite lava at Roche's may be closely related to this final event at South Soufriere Hill. A tentative age of less than 40,000 years has been assigned to the Roche's intrusion on palaeontological grounds (p. 45).

Activity at the Soufriere Hills began with the extrusion of a series of domes, ranging petrographically from two-pyroxene andesite to hornblende-hypersthene andesite. The formation of these domes was probably accompanied by pyroclast flow eruptions. Later in the history of the Soufriere Hills a large crater was formed, its formation being accompanied by the eruption of pumice flows. Subsequent activity included the extrusion of a crater dome and associated eruptions, the most recent of which occurred 320 ± 54 years ago (see p. 64).

St. George's Hill, a small but active centre on the flanks of the Soufriere Hills gave rise to a large quantity of hornblende-hypersthene andesite pyroclast falls at a fairly late stage in the history of the Soufriere Hills.

In the following section on the field geology of Montserrat, the author has described the centres in their order of activity starting with the oldest except that St. George's Hill, which is older than the most recent eruptions of the Soufriere Hills, has been described in a separate chapter following the chapter on the Soufriere Hills.

TABLE 1. PROBABLE ORDER OF ACTIVITY OF THE VOLCANIC CENTRES
ON MONTSERRAT

VOLCANO	PROBABLE PERIOD OF ACTIVITY
Soufriere Hills	? 40,000 yrs. ago - present
St. George's Hill	? 25,000 yrs. ago
Roche's	? 40,000 yrs. ago
South Soufriere Hill (main period of activity)	? 1 m. - 40,000 yrs. ago
Carabald Hill	? 1 m. yrs. ago
Centre Hills	? 1 m. yrs. ago
South Soufriere Hill (early activity)	about 1.6 m. yrs. ago
Silver Hill	about 1.6 m. yrs. ago
Harris - Bugby	about 4.2 m. yrs. ago

SECTION TWO

SECTION TWO

THE VOLCANIC HISTORY OF MONTSERRAT

CHAPTER 5.

NOTES ON CLASSIFICATION.

5:1 NOTE ON THE NOMENCLATURE OF THE FRAGMENTAL DEPOSITS OF MONTSERRAT.

The primary fragmental deposits of Montserrat can be referred to two categories - pyroclast fall and pyroclast flow. The writer uses these terms in the sense of Robson and Tomblin (1966) who state (Introduction, p. IX) that "The term pyroclast is used to describe any fragmental material produced during a volcanic eruption; the term pyroclast fall is used to describe pyroclastic material, which is carried upwards away from the eruptive vent; the term pyroclast flow is used to describe pyroclastic material, which with gaseous material is carried downwards away from the eruptive vent," Pyroclast falls are well-stratified, well-sorted deposits which mantle older topography whereas pyroclast flows are unstratified, unsorted deposits which infill topographic depressions (Kozu, 1934; Kuno 1941).

The pyroclast flows on Montserrat are of two types. Pumice flows are composed of pumiceous blocks and fragments in a fine pumiceous matrix and by analogy with Komagatake (Kozu, 1934) are thought to have been erupted from an open crater. Pelean type pyroclast flows (Williams, 1957) contain both vesicular and non-vesicular blocks and fragments and by analogy with Mont Pelé (Lacroix 1904, Perret 1937), were erupted from craters, containing domes.

Pyroclast falls on Montserrat are less varied than the pyroclast flows. The term pumice fall has been used occasionally to describe pyroclast fall composed mainly of pumiceous fragments.

The writer has largely followed the nomenclature of Wentworth and Williams (1932) when describing pyroclast falls. He has, however, used the term block fall (rather than agglomerate or breccia) to describe pyroclast falls in which fragments of greater than 32 mm. diameter predominate. This allows the term agglomerate to be used non-specifically (see below).

Various types of secondary fragmental deposit, formed by the redistribution of primary volcanic material are recognised on Montserrat. These include:-

Mudflows - which form as dense suspensions of fragmental material in water. Mudflows are unsorted deposits which can be very difficult to distinguish from Pelean type pyroclast flows (see below).

Fluviatile deposits also result from the interaction of water and fragmental material but in this case the proportion of water to detritus is much higher than with mudflows. Fluviatile deposits are better stratified (sometimes cross-bedded) and better sorted than mudflows and included fragments tend to be rounded.

Talus deposits are block-rich deposits which form on the flanks of volcanic domes. Almost all the blocks are non-vesicular.

Agglomerate is the term used in the following chapters to describe block-rich fragmental deposits of uncertain origin.

5:2 NOTE ON THE CRITERIA USED TO DISTINGUISH PELEAN TYPE PYROCLAST FLOWS FROM MUDFLOWS.

In general, the recognition of the different types of fragmental deposits mentioned above does not present much difficulty. However, Pelean type pyroclast flows and mudflows which both give rise to unsorted, block-rich deposits of small volume and tend to infill topographic depressions are much harder to differentiate in the field. The following criteria have been used.

(a) The homogeneity of the included blocks.

MacGregor (1952) considers that the blocks in Pelean type pyroclast flows will vary in vesicularity and to some extent also in composition depending on whether they are derived from the hotter, gas-rich inner part of the dome, from the cooler gas-poor outer parts of the dome or from the fully consolidated debris on the surface of the dome. Thus Pelean pyroclast flows are somewhat inhomogeneous. However, deposits which show extreme heterogeneity are unlikely to be pyroclast flows and deposits containing a very high proportion of non-vesicular lava blocks are more likely to be mudflows or talus

deposits than Pelean pyroclast flows.

(b) Presence of charcoal.

Although carbonised wood occurs in some mudflows e.g. at Mt. St. Helens (Mallineaux and Crandell, 1962) and at Santa Maria, Guatemala (Sapper and Fermer, 1930) it is more common in pyroclast flows.

(c) Association with primary volcanic deposits.

Unsorted, block-rich deposits which occur in association with primary volcanic deposits are more likely to be pyroclast flows than mudflows, whereas similar deposits, occurring within a secondary e.g. fluvial succession are probably mudflows.

Even by using these criteria the author has not always found it possible to decide whether a particular deposit represents a Pelean type pyroclast flow or a mudflow. The measurement of the orientation of natural remanent magnetism (Aramaki and Akimoto, 1957) in some of the more doubtful deposits would help to decide their exact nature but unfortunately the author was not aware of this method when on Montserrat and so did not collect oriented blocks from the deposits.

In the following account the writer has used the terms mudflow and Pelean type pyroclast flow for many deposits where the evidence is suggestive rather than conclusive but in cases where the mode of origin of a block-rich deposit is particularly obscure he has used the term agglomerate.

CHAPTER 6.

THE HARRIS-BUGBY CENTRE.

Bugby Hole is a broad, U-shaped depression situated at the S.E. corner of the Centre Hills. South of Bugby Hole is a broad, steep-sided ridge - referred to here as Harris Ridge - which runs roughly E.N.E. through Harris Village. This area is topographically and petrographically distinct from the rest of the Centre Hills and probably represents the eroded remnants of an older volcanic centre.

Most of the exposures on Harris Ridge are of massive slabs and boulders of dark two-pyroxene andesite lava, which sometimes contains traces of olivine. Lava of similar composition is exposed south and east of the ridge at the bottom of Pea Ghaut. Often the lava boulders occur in very close proximity to one another, forming coherent structures, resembling lava flows. This is particularly noticeable in the road cuts along the main road from Plymouth to Blackburne Airfield and also in Pea Ghaut where two-pyroxene andesite lava extends for some distance along the floor of the ghaut. However the uniform petrography and chemistry (Table 12, Nos. 20, 21 and 23) of the lavas and the fact that lava is so abundant relative to pyroclastic material on the ridge suggest that Harris Ridge is a large homogenous lava body rather than composed of a number of lava flows.

The truncated knolls immediately to the north of the Harris Ridge are covered with boulders of two-pyroxene andesite lava and massive two-pyroxene andesite lava occurs in the north bank of Farm River. However, exposures of dark, well-consolidated agglomerate on the western side of these hills show that they are not composed entirely of solid lava. These dark agglomerates, which contain fragments of two-pyroxene andesite lava are common in Bugby Hole and also outcrop at the bottom of the N.E. corner of Harris Ridge.

Well-consolidated pumice beds were the only other deposits seen in the Harris-Bugby area. These beds occur at various places on the Harris Ridge and apparently

overlie the lavas. The pumice beds contain fairly large fragments of brownish, hornblende-hypersthene andesite pumice in a rather scanty fine-grained pumiceous matrix and are probably pumice falls. The pumice in these beds contains very small phenocrysts and is very finely vesicular. It differs from the pumice seen elsewhere in the Centre Hills or for that matter in the whole of Montserrat. It is more acid than the two-pyroxene andesite lavas of the Harris-Bugby area (Table 12, No. 41).

With the exception of the pumice beds the rocks in the Harris-Bugby area are very uniform petrographically which strongly suggests that they were derived from a common source. Whether or not the hornblende-hypersthene andesite pumice beds were also derived from the same source is not certain but the fact that pumice of this type is restricted to the Harris-Bugby area suggests that they may have been.

Two-pyroxene andesite from an exposure of massive lava, at least 80 ft. thick, in the north bank of Farm River, gave a K-Ar age of $4.31 \pm .22$ m.yrs. (J. C. Briden, pers. comm.), which is almost certainly older than the eruptions of Silver Hill (p. 24) or of the Centre Hills (p. 25).

CHAPTER 7.

SILVER HILL

7:1 STRUCTURE OF SILVER HILL.

Silver Hill (Plate 1A) is a maturely dissected volcanic mass rising to a height of 1,323 ft. a.s.l. Apart from the area immediately north of the summit where dips are steep (30°) the flanks of Silver Hill slope rather gently to the sea but the coast line is fringed with cliffs which reach a height of over 500 ft. at North West Bluff.

The terrain in the Silver Hill area is very rough and is broken up into several small hills separated by broad valleys. The broken-up nature of the country, especially on the west of Silver Hill led Martin-Kaye (1959 p. 84) to suggest that "appreciable faulting has taken place, apparently mainly of approximately E.-W. and N.E.-S.W. strike." Although this fragmentation might have been brought about by very strong dissection it is interesting to note that the Montserrat Sea Trough, considered by Fink (1968) to represent a fault zone has a N.E.- S.W. trend while the oldest volcanic structure on Montserrat, the Harris Ridge, runs from E.N.E. to W.S.W.

The drainage of Silver Hill has a roughly circular pattern and the ghauts are broad U-shaped depressions. Davis (1926) regarded the embayed valleys at Rendezvous Bay and Little Bay as evidence for submergence.

7:2 GEOLOGY OF SILVER HILL.

At present, products of the Silver Hill Centre occupy an area of about 3 sq. mls. but the original area may have been more like 30 sq. mls. (p. 15).

Massive two-pyroxene andesite lava and well-consolidated agglomerate containing blocks of two-pyroxene andesite lava make up virtually all the exposures on Silver Hill. Hornblende is very rare or absent in the Silver Hill lavas. Some of the lavas, especially near the summit of Silver Hill, are extensively oxidised but lower down e.g. in the sea cliffs the lava is relatively fresh. Two-pyroxene andesite lava from

the cliffs about 100 yds. S.W. of Pinnacle Rock gave a K-Ar age of 1.55 ± 0.21 m.y. (D. C. Rex, pers. comm.).

Apart from the lavas and agglomerates the only other deposits seen in the Silver Hill area are beds of yellow-brown andesite tuff, which are generally confined to the eastern sector of the hill but which also occur in the sea cliffs between Little Bay and Carr's Bay. These tuffs, which are very similar to deposits seen at the top of cliffs about $\frac{1}{2}$ mile south of Yellow Hole are almost certainly attributable to the Centre Hills volcano. The tuffs overlies the agglomerates and lavas of Silver Hill unconformably.

As MacGregor (1938, p. 19) has noted, the rocks of Silver Hill are rather like those of the central nucleus of the Centre Hills and the products of Silver Hill may have included a wide range of loose, fragmental deposits like those seen at present on the flanks of the Centre Hills. A similar situation may have existed at the Harris-Bugby Centre.

In any case dissection and erosion have been much more extensive at Silver Hill than at the Centre Hills and it is unlikely that this can be explained entirely by the difference in age of the two centres. After all Silver Hill was still active less than 1.6 m.y. ago and the Centre Hills show signs (extensive redistribution of fragmental deposits, lack of primary volcanic structures) of being a relatively old centre.

It is possible that a prolonged period of submergence, which occurred sometime after the end of activity at Silver Hill but before the start of activity of the Centre Hills, was a major factor in producing the different amounts of erosion at the two centres. Evidence for the submergence of Silver Hill has already been mentioned (p. 15, 23) and it is worth noting that the truncated eastern ends of the Harris Ridge and the hills immediately to the north were almost certainly formed by wave action. Apart from the submarine extension of the Bransby-Richmond ridge (p. 15) which may also be an older feature (p. 29) there is little evidence for submergence elsewhere on Montserrat. With the exception of the tuffaceous limestones at Roche's (p. 44) marine deposits are not seen on Montserrat. The presence of the tuffaceous limestones does not necessarily

imply submergence of the S.E. corner of Montserrat. It is more likely that the tuffaceous limestones were deposited in a sea, which was at approximately the same level as the present sea and that their present position is due to uplift associated with the intrusion of a body of lava (p. 47).

Convincing evidence for submergence is thus found only in deposits of greater age than the Centre Hills and the lack of erosion in the Centre Hills and younger centres is probably related to the fact that they were never extensively submerged. A contributory cause of the extensive erosion of Silver Hills may be the almost complete lack of vegetation on the hill.

CHAPTER 8.

THE CENTRE HILLS.

8:1 STRUCTURE OF THE CENTRE HILLS.

Like the Soufriere Hills, the Centre Hills consist of two distinct physiographic units - the central nucleus and the flanks (Plate 1B).

The central nucleus of the Centre Hills consists of a series of steep-sided peaks of massive andesite lava several of which are over 2,000 ft. high, the highest being 2,429 ft. a.s.l. The peaks are not apparently original volcanic features but have been isolated from the rest of the central nucleus by erosion. Another effect of the strong dissection of the Centre Hills has been the production in the summit area of a series of narrow, roughly N.-S. trending ridges.

The flanks of the Centre Hills are made up almost entirely of gently sloping fragmental deposits, mostly agglomerates but with some tuffs and pumice flows.

The drainage pattern of the Centre Hills is more mature than those of the Soufriere Hills or South Soufriere Hill centres and the valleys e.g. Soldier Ghaat and Bottomless Ghaat are U- rather than V- shaped.

8:2 GEOLOGY OF THE CENTRE HILLS.

The central nucleus of the Centre Hills is very inaccessible and exposure is poor but as far as can be seen it is composed mainly of massive hornblende-bearing two-pyroxene andesite lava.

Primary unreworkeed deposits are the exception on the flanks of the Centre Hills where agglomerates (mostly mud flows and water-lain deposits but probably including some Pelean type pyroclast flows) are more abundant than other types of deposit. The agglomerates show considerable variation, particularly in the type of blocks and the relative proportions of blocks and matrix. Some of the agglomerates have virtually no matrix at all (? talus deposits) and others (mud flows or pyroclast flows) have



PLATE 1A. Silver Hill from the south. Silver Hill is an old volcanic centre that has been broken up into several small hills, probably by faulting, but perhaps by strong dissection. Note the very scant vegetation on the hill.



PLATE 1B. Centre Hills from the north. Photograph taken from near Pinnacle Rock standing on well-consolidated agglomerate of the Silver Hill Centre. The sea cliffs are composed of Centre Hills pyroclastics and the hills in the middle distance are part of the central nucleus of the Centre Hills. The cloud-covered hill in the far distance is Perche's Dome of the Soufriere Hills.

abundant matrix. Blocks in the agglomerates are mostly of non-vesicular two-pyroxene andesite lava, often containing hornblende. Hornblende-hypersthene andesite blocks also occur. Centre Hills lavas can usually be distinguished from Soufriere Hills lavas of similar composition by the presence of a bluish-grey to greenish fine-grained felsitic matrix (MacGregor, 1938, p. 38).

Fine-grained tuffs, coloured yellow or red are interbedded with the agglomerates and are particularly conspicuous in the sea cliffs around the Centre Hills. The proportion of tuff to agglomerate apparently increases upwards in the Centre Hills successions. Mostly the tuffs show obvious signs of reworking e.g. crossbedding but in places they are finely bedded, well-sorted and even pisolitic and it is considered that almost all the tuffs originated as pyroclast fall deposits. The tuffs contain similar material to that found in the agglomerates, i.e. fragments of two-pyroxene and hornblende-hypersthene andesite together with detached crystals of plagioclase, hypersthene, augite and hornblende. Most of the fragments in the tuffs are pumiceous.

Pumice beds are also quite common among the Centre Hill deposits particularly towards the top of the successions. Good exposures are seen in the road cuts between Salem and St. Peter's, near St. John's and in the cliffs behind Woodlands beach. The pumice beds are usually quite well-consolidated with fragments of pumice up to 15 cm. in diameter in a comparatively abundant fine-grained matrix. The presence of the latter suggests that most of the pumice beds are pumice flows. The type of pumice varies considerably in the different exposures but in all cases the pumice had larger phenocrysts and was more vesicular than the pumice which occurs on Harris Ridge (p. 2/). Most of the Centre Hill pumices examined in thin section were two-pyroxene andesites, with or without hornblende.

CHAPTER 9

CARABALD HILL

9:1 STRUCTURE OF CARABALD HILL.

Carabald Hill (or Garibaldi Hill) is a fairly steep-sided, roughly cone-shaped feature that reaches a maximum height of 838 ft. a.s.l. The western boundary of the hill is composed of precipitous sea cliffs up to 250 ft. high, while to the north, the valley of Belham River separates the hill from the Centre Hills. A hollow separates Carabald Hill from St. George's Hill in the east and there is another hollow between the hill and the Bransby-Richmond ridge to the south.

9:2 GEOLOGY OF CARABALD HILL.

The majority of the exposures on Carabald Hill are of agglomerate containing blocks of two-pyroxene andesite (with or without hornblende) or hornblende-hypersthene andesite. Holocrystalline inclusions of basaltic composition are common in the Carabald Hill lavas (p. 109).

Thin yellow or red tuff bands containing small fragments of hornblende-hypersthene andesite pumice also occur. Many of these beds appear to be pyroclast falls. Pumice-rich deposits are also present and matrix-rich varieties may be pumice flows. Reworking of Carabald Hill material as river and mudflow deposit has been common. Minor faulting is seen in the cliff sections Fox's Bay and Old Road Bay.

9:3 RELATIONSHIP OF CARABALD HILL TO THE CENTRE HILLS.

Carabald Hill is very similar to the Centre Hills with respect to types of deposit and the maturity of its drainage system. The rock types associated with the two centres are also very similar. In view of these similarities it is considered probable that Carabald Hill and the Centre Hills are about the same age and that Carabald Hill formed as a small parasitic centre on the flanks of the Centre Hills.

2.4 THE BRANSBY-RICHMOND RIDGE.

The Bransby-Richmond ridge which lies just to the south of Carabald Hill is an elongate, flat-topped ridge which runs westwards for about $1\frac{1}{2}$ miles from Richmond Estate. The ridge also extends westwards for another two miles under the sea (p. 15).

Exposures in ghyats which cut the ridge show that it is made up almost entirely of well-consolidated agglomerate. The agglomerate is overlain in many places by a few feet of well-bedded pyroclast falls, attributed to the St. George's Hill centre (p. 72). Fragments in the agglomerate are mostly of two-pyroxene andesite and one exposure of massive two-pyroxene andesite lava, believed to be a lava flow was found on the ridge. Hornblende-bearing lavas are very rare on the ridge.

The relationship of the Bransby-Richmond ridge to Carabald Hill is rather obscure but certain features suggest that the relationship may be similar to that of Harris Ridge to the Centre Hills (p. 27). In both cases a ridge composed of two-pyroxene andesite lava and agglomerate (the proportion of lava to agglomerate is however much higher on Harris Ridge) is slightly detached from a larger, more varied centre whose products include a majority of hornblende-bearing lavas. Like Harris Ridge, the Bransby-Richmond ridge may be older than the adjacent centre, but the evidence is a good deal less convincing in this case and it is still possible that the Bransby-Richmond ridge may be directly related to the Carabald Hill Centre.

CHAPTER 10

SOUTH SOUFRIERE HILL.

10:1 PHYSIOGRAPHY AND STRUCTURE.

From the south west (Plate 2A) South Soufriere Hill looks like a simple volcanic cone with lava flows and pyroclast falls sweeping down from the summit area of the hill to the sea at angles of about 20° , but views from the north (Plate 2B) and east show that the structure of the hill is more complicated.

The summit area of South Soufriere Hill (Plate 2B) consists of a large, roughly circular, flat area to the south west of which a steep-sided, densely forested ridge rises over 250 ft. to the summit of the hill (2,479 ft. a.s.l.). The summit ridge does not extend far to the south but at the north west end it swings northwards and descends about 400 ft. to joint the col which separates the Soufriere Hills from South Soufriere Hill. The flat area east of the summit is the top part of a fairly steep-sided feature which is considered to be a complex volcanic dome (p. 39).

The physiography of South Soufriere Hill is rather complex but the geological evidence outlined below suggests that the hill consists of the remnants of a cone-shaped strato-volcano, the eastern side of which has been extensively altered by the extrusion of a later dome (or domes, see p. 39). The summit ridge is all that remains of what was originally a large crater.

In the following account of the geology of South Soufriere Hill the pyroclast fall succession of the strato-volcano is described first. The lava flows, agglomerates and mudflows of the strato-volcano are described next and related as far as possible to the pyroclast fall succession. Finally, the volcanic dome is described.



PLATE 2A. South Soufriere Hill from the south west. From this side South Soufriere Hill looks like a simple volcanic cone with lava flows and pyroclast falls (bottom left) sweeping down from the summit of the hill to the sea.



PLATE 2B. South Soufriere Hill from the north. The summit structure of South Soufriere Hill is complex. The flat-topped structure to the east of the summit is the Raspberry Hill Dome which is believed to have been extruded within the old crater of South Soufriere Hill. The growth of the dome destroyed most of the crater and much of the eastern flank of the old South Soufriere Hill strato-volcano. The steep-sided summit ridge of South Soufriere Hill is all that remains of the old crater wall.

10:2 THE WHITE RIVER PYROCLAST FALL SERIES.

The White River Pyroclast Fall Series, which attains a maximum thickness of 125 ft., is a series of andesitic and basaltic pyroclast falls. An almost complete succession can be seen in one exposure in the west bank of White River Ghaut, about 600 yards below the Great Alp Falls (Plate 3A). The bottom 30 ft. of the series are not seen here but are well-exposed further upstream. The upper beds of the series are inaccessible in the main exposure, but are conveniently exposed further downstream in White River Ghaut, along the track to Fergus Mount Estate and also along the track from O'Garra's to Triangle Rock.

The White River pyroclast fall series has been divided into three zones. These are:-

3. Basalt Cinder Zone
2. Andesite Coarse Fall Zone
1. Andesite Lapilli and Ash Zone

In most of the exposures of the pyroclast fall series only the top zone is seen. Exposures of the bottom two zones only occur where dissection is deep e.g. in White River Ghaut or Gingoe's Ghaut. A generalised vertical section through the White River Pyroclast Fall Series is given in Fig. 7 and a map showing the principal localities and approximate thicknesses in Fig. 8. Grain size distributions in beds of the White River Pyroclast Fall Series are given in Fig. 9. These deposits are all unimodal with the exception of 18620, which was collected from a very finely bedded part of the Basalt Cinder Zone and may well be a mixture of two beds.

10:2:1 The Andesite Lapilli and Ash Zone.

The beds of the Andesite Lapilli and Ash Zone are excellently exposed at the bottom of White River Ghaut for about 400 yds. below the Great Alp Falls (Plate 3B). The zone consists of 24 ft. of interbedded lapilli and red-brown semi-consolidated ash. Two beds of pale andesite pumice, which are each three feet thick, occur in the upper

Fig 7

THE WHITE RIVER PYROCLAST FALL SERIES
GENERALISED VERTICAL SECTION.

NOTE:— NUMBERS REFER TO ANALYSED
SPECIMENS (See Tables 12 and 13)

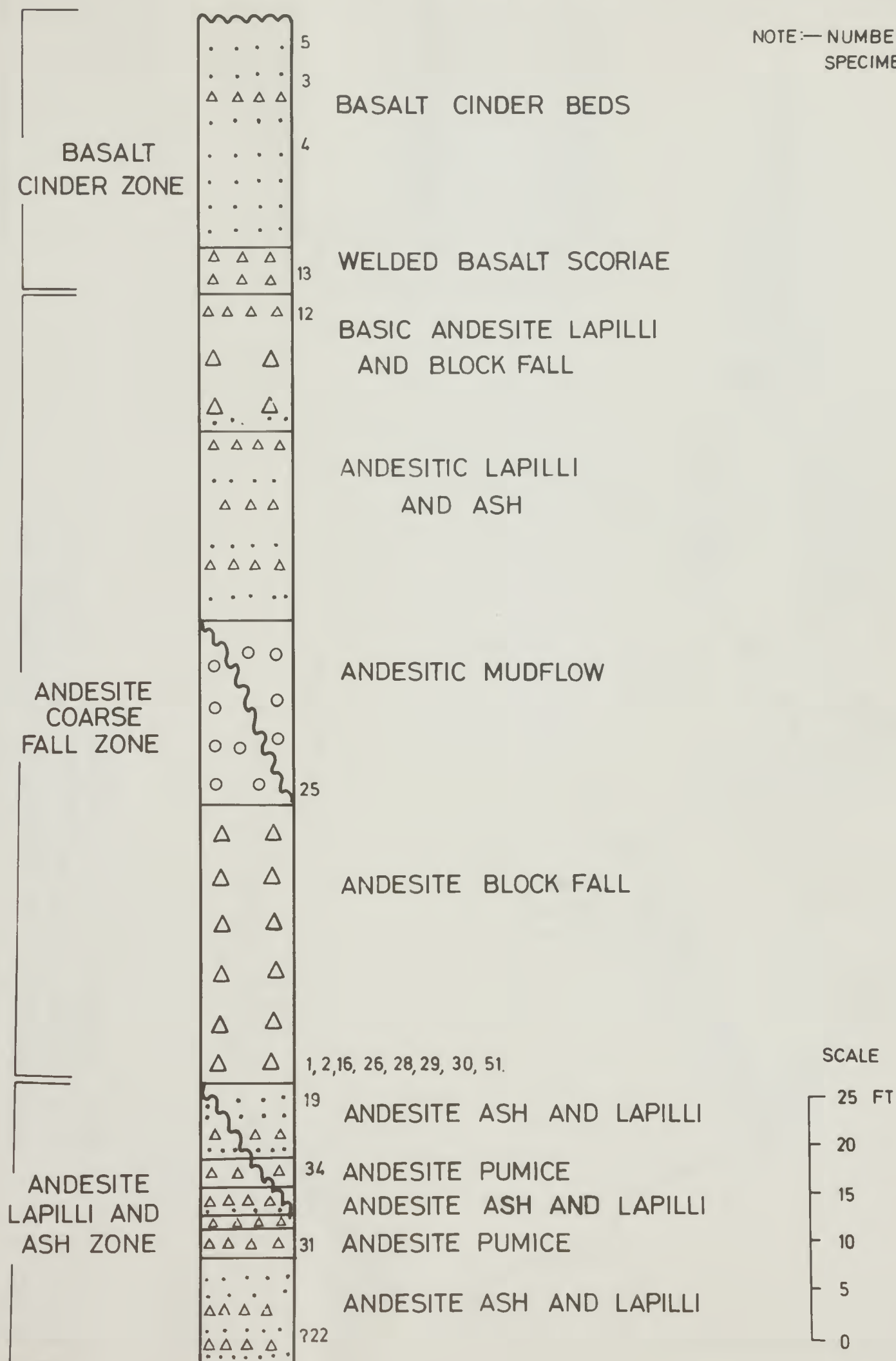


Fig. 8. MAP SHOWING THE PRINCIPAL LOCALITIES OF THE WHITE RIVER PYROCLAST FALL SERIES AND APPROXIMATE THICKNESS

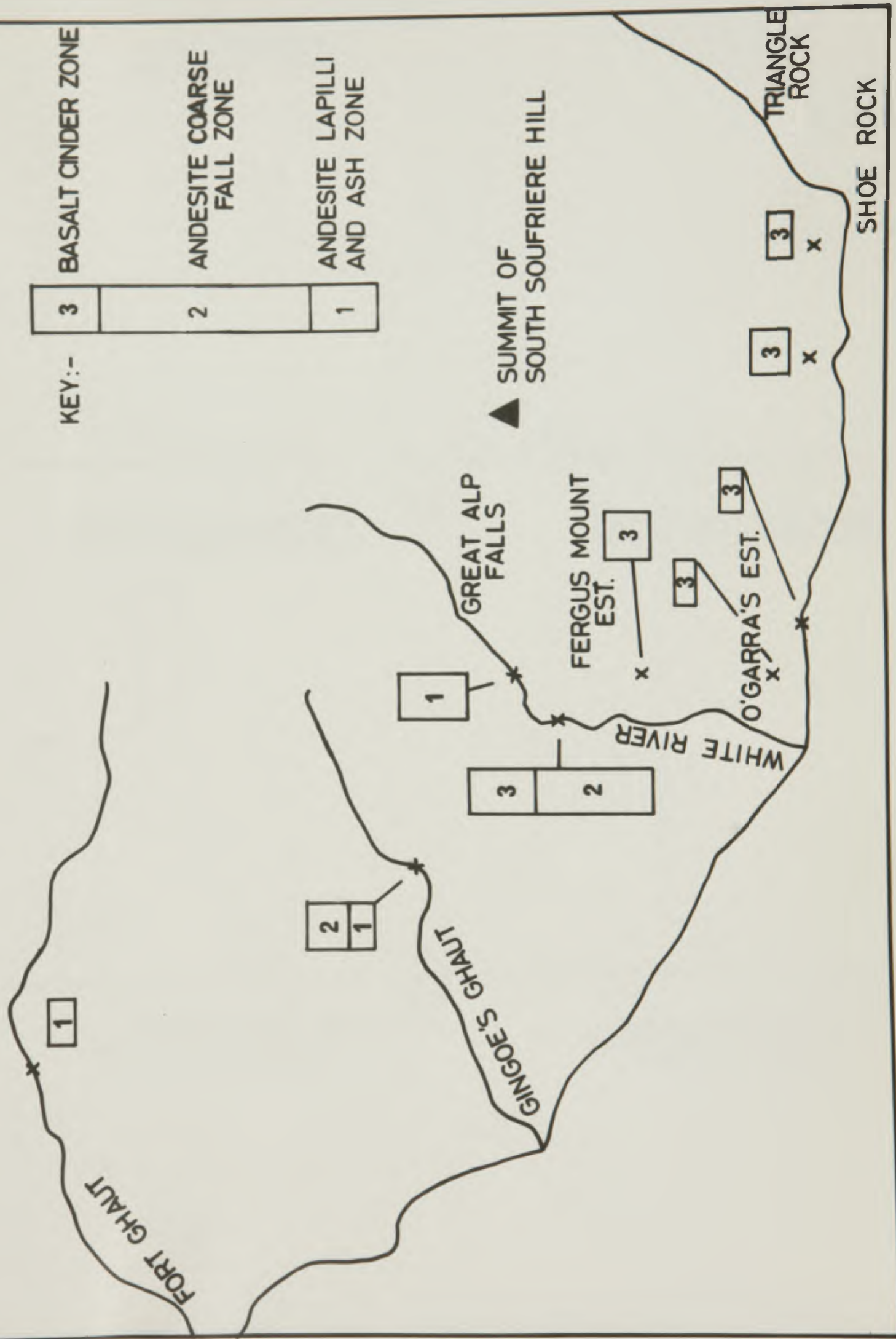
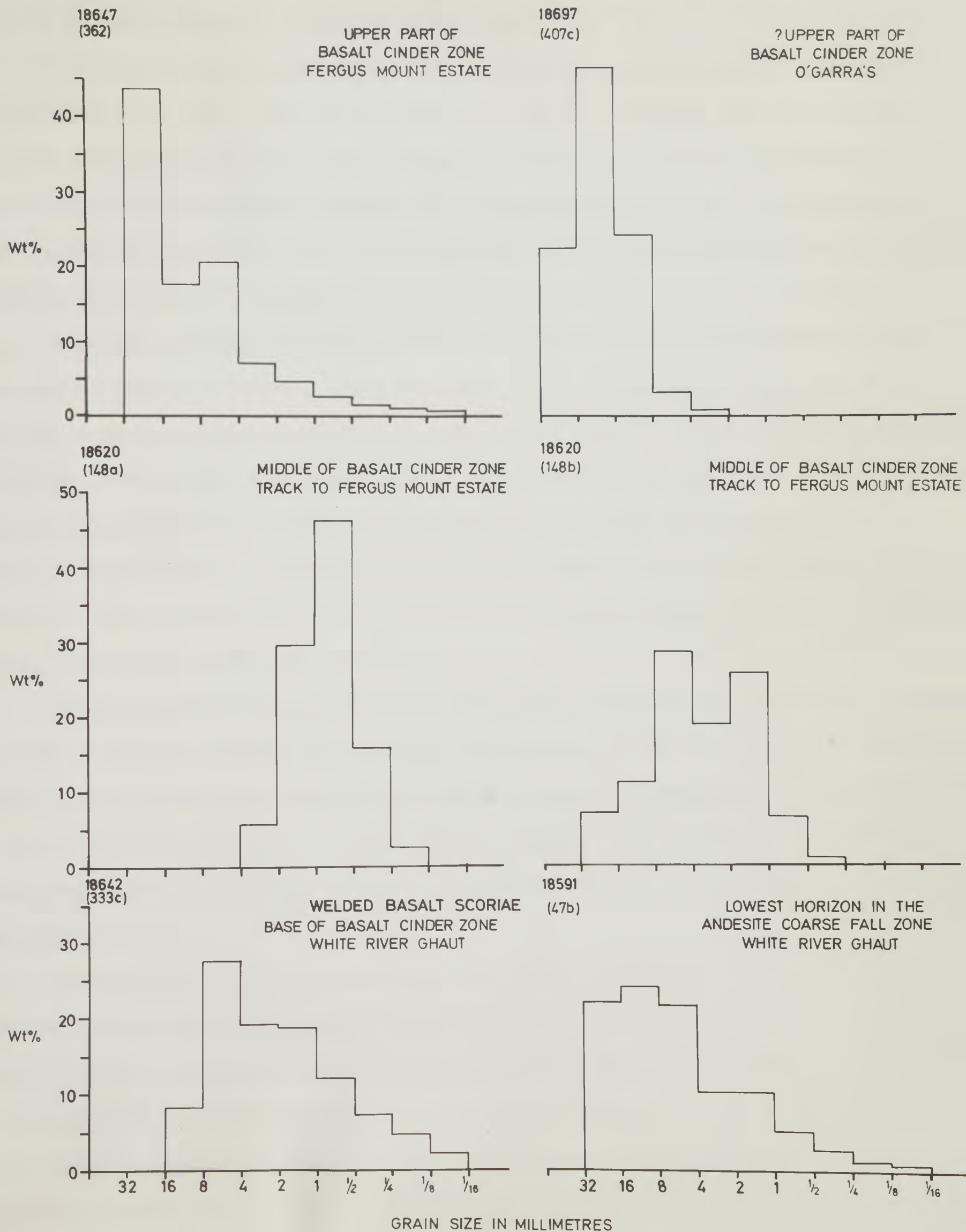


Fig 9. Grain Size Distribution in the White River Pyroclast Fall Series.



part of the zone, making a total thickness of 30 ft., but in places as much as 14 ft. has been removed before the deposition of the next zone.

In the bottom half of the zone, the lapilli beds, composed largely of fragments of dark grey, vesicular, hornblende-bearing, two-pyroxene andesite are more abundant than the ash beds but the proportion of ash to lapilli beds increases in the upper part of the zone. The lapilli beds are well sorted and often graded. They sometimes show inverted grading (i.e. they coarsen upwards) which probably reflects the increasing intensity of an eruptive episode.

The ashes are very fine-grained and are a good deal more consolidated than the inter-bedded lapilli horizons. Their red-brown colour is consistent throughout each unit and is thus probably an original feature, rather than the result of post-depositional oxidation. The ash beds are generally very thin (usually less than 2 in. thick but one bed is 2 ft. thick) and are sometimes contorted, probably due to the weight of the overlying lapilli beds. The ashes appear to be of similar composition to the lapilli deposits. They are made up of small andesitic fragments and contain crystals of plagioclase, hypersthene, augite and hornblende.

The two pumice beds are very alike. They both contain angular fragments of pale, blue-grey hornblende-bearing two-pyroxene andesite pumice, together with a few fragments of dark andesite lava in a scanty, fine-grained matrix. The origin of the pumice beds is not immediately obvious as they are not particularly well-sorted, but on account of their comparative lack of finer material they are considered to be pumice falls rather than pumice flows.

The beds of the Andesite Lapilli and Ash Zone are not widely exposed and were positively identified only in White River Ghaut and Gingoe's Ghaut. The 12 ft. thickness of lapilli, ash and pumice at the bottom of the Gingoe's Ghaut inlier is considered to be equivalent to the lower 16 ft. (i.e. up to and including the first pumice horizon) of the Andesite Lapilli and Ash Zone seen in White River Ghaut. This small decrease in thickness suggests that the beds of the Andesite Lapilli and Ash Zone extend considerably

to the north under Soufriere Hills deposits. Evidence of this is scanty probably due to insufficiently deep dissection, but it is possible that an inlier of pyroclast fall material in Fort Chaut is equivalent to the Andesite Lapilli and Ash Zone.

Two small inliers of pyroclast fall material occur in Fort Chaut. The larger, more easterly inlier has been attributed to St. George's Hill (p. 72) but the affinities of the other inlier are less certain. This inlier consists of about 14 ft. of lapilli, ash and pumice beds which resemble beds of the Andesite Lapilli and Ash Zone in appearance and petrography. It is possible however that these beds are Centre Hills deposits.

10:2:2 The Andesite Coarse Fall Zone.

The basal unit of the Andesite Coarse Fall Zone begins with a few feet of andesitic lapilli (Plate 4A) which coarsen upwards into a block fall, which is about 30 ft. thick. The block fall is composed mainly of fragments of dark grey hornblende-bearing two-pyroxene andesite lava and pumice of very uniform composition (Table 12., Nos. 26, 28, 29 and 30). The deposit also contains some small plutonic blocks with anorthite-hornblende-magnetite as the most usual mineral assemblage, although olivine-bearing blocks are also present (p. 103). Metamorphic and doleritic blocks also occur (p. 109). The blocks are contained in a very scanty fine-grained matrix composed of fine andesitic fragments. The block fall obviously represents the products of a fairly violent eruption - perhaps the clearing of a blocked vent - and its deposition ended what, to judge from the size of the unconformity with the beds of the preceding zone (p. 32), was a longish period of quiescence at the South Soufriere Hill Centre.

In places the block fall is overlain by a pinkish brown mudflow up to 20 ft. thick. The blocks in the mudflow are very similar to those found in the block fall and the mudflow is probably the result of more or less contemporaneous reworking of the block fall. Twenty feet of interbedded lapilli and ash beds, which are quite like the beds of the Andesite Lapilli and Ash Zone, though less well-bedded, overlie the mudflow (Plate 3A), and are themselves overlain by 15 ft. of dark, crudely-bedded lapilli



PLATE 3A. The White River Pyroclast Fall Series exposed in the north bank of White River Ghaut. The whole of the upper two zones of the White River Pyroclast Fall Series are exposed here and the series is unconformably overlain by a Soufriere Hills pyroclast flow.



PLATE 3B. Base of the Andesite Lapilli and Ash Zone in White River Ghaut. The thick coarse unit towards the top of this photograph is the lower of the two pumice horizons in the Andesite Lapilli and Ash Zone.



PLATE 4A. Lowest part of the Andesite Block Fall at the base of the Andesite Coarse Fall Zone. This deposit consists predominantly of angular fragments of grey relatively vesicular two-pyroxene andesite lava. Apart from the occasional bomb (middle left in photograph) this part of the deposit is made up mostly of fragments of coarse lapilli grade but the deposit coarsens upwards.



PLATE 4B. Upper part of the Andesite Coarse Fall Zone in White River Ghaut. The Andesite Coarse Fall Zone gets more basic (and darker in colour) upwards. The welded basalt scoriae bed which marks the base of the Basalt Cinder Zone stands out prominently at the top of the photograph.



PLATE 5A. Welded basalt scoriae bed, north bank of White River Ghaut. The welded scoriae bed, which is the lowest horizon in the Basalt Cinder Zone is more resistant to weathering than the overlying beds and stands out prominently on the walls of White River Ghaut. It overlies the uppermost beds in the Andesite Coarse Fall Zone, which are composed of basaltic or basic andesitic block falls and lapilli. Some of the rare white blocks in the coarse fall deposits are composed of hornblende-bearing, two-pyroxene andesite pumice.



PLATE 5B. Top of Basalt Cinder Zone. Fergus Mount Estate.

and block fall. The latter deposits (Plates 4B and 5A) are apparently a good deal more basic than the lower block fall (Table 12, No. 12). They contain a high proportion of dark, scoriaceous basaltic fragments but also a few fragments of white hornblende-bearing two-pyroxene andesite pumice (p. 35).

Beds of the Andesite Coarse Fall Zone are not very widely distributed, being definitely recognisable only in White River Ghaut (thickness 65 ft.) and Gingoe's Ghaut (thickness 22 ft.). This limited distribution is typical of coarse pyroclast fall deposits which generally occur only in the immediate vicinity of an eruptive vent and grade into finer deposits away from the vent.

10:2:3 The Basalt Cinder Zone.

The uppermost beds of the Andesite Coarse Fall Zone pass upwards into the beds of the Basalt Cinder Zone without any apparent break and there is probably a compositional gradation between the two zones. The zones have been separated on the basis of their relationship to the lowest bed in the Basalt Cinder Zone which is a very distinctive deposit and which separates an essentially coarse-grained, andesitic succession below from a fine-grained, basaltic one above.

Beds of the Basalt Cinder Zone reach a thickness of about 30 ft. in White River Ghaut and are well exposed as far east as Triangle Rock. The lowest bed in the zone (Plate 5A) is 5 ft. thick and composed of brown, welded scoriaceous basaltic lapilli and coarse ash (see Fig. 9). It is better-consolidated than the adjacent beds and stands out prominently on the walls of White River Ghaut (Plate 3A) but is not seen in any of the Basalt Cinder Zone exposures east of O'Garra.

The top 25 ft. of the Basalt Cinder Zone is made up of a group of dark, loosely consolidated basalt cinder beds. The cinder beds are sometimes quite coarse but are usually both fine-grained (Fig. 9) and finely bedded, often with several beds to the foot (Plate 5B). Inverted grading is quite common. Whereas the finer beds are generally composed entirely of fragments of basaltic scoria, the coarser beds have fragments of

non-vesicular basalt lava and rare fragments of pumiceous hornblende-two-pyroxene andesite as well.

Similar hornblende-two-pyroxene andesite fragments occur in lapilli beds at the top of the Andesite Coarse Fall Zone (p. 34) and also in basic agglomerates (p. 38). McGregor (1938, p. 25) thought that these fragments were derived from the Soufriere Hills centre and that their presence in South Soufriere Hill deposits implied that the Soufriere Hills centre was active in late South Soufriere Hill times. The hornblende-two-pyroxene fragments are however similar to material in the lower two zones of the White River Pyroclast Fall Series and the present author believes they were derived from this source rather than from the Soufriere Hills. The relationship of South Soufriere Hill to the Soufriere Hills is discussed more fully in section 10:8.

With the exception of the welded scoriae horizon, the beds of the Basalt Cinder Zone are more widely distributed than the beds of the lower two zones in the White River Pyroclast Fall Series. Even so they are restricted to a 150° segment of South Soufriere Hill and have not been positively identified on the east and northeast flanks of the volcano or in the Gingo's Ghaut Inlier (Fig. 8). The absence of beds of the Basalt Cinder Zone from the east side of South Soufriere Hill is probably a result of disturbances accompanying the formation of the Raspberry Hill Domes (p. 39) but their absence from the Gingo's Ghaut inlier is rather puzzling especially in view of their considerable thickness in nearby White River Ghaut. Non-deposition is hardly possible here and it appears that about 15 ft. of basalt cinders were removed before the deposition of the overlying Soufriere Hills' deposits. The fact that rare fragments of olivine-basalt lava have been found in pyroclast falls from St. George's Hill (p. 70) suggests that beds of the Basalt Cinder Zone may actually extend quite far to the north but are overlain by younger deposits of the Soufriere Hills and St. George's Hills.

10:3 BASALT LAVA FLOWS.

The lava flows of South Soufriere Hill, which include both olivine-basalts and

two-pyroxene basalts (p. 79) are well-exposed along the south coast of Montserrat between O'Garra's and Landing Bay.

The olivine-basalt lava flows vary in thickness from a few inches up to 35 ft. and the two-pyroxene basalts from 20 to 50 ft. The thinner flows are often very irregular. They may be slightly folded and sometimes split into two or more thinner flows or die out altogether. Lava tunnels, later filled with agglomerate also occur (MacGregor 1938, p. 24).

The olivine-basalt lavas almost invariably have scoriaceous tops and bottoms whereas the two-pyroxene basalts do not. Sometimes the tops of the flows, particularly the two-pyroxene basalt flows, are reddened but apart from this signs of erosion are not marked, which led Perret (1939) to suggest that the South Soufriere Hill lavas were of recent origin.

Some of the lavas are flow-banded and some contain small metamorphic inclusions (p. 112).

The relationship of the basalt lava flows to the Basalt Cinder Zone of the White River Pyroclast Fall Series is suggested by an exposure on the S.W. coast of Montserrat, about 150 yards east of O'Garra's. Here, a thin olivine-basalt lava flow (10 ft. thick) is overlain by 9 ft. of basaltic lapilli (Fig. 9) and 10 ft. of andesitic agglomerate. The latter probably represents reworked Soufriere Hills and South Soufriere Hill material but the basaltic lapilli are believed to be equivalent to the upper part of the Basalt Cinder Zone.

No other contacts between lava flows and the beds of the White River Pyroclast Fall Series were seen, but the lava flows are similar in chemistry and mineralogy to deposits of the Basalt Cinder Zone and this together with the limited field evidence suggests that the lava flows are contemporaneous with the basalt cinder beds. It is tempting to correlate all the basalt lava flows with the Basalt Cinder Zone but preliminary age data indicate that this may be an oversimplification.

Dr. J. C. Briden (pers. comm.) has obtained a K-Ar date of 1.6 ± 0.34 m.y. for an olivine-basalt flow (18637) collected by the author from the bottom of the sea cliffs near Shoe Rock but the relationship of South Soufriere Hill lava flows to the Landing Bay dacite suggests that many of the lava flows are younger than this. The Landing Bay dacite (p. 48) which gives a K-Ar age of 0.96 ± 0.25 m.y. (J. C. Briden, pers. comm.) is overlain by South Soufriere Hill basalt lava flows and agglomerates. These agglomerates and lava flows show no signs of having been disturbed so it is very unlikely that they represent older material into which the Landing Bay dacite was intruded. In fact, the agglomerates and lava flows infill hollows on the surface of the Landing Bay dacite and probably overly it unconformably. They are thus almost certainly a good deal younger than 0.96 m.y.

There may, therefore, be two or more sets of basalt lava flows associated with the South Soufriere Hill centre. Of these, probably only the youngest set is related to the Basalt Cinder Zone as it is unlikely that the basalt cinder beds are anything like as old as 1.6 m.y. It is highly improbable that extensive unworked deposits of these loosely-consolidated beds would remain after such a time especially when one considers the amount of erosion that has taken place at the Silver Hill centre during the same period (p. 24).

10:4 AGGLOMERATES.

10:4:1 The Summit Ridge Andesite Agglomerate.

No exposures were seen in the immediate vicinity of the summit of South Soufriere Hill but exposures N.N.E. of the summit and on the col between the Soufriere Hills and South Soufriere Hill, which is apparently the northward continuation of the summit ridge, are of well-consolidated, two-pyroxene andesite agglomerate.

10:4:2 Basaltic Agglomerates.

Basaltic agglomerates, which are invariably inter-bedded with basalt lava flows are abundant along the south and south-east coasts of Montserrat. The most northerly

exposure lies more than a mile north of Roche's Bluff Point.

The agglomerates show considerable variation in regularity of bedding, size of fragments and amount of matrix and are clearly secondary deposits. Bedding is well-marked and fairly regular in some places but is virtually absent in others. Cross-bedding occurs rarely. All sizes of material from ash to large blocks are present in the deposits but block rich, matrix poor agglomerates are the most common type of deposit. Mudflows also occur.

The agglomerates are composed mainly of fragments of dark vesicular olivine-basalt and two-pyroxene basalt together with occasional fragments of pale hornblende-hypersthene-quartz-phyric andesite. (p. 35). The most important source of the basalt blocks was probably the scoriaceous tops and bottoms of the lava flows but some of the basaltic material, especially in agglomerates west of Triangle Rock, may be derived from the Basalt Cinder Zone.

10:5 THE SOURCE OF THE PYROCLAST FALLS AND LAVA FLOWS OF SOUTH SOUFRIERE HILL.

The pyroclast falls and lava flows of South Soufriere Hill can be traced right to the summit ridge of the hill (Plate 2A) and were obviously derived from somewhere near the present summit. Although no vent is visible in this area at the present time the summit ridge is almost certainly the remnant of a crater wall (Plate 2B). The small amount of curvature of the summit ridge suggests that the crater of which it once formed part was a large one - perhaps of the order of a mile or more in diameter.

10:6 SOUTH SOUFRIERE HILL BEFORE THE EXTRUSION OF THE RASPBERRY HILL DORIES.

South Soufriere Hill at the end of the deposition of the White River Pyroclast Fall Series is envisaged as a cone-shaped strato-volcano with a large central crater and with flanks composed of basic lava flows, pyroclast falls and agglomerates (Fig. 11). The products of the strato-volcano are considered to have been voluminous, extending as far north as the cliffs below Tar River Estate and perhaps as far as St. George's Hill (p. 70). Subsequent events have considerably altered this original strato-volcano.

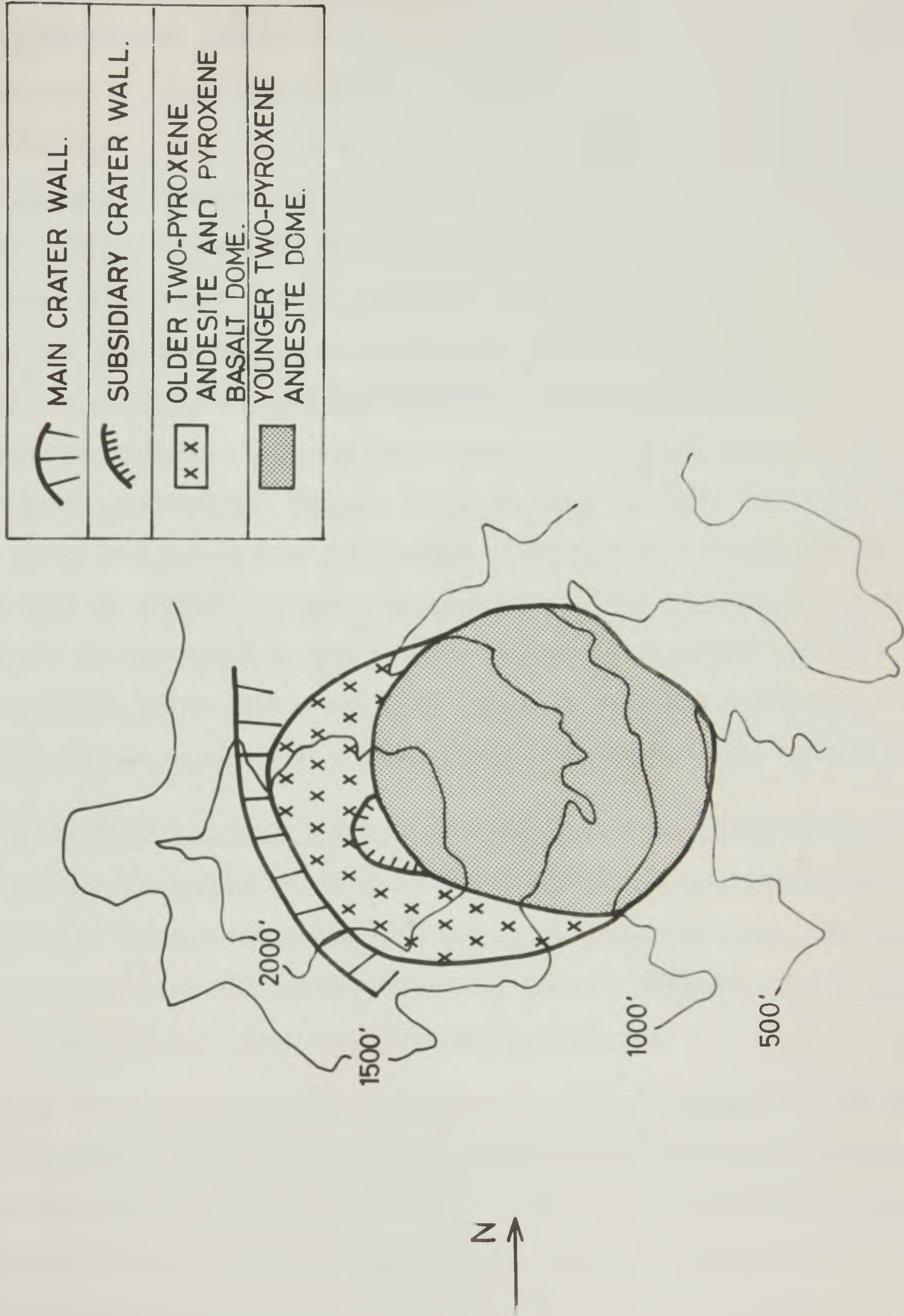
10:7 THE RASPBERRY HILL DOMES.

Views from the north (Plate 2B) indicate the presence of a large, complex structure abutting against the summit ridge of South Soufriere Hill. This feature - referred to here as Raspberry Hill - is clearly younger than the summit ridge.

Exposure is very poor on Raspberry Hill and near the top of the hill virtually no material was seen in situ. The hill is, however, covered by fairly numerous lava blocks of two-pyroxene basalt and olivine-bearing two-pyroxene andesite and lavas of two-pyroxene andesite are well-exposed in Dry Chaut. The uniform petrography of lavas from the hill and from Dry Chaut suggests that Raspberry Hill is a more or less homogeneous lava body but air photographs show that Raspberry Hill probably consists of two coalescing domes (see Fig. 10). Chemical analyses (Table 12, Nos. 14 and 18) suggest that the older dome is more basic than the younger dome. A small irregular crater occurs near the top of the older of the two domes and is truncated on the eastern side by the younger dome. On the ground this crater appears as a hollow, elongated in a N. - S. direction. The western wall is steep and high but the north and south walls are less than 10 ft. high.

The position of the Raspberry Hill Domes in relation to the summit ridge of South Soufriere Hill suggests that they grew within the crater of the original strato-volcano. In view of the similar lithology and morphology of the two domes they were probably extruded within a short time of one another, like the crater domes of 1902 and 1929 at Mont Pelé. The summit topography of South Soufriere Hill is quite similar to that of Mt. Pelé (compare Fig. 10 with Robson and Tomblin, 1966, Fig. 13). The growth of the domes together with associated eruptions was probably responsible for destroying the crater and the eastern flanks of the strato-volcano. The upthrust at Roche's which may be related to the extrusion of the Raspberry Hill Domes (p. 48) and the eruptions of the Soufriere Hills volcano have also had a considerable modifying effect on the northern and eastern flanks of South Soufriere Hill.

FIG.10 FEATURES OF THE SUMMIT AREA OF SOUTH SOUFRIERE HILL.



10:8 RELATIONSHIP OF SOUTH SOUFRIERE HILL TO THE SOUFRIERE HILLS.

Several exposures show clearly that many of the deposits of the Soufriere Hills are younger than those of South Soufriere Hill. Thus, in the north bank of White River Ghaut the uppermost beds of the White River Pyroclast Fall Series are separated by a reddened and irregular surface from overlying Soufriere Hills pyroclast flows. In Dry Ghaut red basaltic tufts are separated by a strong erosional unconformity from the overlying Soufriere Hills pyroclast flow, and in the Gingo's Ghaut Inlier beds of the Coarse Andesite Fall Zone are overlain unconformably by Soufriere Hills mudflows.

In all the exposures mentioned above the Soufriere Hills deposits contain hornblende-hypersthene andesite blocks and these exposures give no indication of the relationship of South Soufriere Hill deposits to the earliest events at the Soufriere Hills centre. Direct evidence of this relationship is unfortunately lacking but the writer believes that the general similarity in composition of the Raspberry Hill Domes and Gage's Dome may be significant in this respect. Indeed, it is possible that the blocking of the South Soufriere Hill crater by the Raspberry Hill Dome may have been partly responsible for the migration of volcanic activity to the Soufriere Hills volcano.

10:9 SUMMARY OF THE HISTORY OF SOUTH SOUFRIERE HILL AND COMPARISONS WITH OTHER VOLCANOES.

In this section the history of the South Soufriere Hill volcano is summarised and its development is compared with other volcanoes in the Lesser Antilles. The general similarity of South Soufriere Hill and Mt. Misery, St. Kitts is stressed. The development of South Soufriere Hill is shown diagrammatically in Fig. 11.

STAGE 1. Not very much can be said about the early development of South Soufriere Hill but the initial eruptions probably included a set of basalt lava flows and associated pyroclastics (?) erupted about 1.6 m.y. ago (p. 37). The pyroclastics would presumably have been extensively removed during the period of submergence of Montserrat which is believed to have occurred between the end of Silver Hill activity and the beginning of activity at the Centre Hills (p. 24).

The early eruptions of Mt. Misery produced a series of basaltic and andesitic lavas and pyroclastics (Baker, 1963, Table 1, p. 41).

STAGE 2. The first set of eruptions for which there is convincing evidence gave rise to the deposition of a group of andesitic pyroclast falls (the Andesite Lapilli and Ash Zone of the White River Pyroclast Fall Series). At the type locality in White River Ghaat the Andesite Lapilli and Ash Zone is only about 30 ft. thick but these deposits may originally have been quite voluminous. Fairly thick deposits occur to the north of South Soufriere Hill (p. 32) and the white andesite tuffs at Roche's Bluff which are probably over 200 ft. thick may in parts be equivalent to the Andesite Lapilli and Ash Zone (p. 44). There is no direct evidence on the age of the Andesite Lapilli and Ash Zone but the Roche's tuffs are probably considerably older than 40,000 yrs. (p. 46).

The Mansion Series of Mt. Misery (Baker, 1963, pp. 47-71) is a series of pyroclast falls, which shows many similarities to the White River Pyroclast Fall Series. The original thickness of the Mansion Series has been estimated at 130 ft. which is very similar to the thickness of the White River Pyroclast Fall Series (125 ft.). In both series andesitic pyroclast falls are more abundant than basaltic pyroclast falls; basalt lava flows are associated with the basaltic pyroclast falls; and ultrabasic coarse-grained blocks occur in andesitic beds. Both series begin with a group of andesitic pyroclast falls.

STAGE 3. A period of quiescence followed the deposition of the Andesite Lapilli and Ash Zone but the succeeding eruptions were violent. The basal andesitic block fall of the Andesite Coarse Fall Zone contains a high proportion of non-vesicular lava fragments and also some ultrabasic cumulates and metamorphic blocks which have probably been carried from depths of around $\frac{8}{10}$ km. (p. 149). The block fall is probably the product of a large-scale vent-clearing eruption. This and other eruptions of the Andesite Coarse Fall Zone may have been responsible for the large size of the crater of the South Soufriere Hill strato-volcano (p. 38).

No lithic block falls have been reported at Mt. Misery. Ultrabasic blocks similar to those found in the Andesite Coarse Fall Zone have been reported from many calc-alkali volcanoes e.g. Mt. Misery, St. Kitts (Baker, 1968, pp. 132-135); Soufriere, St. Vincent (Lewis, 1964) and Hakone, Japan (Juno, 1950). The petrogenetic significance of these blocks is discussed on p. 146.

STAGE 4. Deposits of the Andesite Coarse Fall Zone become steadily more basic upwards and the uppermost beds grade up into beds of the Basalt Cinder Zone. The eruption of the basalt cinders was accompanied by the extrusion of a series of olivine-basalt and two-pyroxene basalt lava flows. These deposits are definitely younger than 0.96 m.y. (p. 37) but in view of the abundance of the easily eroded, unconsolidated basalt cinders, they are probably a good deal younger than this.

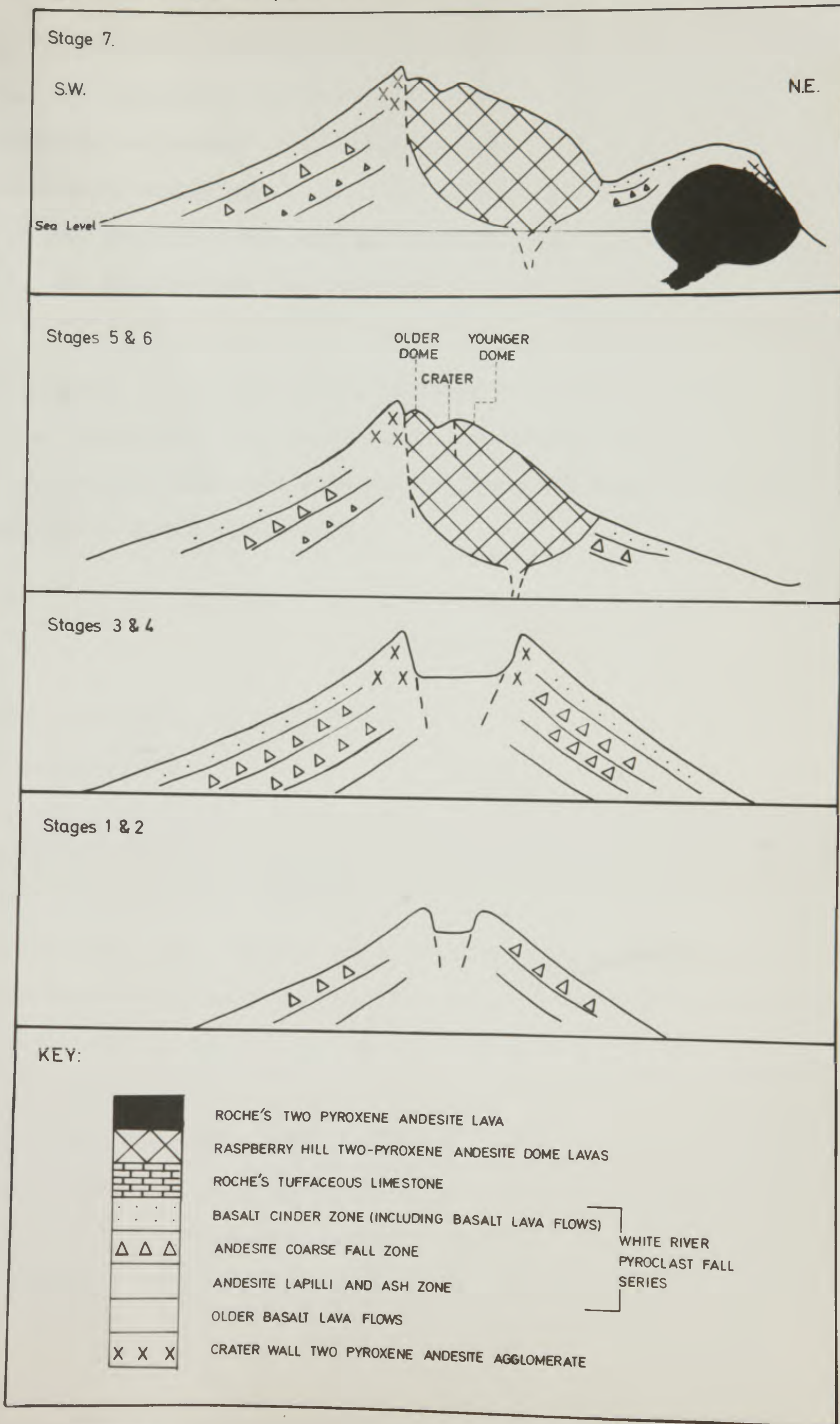
Basalt cinders and associated basalt lava flows occur towards the top of the Mansion Series (Baker, 1963, pp. 52-55 and 67-71) and are also found on Redonda (Martin-Kaye, 1959, p. 77) and St. Vincent (Robson, 1964⁵).

STAGE 5. Sometime after the deposition of the Basalt Cinder Zone^a dome composed of two-pyroxene basalt was extruded within the crater of the strato-volcano. Explosive eruptions of pyroclast flows from flank fissures and also from a small crater at the summit of the dome (Fig. 10) were probably associated with the extrusion of the dome and no doubt contributed to the destruction of the east and southeast flanks of the strato-volcano.

STAGE 6. After what was probably a very short period of time (p. 39) a second dome of similar, though less basic composition to the first, was extruded and its extrusion will also have had a profound effect on the eastern flanks of the strato-volcano. If these domes were extruded at approximately the same time as the intrusion of the two-pyroxene andesite lava at Roche's (p. 48) they may both be less than 40,000 years old (p. 48).

Crater domes are common in volcanoes in the Lesser Antilles e.g. the Castle Peak Dome at the Soufriere Hills (p. 55) and at calc-alkaline volcanoes in general e.g. at

Fig. 11. The Development of South Soufriere Hills.



Mt. Lamington, Papua (Taylor, 1958) and both these domes occur in open, horseshoe-shaped craters. The extrusion of the Castle Peak Dome or an earlier crater dome is believed to have been instrumental in breaching the eastern wall of English's Crater (p. 55). The composite crater dome at Mt. Pele, which was formed by the coalescence of the domes of 1902 and 1929 is very similar morphologically to the Raspberry Hill Domes (p. 39). All the domes mentioned above are more acid than the Raspberry Hill Domes.

STAGE 7. The intrusion of the Roche's lava, which may be closely related to the formation of the Raspberry Hill Dome (p. 48), and dome-building and pyroclast flow eruptions of the Soufriere Hills have considerably altered the eastern and northern flanks of South Soufriere Hill respectively.

CHAPTER 11.

THE ROCHE'S BLUFF CENTRE.

11:1 INTRODUCTION.

The Roche's Bluff Centre (Plate 7B) is a complex centre much confused by faulting and slumping. Three different sets of fragmental deposits occur in the area. Of these one and possibly two are derived from South Soufriere Hill while the third is secondary. All these deposits show signs of post-depositional uplift and brecciation. This uplift is believed to be due to the intrusion of a lava body, which is probably closely related to late stage activity at South Soufriere Hill. Thus, the Roche's Bluff Centre should probably be considered as a subsidiary centre of South Soufriere Hill but in view of its complexity and the uncertainty of some of the correlations suggested below it has been described separately. The Landing Bay Dacite, which occurs about $\frac{1}{2}$ ml. to the south of the Roche's Bluff Centre is also described below.

11:2 FRAGMENTAL DEPOSITS OF ROCHE'S BLUFF.

11:2:1 White Andesite Tuffs.

Beds of white andesite tuffs are well-exposed along the coast for about $\frac{1}{4}$ mile north of Roche's Bluff. Locally, bedding is absent and the deposits are structureless agglomerates and mudflows. In places, too, the orientation and inclination of bedding in the white tuffs are rather irregular. Minor faulting also occurs.

Fragments in the white tuffs are quite varied. Pumiceous two-pyroxene andesite is probably the most common type but hornblende-bearing lavas and pumices are also present.

The white tuffs represent a thick (probably over 250 ft. thick) series of partially reworked pyroclast falls, which has undergone post-depositional uplift. On petrographic grounds it is possible that the white tuffs are equivalent to the two andesite zones of the White River Pyroclast Fall Series and the fact that the white

tuffs are overlain unconformably by basaltic agglomerates (p. 46) supports this suggestion. There are, however, certain differences between the two series (Table 2). Another possible correlation is with the hypersthene-andesite pumice falls of the Soufriere Hills (p. 59) but here the evidence is even more tenuous (Table 2).

11:2:2 Tuffaceous Limestones.

Tuffaceous limestones occur in the north bank of Dry Ghaut and on the coast near Landing Bay. These crudely bedded deposits contain rounded fragments of two-pyroxene andesite lava (with or without hornblende) as well as crystals of plagioclase, augite, hypersthene, hornblende and olivine and are richly fossiliferous. The fossil assemblage which includes corals and abundant foraminifera has been described in detail by MacGregor (1938, pp. 80-82) and Westermann and Kiel (1961, pp. 129-130). It indicates an age of not later than Pleistocene for the limestones and MacGregor (1938, p. 20) considers that the Roche's Bluff Centre is early Pleistocene in age. Westermann and Kiel (1961, p. 158), however, have tentatively assigned an age of about 40,000 yrs. to the Roche's limestones on the basis of their similarity, in fossil content and state of preservation to the White Wall Formation of Statia (radiocarbon age:- $32,640 \pm 300$ yrs.) and the limestones at Brimstone Hill, St. Kitts (radiocarbon age:- $44,400 \pm 1,200$ yrs.).

The fossil assemblage in the limestones indicates that they were deposited in a shallow water, marine environment. The tuffaceous limestones which are found, at present, at heights of up to 400 and perhaps even 700 (Martin-Kaye, 1959, p. 85) ft. a.s.l. have obviously been subjected to uplift. The limestones are also quite disoriented. The general dip is about 60° to the N.E. but the direction and inclination of the bedding varies considerably.

The relationship of the tuffaceous limestones to the white andesite tuffs is not immediately obvious since no contacts are seen but the tuffaceous limestones are believed to be younger than the andesite tuffs. Some of the volcanic fragments in the limestones are very similar in composition to fragments in the white tuffs and may represent erosion

TABLE 2. Comparison of the characteristics of

- a. The Roche's white andesite tuffs (p. 44)
- b. The andesite zones of the White River Pyroclast Fall Series (p. 31)
- c. The hypersthene-andesite pumice falls of the Soufriere Hills (p. 59)

	a	b	c
Thickness	? 250 ft.	at least 100 ft.	at least 80 ft.
Size of fragments	ash to blocks, ash predominates	ash to blocks, ash predominates in lower parts, coarse lapilli in upper parts	ash to lapilli, ash predominates
Sorting	moderately well-sorted	very well-sorted	well-sorted
Bedding	quite well-bedded	varies, very well-bedded in lower parts	well-bedded
Lithology of fragments	Two-pyroxene andesite, some with hornblende	Two-pyroxene andesite, almost with hornblende	Hypersthene-andesite with subordinate hornblende
Age	unknown, but older than Roche's basaltic agglomerates and lava flows	unknown but older than Basaltic Cinder Zone	unknown

products of this series. It is also worth noting that limestone does not in general form near to active volcanoes (limestone is forming at present off Silver Hill and the Centre Hills but not around the Soufriere Hills) and the tuffaceous limestones are unlikely to have been deposited while the volcano which erupted the white andesite tuffs (? South Soufriere Hill) was active. The limestones are probably too young (see above) to have formed before activity at South Soufriere Hill began, but could have formed during a longish period of quiescence at the volcano.

11:2:3 Basaltic Agglomerates.

Reddish-brown agglomerates, tuffs and mudflows, containing fragments of olivine-basalt and pyroxene-basalt, and locally interbedded with thin lava flows occur in Dry Ghat and along the coast from Landing Bay for more than a mile to the north of Roche's Bluff. These beds are similar to the basic agglomerates of South Soufriere Hill (p. 37) and like them may be largely attributable to the Basalt Cinder Zone of the White River Pyroclast Fall Series.

The basaltic agglomerates overlie the white andesite tuffs, probably unconformably but their relationship to the tuffaceous limestones is less certain. Near Landing Bay the tuffaceous limestones are overlain towards the N.E. by brown basaltic agglomerates and underlain towards the S.W. by reddish basic agglomerates (see MacGregor, 1938, Plate 17). According to MacGregor (p. 23) the southern junction is a fault and the northern junction is an unconformity with the basic agglomerates overlying the tuffaceous limestones unconformably. The evidence for the unconformity is, however, rather inconclusive and in view of the fact that limestones do not form around active volcanoes (p. 46) the author believes that the tuffaceous limestones may actually be younger than the basaltic agglomerates. The abundance of augite and the rare occurrence of olivine, which may have been derived from erosion of the basaltic agglomerates, in the tuffaceous limestones tends to support this view.

It appears that the basaltic agglomerates have been subjected to the same forces that disrupted the white andesite tuffs and the tuffaceous limestones. Southerly dips

of 70° . westerly dips of 15° and northeasterly dips of 10° were recorded in basaltic agglomerates and tuffs near Landing Bay, in Dry Ghaut and north of Roche's Bluff, respectively.

The westerly dip in Dry Ghaut led MacGregor (1938, p. 21) to suggest the possible existence of a pre-Roche's volcanic centre somewhere to the east of Sweeney's Well but there is no doubt of the South Sopsriere Hill affinities of these tuffs which contain fragments of olivine-basalt. Their present orientation may be due to deposition on a westwards-dipping surface but is more probably a secondary feature associated with the upthrust of the Roche's two-pyroxene andesite lava.

11:3 THE ROCHE'S TWO-PYROXENE ANDESITE LAVA.

The cliffs for about 300 yards on either side of Roche's Bluff are made up of massive white to grey lava. The lava is an augite-hypersthene andesite of similar composition to the two-pyroxene andesite of Raspberry Hill (Table 12, Nos. 14, 17 and 18).

This lava body is too large to represent a lava flow and it is probably a lava dome or plug. This agrees well with Martin-Kaye (1959, p. 85) and Westermann and Kiel (1961, p. 158) who consider that the Roche's Centre is a centre of upthrust like Brimstone Hill, St. Kitts. Neither Martin-Kaye nor Westermann and Kiel seem to have been aware of the occurrence of the Roche's two-pyroxene andesite lava and Westermann and Kiel (1961, p. 159) invoked uplift by a "hypothetical intrusion" to explain the present position of the tuffaceous limestones. Although the Roche's lava is rather small to have caused the widespread uplift and brecciation seen in fragmentary deposits at Roche's it may be considerably larger at depth. The Roche's Centre may represent an intermediate stage between Statia where no lava is seen and where a hypothetical intrusion is considered to be responsible for the present position of the White Wall Formation (Westermann and Kiel, 1961, p. 159) and Brimstone Hill, St. Kitt's where a large mass of lava is exposed.

The uplift in the Roche's area obviously post-dates the deposition of the

tuffaceous limestones the deposition of which may have occurred about 40,000 years ago (p. 45). This means that the intrusion of the lava is a comparatively recent event in the volcanic history of Montserrat. On petrographic and chemical grounds (Table 12, Nos. 14, 17 and 18) the Roche's Lava is probably related to the Raspberry Hill Domes.

11:4 THE LANDING BAY DACITE.

The Landing Bay Dacite makes up the lower part of the sea cliffs from just south of Landing Bay for about $\frac{3}{4}$ mile towards Triangle Rock. It reaches a maximum thickness of almost 300 ft. and is everywhere overlain by flat-lying basic agglomerates and lava flows from the South Soufriere Hill volcano. The Landing Bay Dacite, which is strongly jointed in places is a white, quartz-bearing hornblende-hypersthene dacite with a K-Ar age of 0.96 ± 0.25 m.y. (J. C. Briden, pers. comm.).

MacGregor (1938, p. 23) regarded the Landing Bay Dacite as intrusive but as the overlying lavas and agglomerates show no sign of disorientation it cannot have been intruded into these deposits. In fact, the agglomerates and lava flows infill hollows on the surface of the Landing Bay Dacite and thus overlie the dacite unconformably.

MacGregor (1938, p. 23) also considered that the intrusion of the Landing Bay Dacite was related to the brecciation and uplift at the Roche's Centre but this is very unlikely in view of the vastly different ages for these two events (p. 48) and the considerable difference in the chemistry of the Roche's Lava and the Landing Bay Dacite. Chemically and petrographically the Landing Bay Dacite is similar to the older hornblende-hypersthene andesite domes of the Soufriere Hills and to hornblende-hypersthene andesite pumice from St. George's Hill but it is almost certainly older than either of these.

It is thus very difficult to relate the Landing Bay Dacite to any other rocks outcropping in the south of Montserrat. It may perhaps have been associated with the andesitic zones of the White River Pyroclast Fall Series but it is more acid than any of the analysed fragments from these deposits.

CHAPTER 12.

THE SOUFRIERE HILLS.

12:1 PHYSIOGRAPHY AND STRUCTURE.

The Soufriere Hills can be divided into two distinct physiographic units. The central nucleus which is composed largely of massive andesite lava consists of an irregular group of four steep-sided domes, truncated by a large breached crater containing a central dome (Frontispiece).

Fragmentary deposits - mostly pyroclast flows and mudflows - which dip away from the central nucleus at angles of a few degrees make up the flanks of the volcano. Dips on the eastern flanks, which end in high sea cliffs are higher than on the other flanks. The contrast between the steep, forested slopes of the central nucleus and the gentler, usually cultivated outer slopes is striking (Plate 6B).

The drainage of the Soufriere Hills shows a radial pattern with ghauts converging towards the summit area. The valleys are in a youthful stage of development.

In the following section the geology of the central nucleus is described first. The pyroclastic succession of the Soufriere Hills is then described and related as far as possible to events at the central nucleus. Finally the history and development of the Soufriere Hills is summarised.

12:2 THE GEOLOGY OF THE CENTRAL NUCLEUS.

12:2:1 The Older Andesite Domes - General Statement.

The town of Plymouth is overlooked by the steep-sided peaks of Gage's Mountain and Chance's Mountain, which are separated by an exceptionally deep valley - Gage's Soufriere Ghaut (Plate 6A). On the south side of English's Crater another two peaks, also separated from one another by a deep valley and referred to here as Galway's Mountain and Perche's Mountain occur.

Robson and Tomblin (1966, p. 15) suggest that these peaks are the remnants of an irregular cone-shaped strato-volcano which formed near the start of the period of



PLATE 6A. Gage's Dome and Chance's Dome from St. George's Hill. Both domes have prominent "shoulders" which probably represent thick lava flows, poured out from near the summit of the domes. The large white gash, which extends almost to the summit of Chance's Dome marks the site of Gage's Upper Soufriere and the smaller white patch below it is Gage's Lower Soufriere.



PLATE 6B. Gage's Dome and the outer wall of English's Crater from the north. Gage's Dome is somewhat detached from the crater wall, which is here composed mostly of well-consolidated two-pyroxene andesite agglomerate. The contrast between the steep, forested slopes of the central nucleus and the gentler, cultivated outer slopes (in the foreground of the picture) is striking.

Soufriere Hills activity and was later modified by the formation of English's Crater and subsequent eruptions. This is contrary to the view expressed by Perret (1939, p. 10) that the peaks of the Soufriere Hills "have a status no less than that of true pitons or giant aiguilles." Although the terms "piton" and "aiguille" seem inappropriate to describe bodies of the size and shape of the Older Domes various lines of evidence suggest that Perret was correct in considering these hills to be separate monogenetic masses of lava.

Exposures of in situ material are rare on any of the hills, which are thickly forested but where seen they are invariably of solid lava and the hills are strewn with large lava boulders. The boulders on each hill are of a uniform petrographic type and there are slight though recognisable differences in the type of lava characteristic of each hill. Slight differences in the physiography and drainage patterns of the different hills can be recognised from the air photographs. Finally, it is difficult to envisage the production of such detached masses as Gage's Mountain from a cone by processes of erosion (Plate 6B).

The writer regards Gage's, Chance's, Galway's and Perche's Mountains as separate volcanic domes of different age. They are believed to have formed as endogenous domes (Williams, 1932, pp. 52-54) i.e. by expansion from within. The individual domes are described in detail below.

12:2:2 Two-Pyroxene Andesite Domes - Gage's Dome and Perche's Dome.

Gage's Dome (2,560 ft. a.s.l.) is a smooth, steep-sided, more or less circular hill, bounded on the south and northeast sides by deep valleys. On the west and north-west sides the boundary between the solid lava of the dome and the gently dipping pyroclast flows and mudflows on the flanks, more or less follows the 1,250 ft. contour. To the east of the summit the ground dips away steeply for about 300 ft. to join a narrow ridge running eastwards for about half a mile to the edge of English's Crater. Gage's Dome is thus somewhat detached from the crater wall and the rest of the central

nucleus (Plate 6B).

Exposures of solid lava are seen in the north bank of Gage's Soufriere Ghaut but are otherwise rare. Numerous lava boulders cover the hill. The lava is a rather oxidised two-pyroxene andesite with augite considerably more abundant than hypersthene. Hornblende is very rare but olivine phenocrysts occur and their presence is reflected in the high Mg and Ni contents of the lava (Tables 12 and 14, No. 24).

Perche's Dome (2,778 ft. a.s.l.) is separated from Galway's Dome to the west by a deep ghaut and on the south and east sides of the hill the boundary with mudflow and talus deposits approximately follows the 1,250 ft. contour. At first sight the north flank of Perche's Dome appears to form part of the wall of English's Crater but the crater wall actually ends a little to the west of Perche's Dome (Frontispiece). However, the north side of Perche's Dome is considerably steeper (54°) than the other sides (34°) and it was probably modified by the formation of English's Crater.

Solid lava is exposed northeast of the summit of the dome and loose lava blocks cover the hill. The lava is an oxidised hypersthene-augite phyric andesite. A little olivine is present but no hornblende.

12:2:3 Older Hornblende-Hypersthene Andesite Domes - Chance's Dome and Galway's Dome.

Chance's Dome (3,000 ft. a.s.l.) is an elliptical mass, elongated in a N.E. - S.W. direction even though it is truncated on the northeast side by the wall of English's Crater. Chance's Dome is separated from Gage's Dome by Gage's Soufriere Ghaut (Plate 6A) and in the west the boundary with fragmental deposits more or less follows the 1,500 ft. contour. On the south side of the hill a ridge of white coarsely-bedded fragmental deposits extends almost to the summit but there is no doubt that the hill itself is composed entirely of solid lava. Massive weathered andesite is exposed to the south of the summit where vegetation was stripped by a plane crash in 1965, while exposures in the crater wall east of the summit are also of massive andesite lava. The lava seen in these exposures and in the loose boulders on the flanks of the hill is a grey, sometimes

banded, hornblende-hypersthene andesite with subordinate quartz. Clinopyroxene is present in the groundmass.

About 150 yards to the E. of the summit of Chance's Mountain is Chance's Pond, a muddy, reed-covered swamp. It is about 60 yards long by 30 yards wide and enclosed by low walls, not more than 15-20 ft. high. MacGregor's interpretation (1938, p. 30) of Chance's Pond as a small explosion crater is probably correct.

Galway's Dome is bounded on the south and east sides by deep valleys and in the north by the wall of English's Crater. The western boundary is more obscure but apparently lies to the west of the ridge on the east side of Galway's Soufriere, which although capped by bedded pyroclastic material is composed of solid lava of very similar composition to the boulders found elsewhere on the flanks of Galway's Dome. To the west of the summit of the dome is a broad flat ridge running E.S.E. - W.S.W. towards Chance's Mountain. This ridge becomes progressively narrower towards the west.

Galway's Dome is composed of slightly oxidised hornblende-hypersthene andesite containing small amounts of quartz and clinopyroxene. The lava is very similar to the Chance's Dome lava but banding is less common. The Galway's Dome lava contains abundant holocrystalline inclusions of basaltic andesite composition (p. 109).

12:2:4 Order of Emplacement of the Older Andesite Domes.

As the Older Domes do not show clear time relationships with one another it is necessary to use indirect criteria to establish their relative ages. Useful evidence is obtained from the pyroclastic deposits on the flanks of the Soufriere Hills, where two-pyroxene andesite blocks occur in the lower parts of the succession and hornblende-hypersthene andesite blocks are found only in the more recent deposits. This suggests that Gage's and Perche's Domes are older than Chance's and Galway's Domes and this view is supported by the relative dissection of the domes. From the air photograph evidence Gage's Dome, is almost certainly the oldest structure, and Galway's Dome is probably the youngest, although the youthful appearance of the latter may in part be due to a

covering of recent pyroclast fall. The amount of weathering of the dome lavas may also give a clue to the relative ages of the domes. Gage's and Perche's Domes are both characterised by red, oxidised lava whereas Galway's and Chance's Dome are made up of comparatively fresh grey lava. While admitting the rather unsatisfactory nature of the evidence the writer considers that the Older Andesite Domes were probably extruded in the order - Gage's Dome (oldest) - Perche's Dome - Chance's Dome and Galway's Dome (youngest), i.e. in the order basic to acid (see Table 12).

The ages of the Older Andesite Domes in relation to the formation of English's Crater are easier to establish. Both Galway's Dome and Chance's Dome are truncated by the crater wall and there is evidence that the north side of Perche's Dome was also affected by the formation of the crater so that these three domes predate the crater. As Gage's Dome is probably older than the other domes its formation may also be assumed to predate the formation of English's Crater.

The general chemical and mineralogical similarity of the Gage's Dome lava to the Raspberry Hill domes and the Roche's intrusion has already been mentioned (p. 40) and these three bodies may have been emplaced at about the same time.

12:2:5 English's Crater.

English's Crater (Frontispiece) is a moderately large crater with a diameter of about 800 yards. To the north, west and south its walls rise steeply to about 500 ft. above the crater floor but the crater is open on the east. The crater is almost entirely filled by the Castle Peak hornblende-hypersthene andesite dome, which is described in the next section.

Inner Walls.

Exposure on the inner walls of English's Crater is very poor as the walls are covered by vegetation and although landslips have exposed bare rock in places, these exposures are generally inaccessible. It appears, however, that a considerable part of the crater wall is composed of massive andesite lava, representing the truncated flanks of the Older Andesite Domes. In places, e.g. due north of the summit of Castle Peak or

to the southeast of Chance's Dome, the crater wall is, as far as can be seen, composed of well-consolidated two-pyroxene andesite agglomerate. This agglomerate which obviously predates the formation of the crater may, at least in part, represent fragmentary deposits formed on the flanks of the Older Domes.

Outer Walls.

The outer walls of English's Crater show considerable variation in structure and appearance (Plates 6A, 6B, 7A and Frontispiece). In the north the edge of the crater is marked by a steep-sided serrated ridge (Plate 6B), which from the evidence of exposures on the inner walls is composed mainly of two-pyroxene andesite agglomerate. A great flat-topped sheet of pyroclastic material, truncated in places by deep ghaunts flows away northeastwards from the ridge.

Further west the skyline is broken by Gage's Dome which stands some way back from the crater wall to which it is connected by a flat, rather broad ridge. This flat area and a similar one lying to the west of the summit of Galway's Dome may possibly, by analogy with the Atrio del Cavallo of Vesuvius, represent parts of an earlier crater infilled before the formation of the present one.

Moving to the south the outer walls of English's Crater are made up of the truncated domes of Chance's, Galway's and Perche's. Between Chance's and Galway's is an area of some interest.

The summits of Chance's and Galway's Domes are joined by a high ridge, which is broad near the summits of the domes, but becomes progressively narrower away from them, until, in the middle part, it is no more than a knife-edge with precipitous slopes of over 500 ft. on either side. The western slope (60°) is extremely steep for the outer wall of a crater.

Viewed from the track below Galway's Soufriere this ridge is seen to be in apparent continuity at its western end with a steep-sided ridge running approximately N. - S. from Chance's Dome and at its eastern end with a slightly less steep ridge



PLATE 7A. Galway's Soufriere and the outer walls of English's Crater looking east. The extreme steepness of the outer walls here suggests that Galway's Soufriere may possibly occupy the site of an old crater.



PLATE 7B. East coast of Montserrat looking south from Tuitt's Ghaut. The cliffs in the foreground which rise to about 300 ft. a.s.l. are composed of well-bedded, fluviatile deposits and mudflows belonging to the Soufriere Hills centre. The hill on the left of the picture is Perche's Dome and the flat-topped feature further to the east is Roche's Bluff.

running approximately N. - S. from Galway's Dome. The feature has the general appearance of a semi-circular crater, open on the south side, and the small hill, north of Galway's Soufriere looks somewhat like a small crater dome (Plate 7A).

The writer is however rather cautious about accepting this explanation of the topography around Galway's. For a start, the whole feature is considerably more obscure than English's Crater and is difficult to pick out on air photographs. There is a suggestion, too, that the bedded deposits which make up the eastern and western parts of the ridge may be somewhat different. Those on the western side are grey and rather coarsely bedded and may represent pyroclast flows or mudflows, whereas those on the eastern side are darker and more finely bedded and may be pyroclast falls. There is little good evidence, either, for regarding the hill north of Galway's Soufriere as a dome. It appears to be made of pyroclastic material, though exposure is poor and rotting due to soufriere emanations is widespread. It is possible that this hill was formed by a landslip of material from the outer wall of English's Crater and this would explain the extreme steepness of this part of the wall.

The evidence available is hardly sufficient to decide definitely whether "Galway's amphitheatre" represents a crater or not. If it is a crater it is obviously older than English's Crater and it may have been active at a late stage in the development of the Older Andesite Domes. It is possible that Galway's Soufriere represents the final stages of activity of the old vent.

12:2:6 The Castle Peak Hornblende-Hypersihene Andesite Dome.

The Castle Peak Dome which almost completely fills English's Crater is a roughly circular hill with two separate summits the higher of which rises to 2,670 ft. a.s.l. Unlike the Older Andesite Domes the summit topography of Castle Peak is very irregular and large lava pinnacles, which probably represent broken-off spines, form the topmost part of the hill (Frontispiece). The lava exposed at the summit and in the numerous boulders which litter the eastern flanks of the hill is a pale grey hornblende-

hypersthene andesite. It is characterised by very large black hornblende phenocrysts which together with the absence of reddening serve to distinguish it from the hornblende-hypersthene andesites of Galway's and Chance's Domes.

The north, west and south flanks of Castle Peak together with the walls of English's Crater form the sides of a deep semicircular valley (the "fosse" of MacGregor, 1938). West of the summit of Castle Peak the fosse is flat-bottomed but to the north and south it joins the heads of two steeply-dipping valleys. In the fosse approximately due east of the summit of Chance's Mountain is a small circular hollow, which is almost certainly an explosion crater. It is about 50 yards in diameter with walls from 40 to 60 ft. high, composed of andesite agglomerate.

The formation of the Castle Peak Dome is obviously a late event in the history of the Soufriere Hills. Mudflow and pyroclast flow deposits which contain blocks of Castle Peak type lava invariably occur at the top of the pyroclastic successions on the flanks of the Soufriere Hills. Also, the irregular topography of the summit area of Castle Peak suggests that the hill has not been exposed to erosion for very long. It is possible that Castle Peak is the last of a series of domes which have filled English's Crater for some time before being violently destroyed but evidence for the existence of earlier domes is inconclusive. It is also probable that the breaching of the crater wall was related to the growth of a crater dome.

12:3 PYROCLASTIC DEPOSITS ON THE FLANKS OF THE SOUFRIERE HILLS.

12:3:1 Introductory Statement.

The fragmental deposits of the Soufriere Hills are mostly pyroclast flows and mudflows. Pyroclast falls are very rare. Certain problems arise in the correlation of deposits of this type and one of the fundamental difficulties - that of distinguishing primary pyroclast flow from secondary mudflow deposits - has already been discussed (p. 19). Another major difficulty lies in the fact that Pelean type pyroclast flows are geographically restricted to a small segment of the volcano (MacGregor, 1952, p. 55)

so that deposits found in one area do not necessarily have equivalents elsewhere. Unfortunately, the use of the rare pyroclast fall beds for correlation is limited by various factors. These beds are always very thin and the effects of erosion have led to their absence in places. It is also possible that some of the pyroclast falls were formed by directed blast explosions and were deposited over a limited area anyway.

The approach adopted in unravelling the pyroclastic stratigraphy of the Soufriere Hills has been as follows. Where possible, detailed successions have been worked out but the detailed correlation of these successions with those in other areas is usually impossible (see Fig. 12). However, in all the successions examined, a similar change, with age, in the lithology of the predominant block type is observed. On this basis three main groups of pyroclastic deposits have been recognised. These are, starting with the oldest:

- (1) Two-pyroxene andesite pyroclast flows and mudflows.
- (2) Older hornblende-hypersthene andesite pyroclast flows, pyroclast falls and mudflows.
- (3) Younger hornblende-hypersthene andesite pyroclast flows, pyroclast falls and mudflows.

With the exception of the widely distributed pumice flow which is the basal member of Group 3 the deposits of this group are rather difficult to distinguish from those of Group 2. However, deposits can usually be assigned to one group or the other on the basis of their relationship to the pumice flow. In addition, Group 3 deposits contain a preponderance of lava blocks with large hornblende phenocrysts (Castle Peak type).

All the fragmentary deposits of the Soufriere Hills can be fitted into these three groups except for a rather obscure outcrop of hypersthene-andesite pumice, which is described separately below.

It should be noted that this broad lithological classification for the fragmental

deposits of the Soufriere Hills has the advantage of reducing the need to distinguish Pelean type pyroclast flows and mudflows. Since mudflows redistribute material largely from the top of the volcanic pile they contain blocks of similar lithology to those in the most recent pyroclast flows so that the general change of block types with time in a mixed succession of pyroclast flows and mudflows will be the same as in a succession made up entirely of pyroclast flows.

The best exposures of Soufriere Hills pyroclastics are found in the banks of ghaunts or in sea cliffs. A very extensive section, over 300 ft. thick, is seen in the high cliffs on the east coast of Montserrat (Plate 7B) where the general dip of deposits towards the N.E., results in beds successively higher in the succession being exposed at the base of the cliffs and in adjacent ghaunts as one goes north. The deposits in these cliffs are well-bedded and contain some rounded boulders (Plate 8A) and are considered to be predominantly fluvial deposits but unworked facies of the same material are exposed further inland. On the west side of the Soufriere Hills the pyroclastic deposits are less dissected and rather less than the top 100 ft. of the succession can be seen.

Sections through the pyroclastic successions at various localities in the Soufriere Hills are shown in Fig. 12 and a composite section showing the full pyroclastic succession is given for comparison.

Histograms showing grain size distribution in Soufriere Hills pyroclastics are given in Fig. 13. With the exception of 18580 and 18570 all the samples are completely unsorted. It should be noted, however, that the two samples of pumice flow (18615 and 18606) have very similar grain size distributions although they were collected from widely separated localities. The two pyroclast falls (18580 and 18570) do not show such good sorting as the pyroclast falls of South Soufriere Hill (Fig. 9). This may be due to the fact that these deposits are very thin and that some material from overlying or underlying deposits was inadvertently included in the sample.

Fig.12 Sections Through the Pyroclastic Successions of the Soufrière Hills

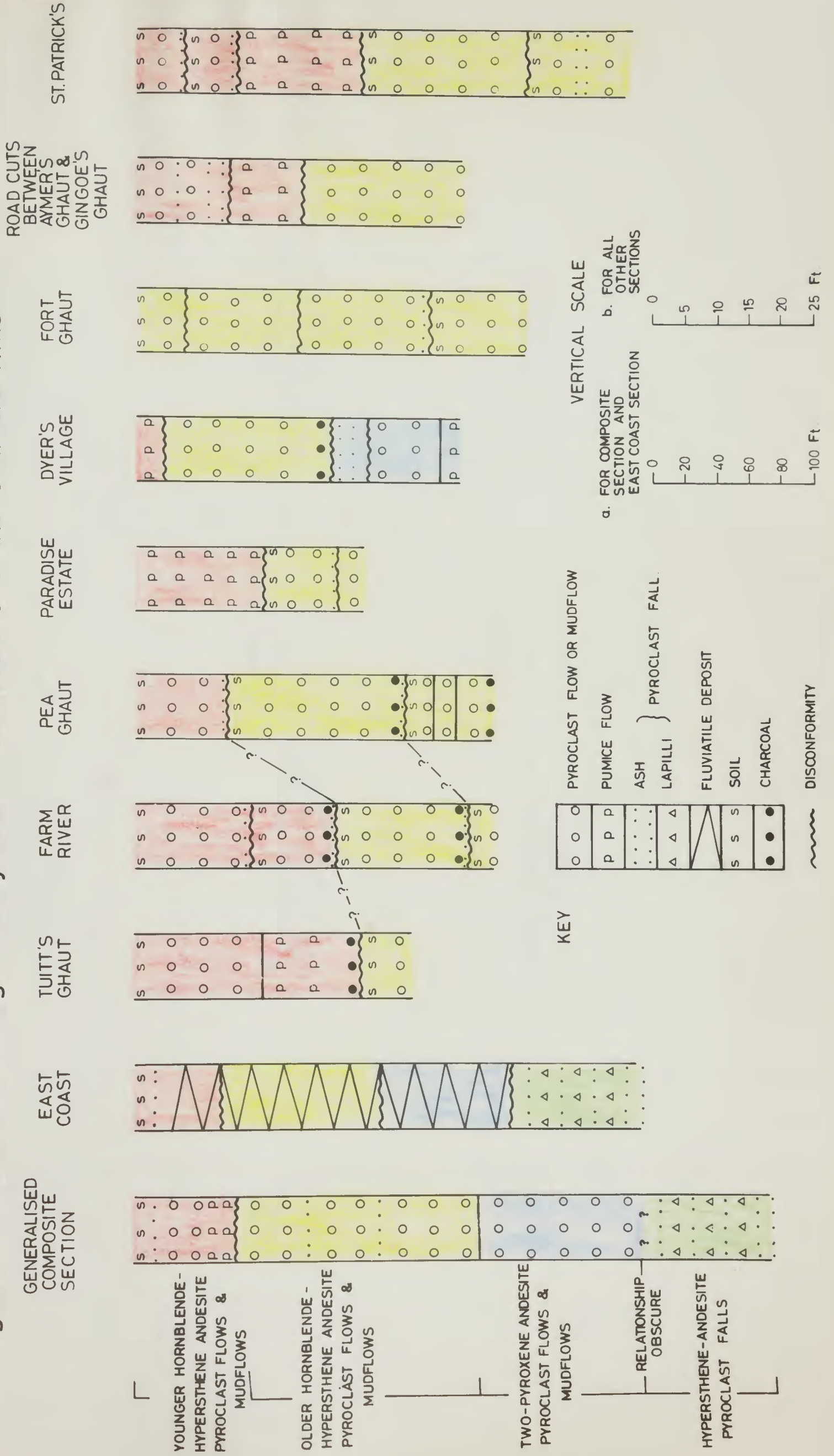
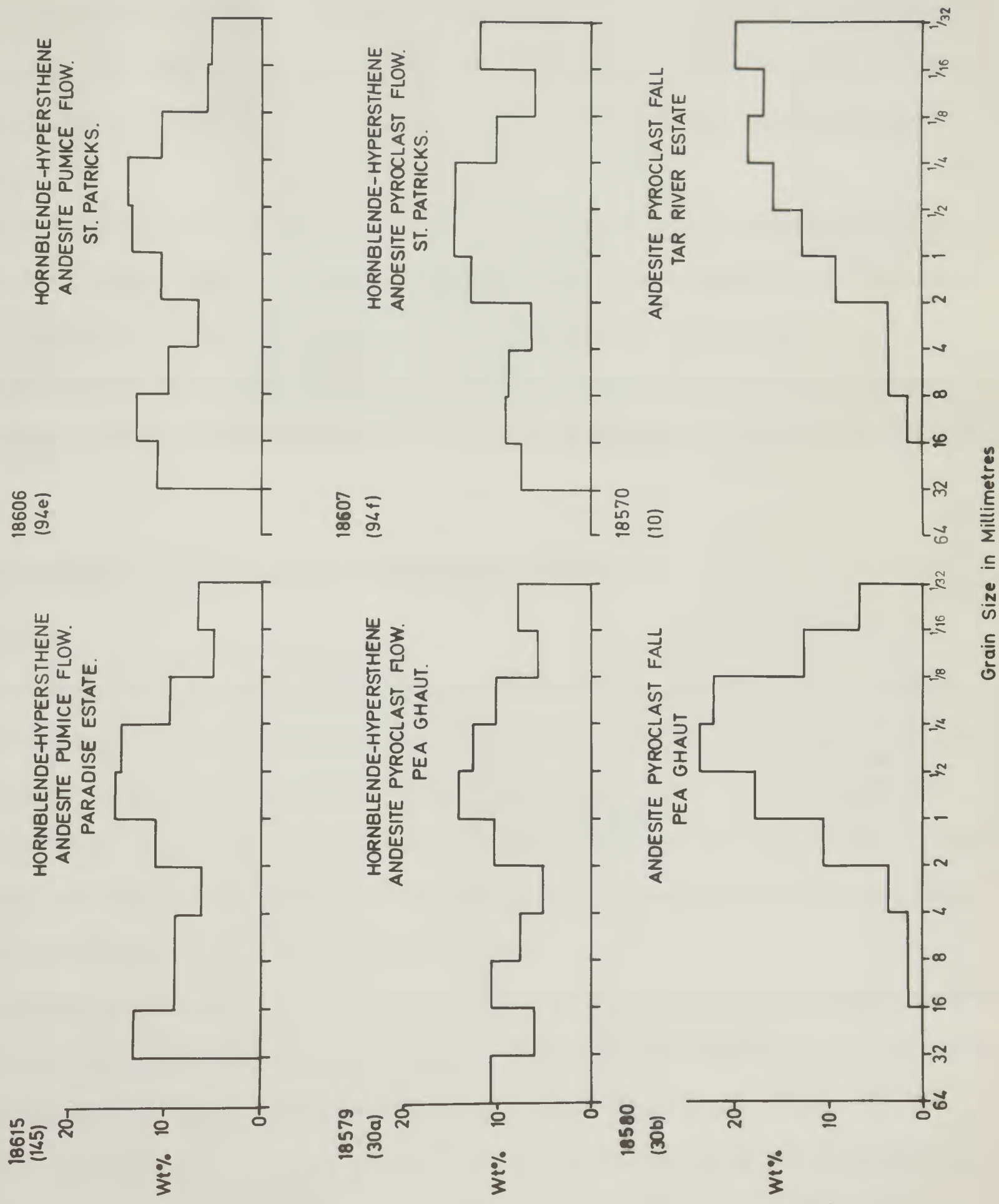


Fig 13. Grain Size Distribution in Pyroclastic Deposits of the Soufriere Hills.



12:3:2 Hypersthene-Andesite Pumice Falls.

At the bottom of the high cliffs about $\frac{1}{2}$ ml. northeast of Tar River Estate is a thick series (30 - 80 ft.) of moderately finely bedded white ash and lapilli beds (Plate 8B). Most of the fragments in these beds are of white hypersthene-(hornblende)-andesite pumice. The beds are slightly cross-bedded in places and have obviously been somewhat reworked - probably as fluvial material. They probably represent original pumice falls.

Nothing resembling these beds has been seen elsewhere in the Soufriere Hills, and although this series bears a superficial resemblance to the Roche's tuffs the two are probably unrelated (Table 2). From their position at the base of the east coast pyroclastic succession the hypersthene-andesite pumice fall beds are probably early Soufriere Hills deposits and dissection may not be deep enough to expose them anywhere else.

12:3:3 Two-Pyroxene Andesite Pyroclast Flows and Mudflows.

Gage's Dome Area.

In the deep ghaat which marks the eastern boundary of Gage's Dome, in the upper part of Fort Ghaat and in road cuts between Gage's Estate and Dyer's Village, mudflows containing blocks of Gage's Dome lava (augite-hypersthene andesite) are interbedded with pyroclast flows containing fragments of augite-hypersthene andesite pumice. These beds are sometimes unconformably overlain by hornblende-hypersthene andesite pyroclast flows and mudflows (Fig. 12, Dyer's Village section).

The formation of Gage's Dome and the ejection of these augite-hypersthene andesite pyroclast flows were obviously closely related. Apart from the lithological similarity pyroclast flows of this type are restricted to the area around Gage's Dome. It is probable that the pyroclast flows originated during the formation of the dome, due to the violent escape of gaseous products through the piles of lava. The relationship of the Gage's augite-hypersthene andesite pyroclast flows to the hypersthene-andesite



PLATE 8A. Close-up of reworked Soufriere Hills deposits. East coast of Montserrat, about 400 yds. south of Tuitt's Ghaut. The picture shows younger fluvial deposits (above right) infilling a channel cut in an older mud flow (bottom left). The boulders in these deposits are better rounded than those in the Soufriere Hills pyroclast flows (Plate 9).



PLATE 8B. Cliffs on the east coast of Montserrat, below Mulcare's. The cliffs are composed mainly of reworked Soufriere Hills deposits but some relatively unworked hypersthene-andesite pumice falls occur at the base. The landslipped material in the foreground of the picture may obscure the site of Mulcare's Soufriere.

pumice falls on the east coast is uncertain but as the Gage's beds are associated with what is the earliest recognisable event in the evolution of the central nucleus (p. 53) it is possible that the Gage's beds are older.

Perche's Dome Area.

Beds of hypersthene-augite andesite tuffs and mudflow are well displayed on the easterly flanks of Perche's Dome. Hornblende-hypersthene andesite mudflows overlie these beds in places.

East Coast Exposures.

Immediately above the irregular, reddened upper surface of the white hypersthene-andesite pumice beds is 30 - 80 feet of pinkish, well-bedded agglomerate. The agglomerate contains mostly blocks of dark two-pyroxene andesite but some of the highest beds contain fragments of hornblende-bearing two-pyroxene andesite.

12:3:4 Older Hornblende-Hypersthene Andesite Deposits.

Hornblende-hypersthene andesite mudflows and river deposits, amounting to a thickness of over 150 ft., are exposed in the east coast cliffs (Plate 8). Unworked deposits of the same material can be seen in Tuitt's Ghaut and in excellent sections in the banks of Pea Ghaut, and Farm River (Fig. 12) though unfortunately the uppermost 20 ft. of the succession is inaccessible here.

The deposits in the banks of Pea Ghaut and Farm River are rhythmic and at least three and possibly four rhythmic units are represented. Each unit begins with a thin, fine-grained well-sorted pyroclast fall. This is overlain by a Pelean type pyroclast flow (usually about 20 ft. thick) with charcoal in a thin layer at the base. The pyroclast flows redden upwards and up to three feet of soil have developed at the surface, suggesting that there was a fairly long time interval between the deposition of successive units. Charcoal from the base of the second pyroclast flow, which is 40 ft. and two cycles below the present surface, gave an age of $23,566 \pm 786$ years (Shotton et al., 1968) compared with an age of 320 ± 54 years for the most recent eruption of the Soufriere Hills (p. 63).

The pyroclast flows are poorly sorted (Fig. 13) and contain blocks which vary somewhat in vesicularity, but most of the blocks are moderately vesicular. Extremely vesicular fragments are rare but about 10 - 20% of the blocks are of non-vesicular lava. All the blocks collected were composed of hornblende-hypersthene andesite. Blocks containing large hornblende phenocrysts (Castle Peak type) were not seen but may occur in the inaccessible beds at the top of the succession.

In the lowest of the pyroclast flows almost all the blocks are banded. Rather irregular, dark and intermediate bands occur within an otherwise light coloured pumice. The different bands are all apparently composed of hornblende-hypersthene andesite. Numerous blocks of non-vesicular lava, showing a similar type of irregular banding except that grey and black bands are more abundant than white lie loose in Pea Ghaut (Plate 22B) and the two sets of blocks may be genetically related. The banded lava has not been seen anywhere in situ but the blocks are probably of dome lava, since lava flows are unknown in the Soufriere Hills and banding of the type described is sometimes found in dome lavas. (Tomblin, 1964, p. 43 reports the presence of similar, though rather more regular banding in the Petit Piton dacite, St. Lucia. See also Tomblin, 1964, p. 62). The original dome has apparently been destroyed but as the blocks are found only on the northeast side of English's Crater, its most likely location is on the north side of the crater. The "banded" pyroclast flow probably occurred during the formation of this dome. The petrology of the banded blocks are discussed on page 131.

Good exposures of hornblende-hypersthene andesite deposits are also found on the western side of the Soufriere Hills, notably in the St. Patrick's area but also in Fort Ghaut and in road cuts between Plymouth and St. Patrick's (Fig. 12). At St. Patrick's at least three separate pyroclast flows, with a total thickness of over 70 ft., have been distinguished but the uppermost of these contains an appreciable proportion (60 - 70%) of blocks of Castle Peak type pumice and is described in the next section. The bottom two flows contain blocks of hornblende-hypersthene andesite of varying vesicularity.

but no banded blocks were seen. None of the pyroclast flows on the west side of the volcano were found to contain charcoal, though some partially carbonised root debris occurs at the base of a pyroclast flow in Fort Ghaut.

Up to 12 in. of finely bedded, pisolitic, pyroclast fall deposit underlies the second of the pyroclast flows at St. Patrick's (Plate 9A) but the western pyroclast flows are not always underlain by pyroclast falls as is the case in the Pea Ghaut exposures. Soils are, however, usually developed at the top of the pyroclast flows.

The older hornblende-hypersthene andesite deposits were probably deposited during the period in which Galway's Dome and Chance's Dome were extruded. There is little evidence for the existence of a crater at this stage of the development of the central nucleus (p. 55) and it is probable that these deposits were erupted from a series of hornblende-hypersthene andesite domes. There may originally have been more domes than the two that exist at the present time.

12:3:5 Younger Hornblende-Hypersthene Andesite Deposits.

Exposures in Tuitt's Ghaut, at Paradise Estate and in the St. Patrick's area (Fig. 12) show hornblende-hypersthene andesite pyroclast flows and mudflows, overlain by pumice flows (Plate 9B). There is usually an indication of some time interval between the deposition of the pyroclast flows and the pumice flows. In the St. Patrick's area, for instance, two feet of soil formed at the top of the pyroclast flow before the deposition of the pumice flow, while at Paradise Estate, the pumice flow apparently infills a river valley, cut in older pyroclast flows. Although the exposures of pumice flow are widely separated the deposits in the different exposures are very similar with respect to their grain size distribution (Fig. 13), the ratio of lava to pumice blocks (less than 1:10) and the lithology of the included pumice fragments. The pumice is a pinky, cream-coloured hornblende-hypersthene andesite pumice with large phenocrysts of hornblende. It is richer in phenocrysts than any of the other Montserrat pumices and the phenocrysts are larger. The different pumice flows are so similar that they almost



PLATE 9A. Hornblende-hypersthene andesite pyroclast flow, 200 yds. west-south-west of St. Patrick's Village. The pyroclast flow is unsorted and contains fragments which vary with respect to lithology and vesicularity. The pyroclast flow overlies a thin, rather irregular, fine grained pyroclast fall which overlies another pyroclast flow.



PLATE 9B. Close-up of hornblende-hypersthene andesite pumice flow, Paradise Estate. This deposit is also unsorted with respect to the grain size of its constituents. However, over 90% of the fragments are composed of creamy white hornblende-hypersthene andesite pumice of very uniform lithology.

certainly belong to the same phase of volcanic activity.

The most obvious difference between the pumice flows and the underlying pyroclast flows lies in the vesicularity of the included fragments and this is in turn considered to reflect a difference in the mode of origin of the two types of deposit. As pointed out above (p. 19) pyroclast flows erupted from a dome will contain lava blocks showing varying degrees of vesicularity, whereas pyroclast flows erupted from an open vent will contain a much higher proportion of pumice.

No doubt, the hornblende-hypersthene andesite pumice flows were erupted from an open vent and the most likely source is English's Crater before the growth of the Castle Peak dome and before the breaching of the crater wall. This second proviso is necessary to explain the circum-volcanic distribution of the pumice flow deposits. Pumice flows erupted from the present crater would be concentrated on the eastern flank of the volcano.

It is possible that the pumice flows actually accompanied the formation of English's Crater. The explosive eruption of a gas-charged magma such as that which gave rise to the pumice flows would probably be capable of producing a crater and there are well-documented cases of pumice flow eruptions accompanying the formation of calderas as at Crater Lake (Williams, 1942). The youthful morphology of English's Crater and the fact that it truncates the Older Domes suggest that the crater is of fairly recent origin but charcoal collected by the writer from the base of a pumice flow in Tuitt's Ghaut has given an age of $18,390 \pm 360$ yrs. (F. W. Shotton, 1969, pers. comm.). It is possible therefore that English's Crater owes its well-preserved morphology to more recent eruptions than the pumice flows.

The most recent deposits of the Soufriere Hills appear to be associated with the Castle Peak Dome. The eastern flank of the dome is largely covered by talus and mud-flow deposits but these are overlain in places by up to three feet of grey ash and by thin pyroclast flows, containing blocks of Castle Peak type lavas. Certain fine-grained beds that occur at the top of the pyroclastic succession on the west side of the

Soufriere Hills may be related to the ash seen in the Tar River area.

Charcoal was not seen in the thin pyroclast flows examined by the writer but Prof. L. R. Wager and Dr. G. R. Robson, who visited Montserrat in 1959 collected charcoal from a thin pyroclast flow deposit, less than three feet below the present surface, at a locality about half a mile southwest of Tar River Estate. This charcoal has given an age of 320 ± 54 yrs. (J. F. Tomblin, 1968, pers. comm.) which dates the eruption at 1646 A.D. or between 1592 and 1700 A.D. In view of the fact that volcanic activity on one island in the Lesser Antilles is often accompanied by disturbances on other islands (as in 1902) it is worth noting that there was a period of intense solfataric activity on Guadeloupe in 1645 (Robson and Tomblin, 1966, p. 19). Other volcanic disturbances in the Lesser Antilles which fall within the limits of the age of the Montserrat eruption are the phreatic eruptions at Guadeloupe in 1680 and 1696 and at St. Kitts in 1692/93 (Robson and Tomblin, 1966).

The Montserrat eruption occurred about 150 years after Columbus discovered the West Indies and it probably also postdates the European colonisation of the island (1632). The complete lack of reports of an eruption on Montserrat about this time is, therefore, rather puzzling but can be explained by assuming that the eruption was a minor one, which was not observed or recorded by the white settlers, who, at this time only occupied the north and west of Montserrat. The author feels, however, that the lack of reports precludes the possibility that a major series of eruptions, culminating in the formation of the Castle Peak Dome occurred at this time. It is probable that the Castle Peak Dome was extruded in late pre-Columbian times and that the dated eruption was a later minor affair, perhaps like the phreatic eruption of the Soufrière, Guadeloupe in 1956 (Barrabé and Jolivet, 1958).

12:4 THE SOUFRIERES AND RECORDED VOLCANO-SEISMIC ACTIVITY.

Seven active soufrieres occur on the flanks of the Soufriere Hills. Their positions are shown on the geological map (end pocket). The two largest soufrieres -

Gage's Upper Soufriere and Galway's Soufriere (Plates 7A and 10A) occur on the west side of English's Crater in the depressions which separate Gage's Dome from Chance's Dome, and Chance's Dome from Galway's Dome, respectively. In 1953 Robson and Willmore (1955) measured heat flows of 1.2×10^6 cal/sec at Gage's Upper and of 0.3×10^6 cal/sec. at Galway's Soufriere. The heat flow from the other soufrieres was less than a few thousand calories per second. Detailed descriptions of Gage's Upper, Galway's and the other soufrieres are given in MacGregor (1938, pp. 39-47), Perret (1939), Robson and Willmore (1955, pp. 32-34) and Martin-Kaye (1959, pp. 86-92) and the writer has very little new to add to these accounts.

However, the writer did visit Mulcare's (Mulcair's) Soufriere, which was regarded by MacGregor and Martin-Kaye as inaccessible but which can in fact be reached by scrambling along the east coast from Spanish Point. Unfortunately, there is nothing to see when one gets there! There is a strong smell of hydrogen sulphide but no steam, no active vents and very little alteration. Recent landslip material (Plate 8B) may cover some of these features.

Three periods of unusually intense solfataric activity, accompanied by swarms of shallow focus earthquakes have occurred within the last 70 years (Robson and Tomblin, 1966, p. 16). The first of these periods of activity was between 1897 and 1898 and the second, which stimulated the Royal Society Expedition to Montserrat was between 1933 and 1936. In 1933-6 emission of gas (mainly steam at 100°C and hydrogen sulphide) increased considerably in volume, but remained unchanged in composition and temperature. The earthquake foci were at a depth of one or two kilometres, many of them originating beneath the Soufriere Hills and St. George's Hill (Powell, 1938).

The most recent crisis which began in March, 1966, and ended in November, 1967, was thoroughly investigated by members of the Seismic Unit of the University of the West Indies (Shepherd, et al., 1969). Between May, 1966 and December, 1967 they recorded over 700 local earthquakes and determined hypocentres for 190 of these. They found that the majority of these hypocentres lay in a belt running W.N.W. - E.S.E. beneath the



PLATE 10A. Galway's Soufriere. Small, relatively inactive vent emitting mostly steam and H_2S .



PLATE 10B. St. George's Hill (foreground) and Gage's ^{and} ~~s~~ Chance's Domes from Richmond Estate.

Soufriere Hills at depths of less than 15 km. It should be noted that this direction parallels the main alignment of volcanic centres on Montserrat (p. 14). The average depth of the earthquakes decreased from 5.2 km. in April and May, 1966 to a minimum of 2.8 km. from July to September, 1966. After September the mean focal depths increased again and by the end of the crisis in November, 1967 the mean focal depth was 9.7 km. Tilt measurements showed that the region 2-3 km. southeast of the Soufriere Hills was doming upwards until January, 1967, then subsided between March and September, 1967 (Fig. 14). The rate of heat flow from Galway's Soufriere which was 3×10^5 cal/sec. in 1954 increased to a maximum of 2×10^6 cal/sec. in October, 1966, then declined to 5×10^5 cal/sec. in September, 1967. Shepherd et al. (1969) also published analyses of gas samples from the Montserrat soufrieres. The gas emitted consisted largely of superheated steam. Non-condensable gases included CO_2 (70-80% of total non-condensable gases), H_2S (15-30%) with small amounts of N_2 , H_2 , CH_4 and other hydrocarbons, Ar and CS_2 . The proportion of CO_2 increased while that of H_2S decreased with increased heat flow.

As a result of their investigations Shepherd et al. (1969) concluded that there is a magma chamber beneath and to the southeast of the Soufriere Hills. They considered that the earthquake series was not the aftershock sequence of any major tectonic earthquake but that it resulted from the migration of magma upwards until about August, 1966 and laterally or downwards after this date.

Seismic crises of similar type to the three which have occurred in Montserrat are quite common in the Lesser Antilles. Recent crises include those in St. Vincent (1947); Nevis (1950 and 1961); Guadeloupe (1956) and Dominica (1967). In only one of these cases (Guadeloupe, 1956) was the seismic crisis followed by an eruption. It appears, therefore, that the rise and subsequent withdrawal of magma may occur several times beneath a volcano before an eruption takes place. The possible petrological effects of this are discussed in chapter 15.

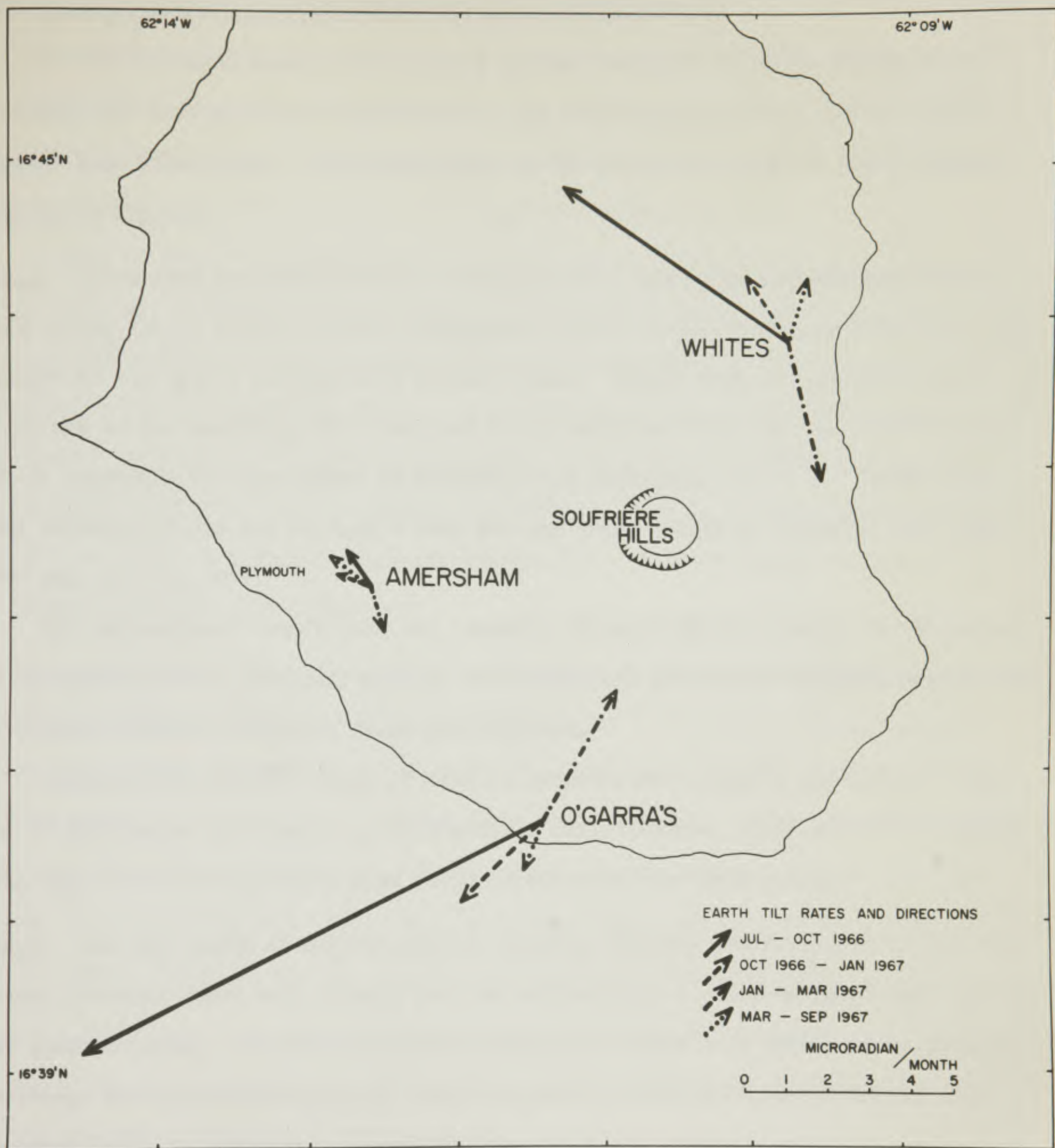


FIGURE 14. Earth tilt rates and directions during the 1966-67 seismic crisis on Montserrat, measured by Hawaiian-type long base water tube tiltmeter, (after Shepherd et al., 1969, Fig. 8).

12:5 SUMMARY OF THE VOLCANIC HISTORY OF THE SOUFRIERE HILLS.

In the following section the history of the Soufriere Hills is described and comparisons are made with other volcanoes in the Lesser Antilles and with andesitic volcanoes from other areas. The development of the Soufriere Hills is shown diagrammatically in Fig. 15.

STAGE 1. Apart from the problematical deposition of a series of hypersthene-andesite pumice falls, (p. 59) the earliest recognisable event at the Soufriere Hills was the extrusion of the Gage's two-pyroxene andesite dome. Gage's Dome may possibly be of similar age to the Raspberry Hill Domes of South Soufriere Hill and the Roche's lava, which it resembles to some extent in chemistry and mineralogy (p. ⁴⁰~~59~~). There is no direct evidence of the age of Gage's Dome but the Roche's Lava is probably less than 40,000 yrs. old (p. 48).

The extrusion of Gage's Dome was probably followed fairly closely by the formation of Perche's Dome. The extrusion of both domes was associated with the eruption of two-pyroxene andesite pyroclast flows and mudflows.

Two-pyroxene andesite domes of similar composition to Gage's and Perche's Dome occur in the Lesser Antilles, e.g. Saddle Hill, Nevis (Hutton, 1965) but MgO is higher in the Gage's Dome lava than in most other Lesser Antillean dome lavas.

STAGE 2. The next phase of activity which probably followed the extrusion of the two-pyroxene andesite domes very closely saw the extrusion of a group of hornblende-hypersthene andesite domes. Of these, Chance's Dome and Galway's Dome remain today but there is evidence for the extrusion of at least one other hornblende-hypersthene andesite dome which has been subsequently destroyed (p. 61).

Extensive pyroclast flows and mudflows were erupted at this stage together with minor pyroclast falls. Charcoal from a hornblende-hypersthene andesite pyroclast flow, collected from about 40 ft. below the present surface gave an age of $23,566 \pm 786$ yrs. (p. 60). It is probable also that St. George's Hill, a small centre on the north-west

flank of the Soufriere Hills was active about this time (p. 72). St. George's Hill erupted a large volume of hornblende-hypersthene andesite pumice falls.

Hornblende-hypersthene andesite domes of similar composition to Chance's Dome and Galway's Dome are quite common in the Lesser Antilles, e.g. Nevis Peak, Nevis (Hutton, 1965) or the Pitons du Carbet, Martinique (Lacroix, 1926).

There is not much evidence for the existence of a crater during stages 1 and 2 of the evolution of the Soufriere Hills (p. 55) and the two-pyroxene andesite pyroclast flows and the older hornblende-hypersthene andesite pyroclast flows were probably erupted from the flanks of the growing domes. Domes without craters include the Mountain, Saba (Westermann and Kiel, 1961) which is associated with extensive pyroclast flows and the Soufriere, Guadeloupe. Lewis (1968^a) has described a cluster of five volcanic domes at Tauhara, New Zealand, which are not associated with any major crater although some of the domes have small summit craters.

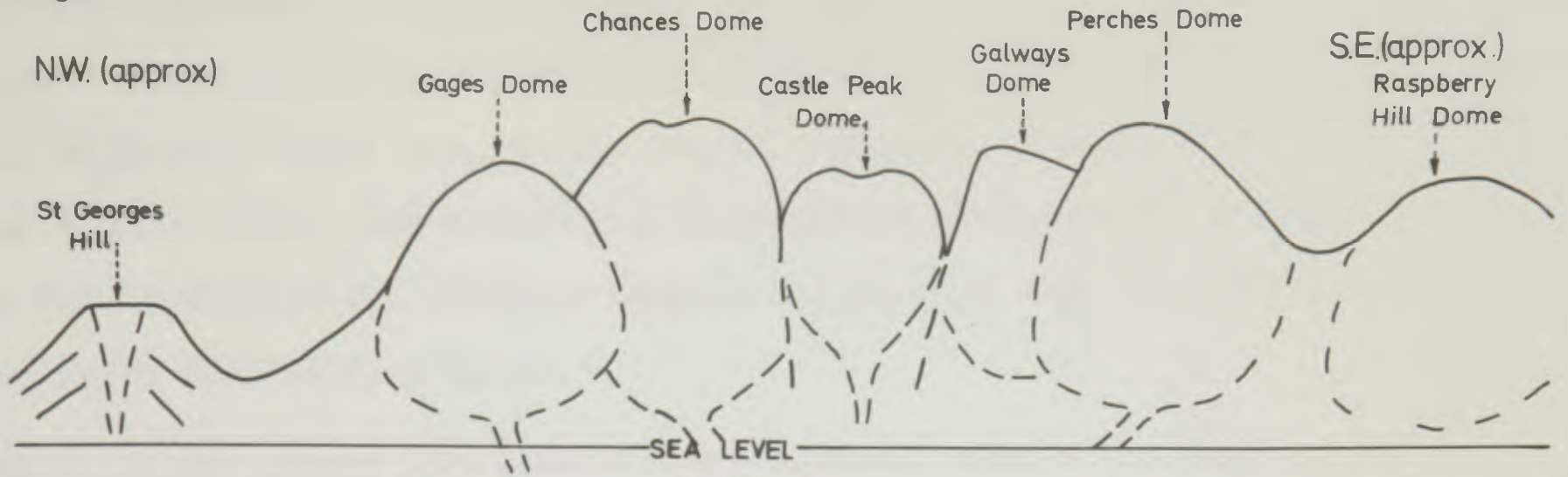
STAGE 3. Some time after the extrusion of the older domes explosive eruptions removed part of the eastern flanks of the Older Domes and led to the formation of English's Crater. Hornblende-hypersthene andesite pumice flows were probably the main products of these eruptions (p. 63), and charcoal from one of these has given an age of $18,390 \pm 360$ yrs. (p. 63). The eruption of pumice flows accompanied the formation of the caldera at Crater Lake (Williams, 1942) but pumice flows are rare in the Lesser Antilles. They have been described only on St. Lucia and Dominica (Tomblin, 1964, p. 163).

STAGE 4. The final phase of activity at the Soufriere Hills included the formation of the Castle Peak hornblende-hypersthene andesite dome although it is possible that the present dome is the last of a series of domes that have occupied English's Crater. The growth of the Castle Peak Dome was apparently accompanied by the eruption of pyroclast flows and mudflows and minor eruptions of pyroclast flows and pyroclast falls have occurred since the consolidation of the dome (p. 63). The most recent of these eruptions occurred 320 ± 54 yrs. ago (p. 64).

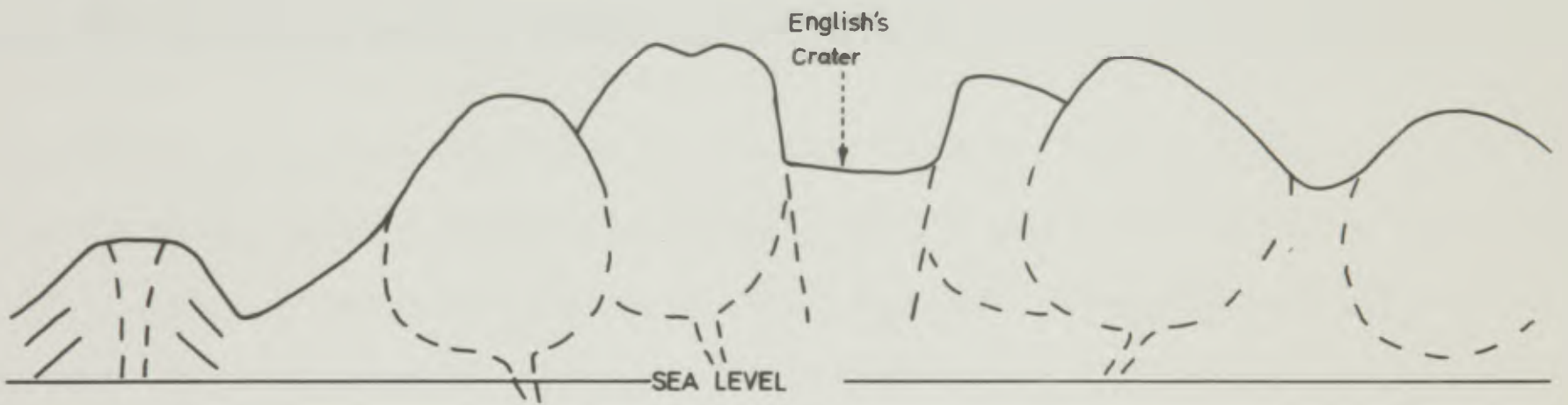
Fig 15

The Development of the Soufriere Hills

Stage 4.



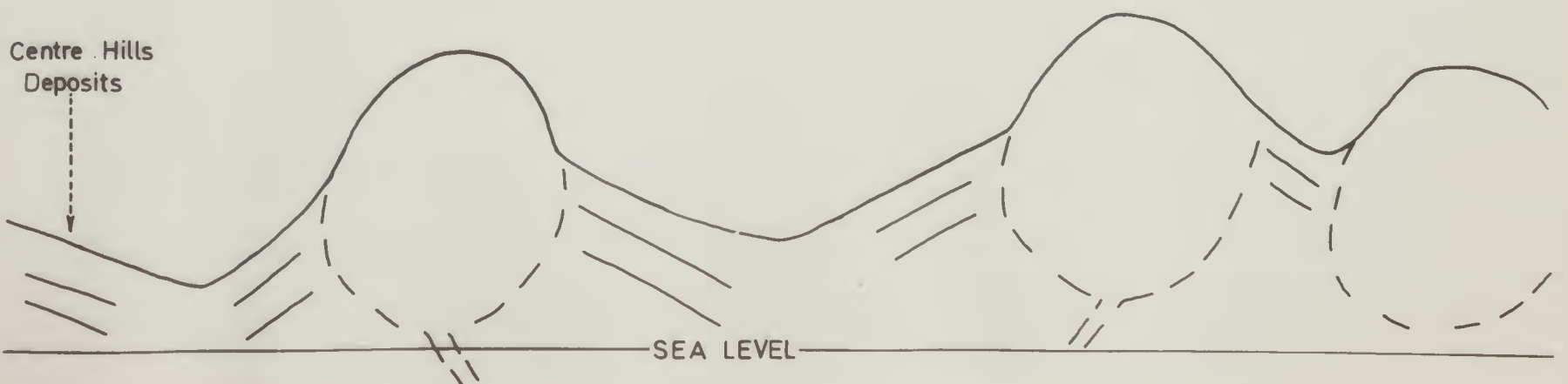
Stage 3



Stage 2



Stage 1



The growth of the Castle Peak Dome or an earlier crater dome is believed to have been responsible for the breaching of the eastern wall of English's Crater (p. 56). Breached craters containing crater domes include South Soufriere Hill (p. 39); Mont Pele, Martinique; Nevis Peak, Nevis; Mt. St. Catherine, Grenada; and Mt. Lamington, Papua (Taylor, 1958). The structure of the Soufriere Hills is in fact closely comparable with the structure of Mt. Lamington (compare Taylor, 1958, Fig. 4, with the summit structure of the Soufriere Hills).

STAGE 5. At the present time seven active soufrieres occur on the flanks of the Soufriere Hills. Recorded volcanic activity has included three periods of intense seismic and solfataric activity within the last 70 years.

CHAPTER 13.

ST. GEORGE'S HILL.

13:1 INTRODUCTION.

St. George's Hill (Plate 10B) which rises to 1,185 ft. a.s.l. is a more or less flat topped hill but the summit area is divided into two S.E. - N.W. trending ridges - a higher one in the south-west and a lower one in the north-east - separated by a broad valley. No major vent is visible but some small hollows near the summit of the hill are probably small explosion craters.

The eruptions of St. George's Hill have almost all been explosive and the centre has given rise to a large quantity of acid andesite pyroclast falls. No lava flows or domes have been positively identified and although the hill is littered with lava boulders most of these are probably attributable to the Soufriere Hills or Centre Hills volcanoes. However, a number of large lava blocks, of dark grey hornblende-hypersthene andesite which occur in close proximity to one another on the N.E. ridge of the hill about ¼ ml. north of the summit may represent a broken-up flow.

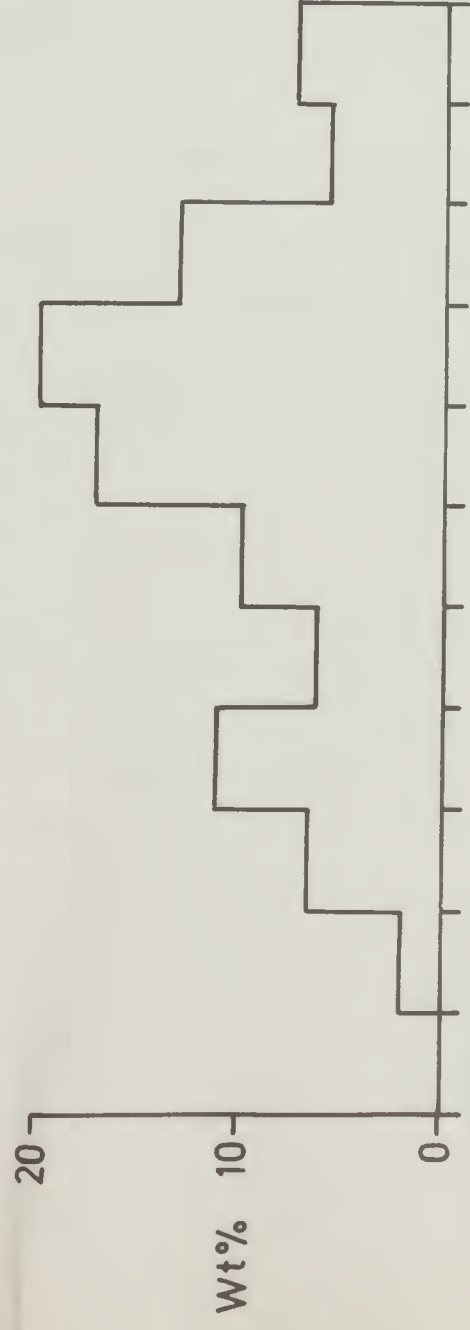
13:2 ACID ANDESITE PYROCLAST FALLS.

Deposits on St. George's Hill include some quite finely-bedded pumiceous ash falls but most of the exposures on the hill itself are of coarse, massive ill-sorted (Fig. 16) pumice-rich material. Blocks of hypersthene-hornblende andesite pumice account for about 90% of all the fragments in these deposits while the other 10% are usually fragments of two-pyroxene andesite lavas which probably represent fragments of older Centre Hills material through which the pumice has been erupted. Rare fragments of olivine-basalt are also found in some of the pyroclast falls, which suggests that material derived from South Soufriere Hill may underlie St. George's Hill (p.35).

The mode of origin of the pumice beds is somewhat problematical. They have the sorting characteristics of pyroclast flow deposits (Fig. 16) but as Murai (1961, p. 199) has pointed out coarse, bomb-rich pyroclast falls deposited in the immediate vicinity

Fig 16. Grain Size Distributions in Pyroclastic Deposits from St. George's Hill.

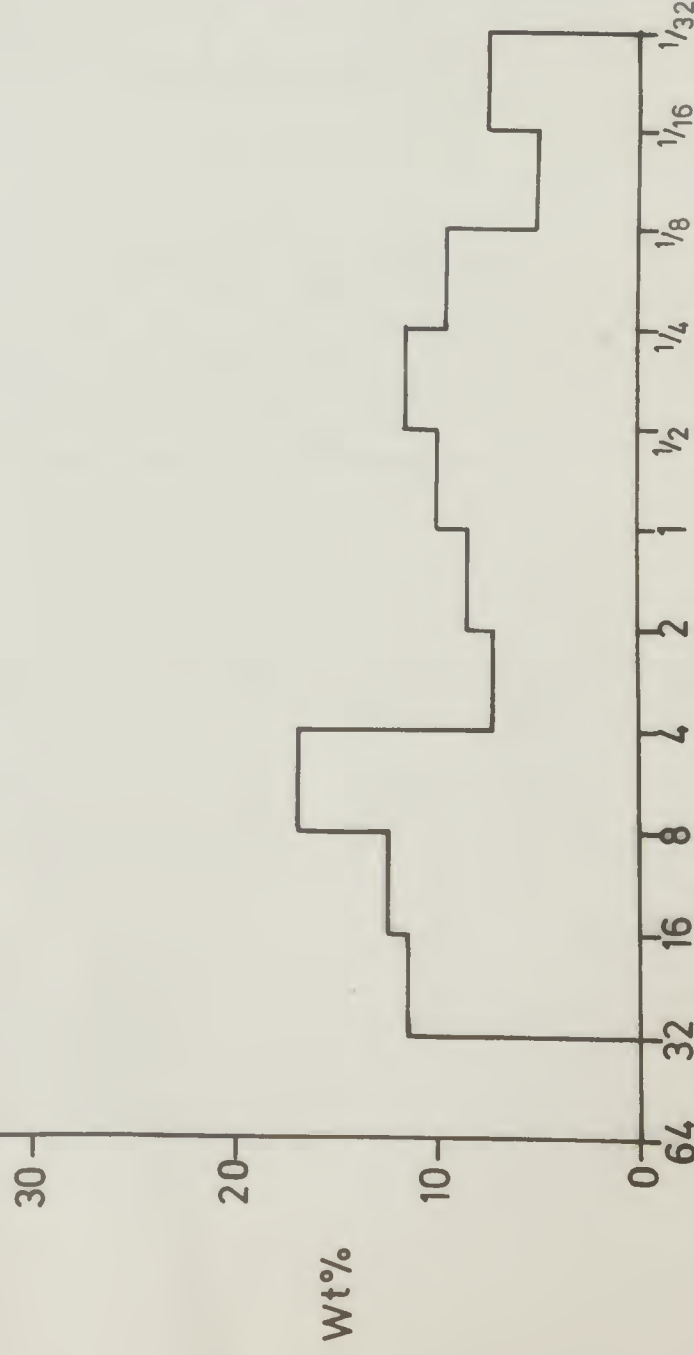
18696
(20)
400yds. EAST OF SUMMIT.



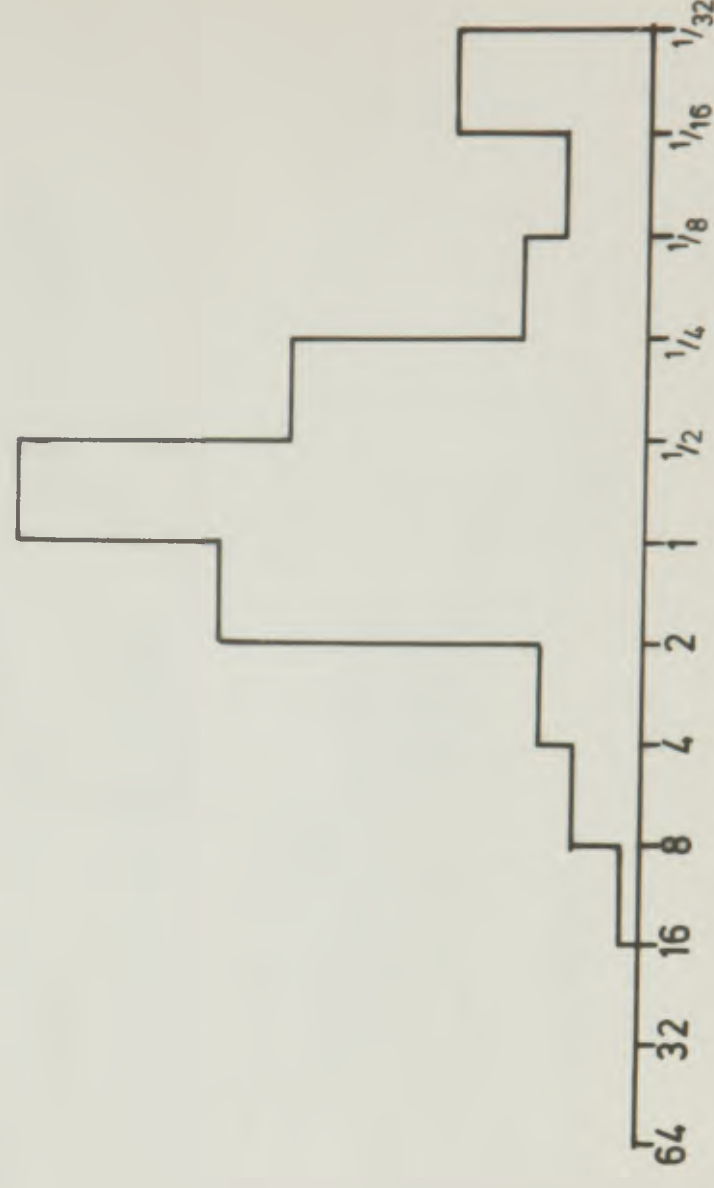
18573
(22)
900yds. NORTH-EAST OF SUMMIT.



18650
(377a)
900yds. EAST OF SUMMIT.

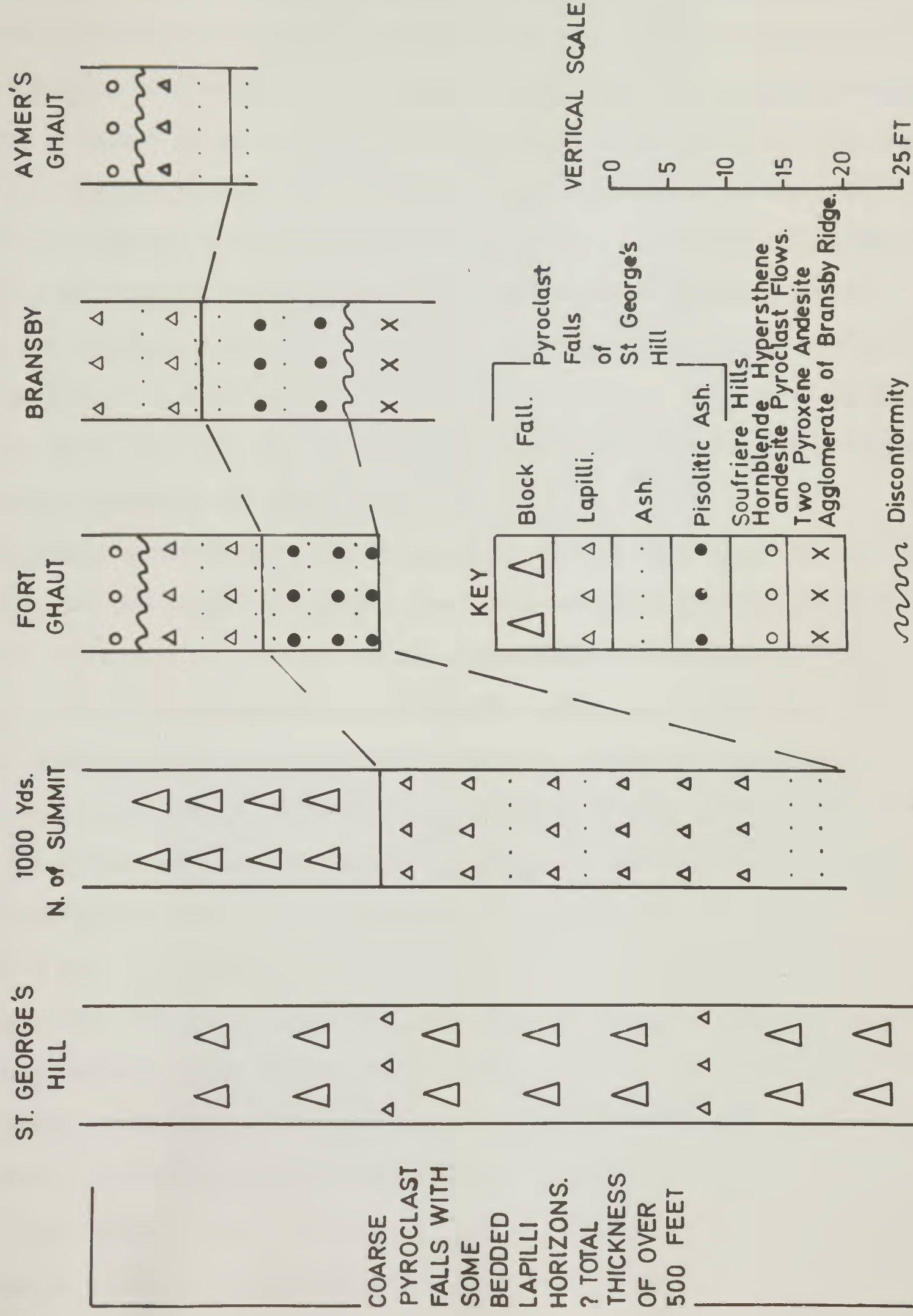


18600
(57)
2640yds. SOUTH OF SUMMIT.



Grain Size in Millimetres

Fig. 17. SECTIONS THROUGH ST. GEORGE'S HILL PYROCLAST FALLS.



of an eruptive vent may have similar sorting characteristics to pyroclast flows. The fact that the coarse, unsorted pumice deposits cannot be traced away from St. George's Hill suggests that they are pyroclast falls rather than pyroclast flows and the occurrence of deposits, intermediate in character between these structureless beds and the well-bedded pyroclast falls, which surround St. George's Hill, confirms this view. Intermediate deposits were seen north of St. George's Hill, e.g. in the south bank of Belham River. They are coarse-grained (mostly lapilli), moderately well-bedded pyroclast falls, composed of fragments of hypersthene-hornblende andesite pumice.

As was mentioned above, pyroclast falls attributable to the St. George's Hill centre have been recognised at several localities around the hill, some of which are as much as two miles away from the present summit. Detailed stratigraphic sections at some of these localities are shown in Fig. 17.

In general these deposits are fine-grained, well-bedded (Plate 11) and well-sorted (Fig. 16) and pisolitic horizons are common but the overall composition of the deposits is apparently very similar to the composition of deposits nearer the hill. Thin beds of fine hypersthene-hornblende andesite pumice are interbedded with finely comminuted ashes containing crystals of plagioclase, hornblende, hypersthene, clinopyroxene, quartz and ore together with tiny fragments of hypersthene-hornblende andesite pumice. In all the sections examined the proportion of coarser beds increases upwards.

Estimation of the original thickness distribution of the pyroclast falls of St. George's Hill is complicated by several factors. The numerous mudflows on St. George's Hill and the cross-bedding, slumping and channel-fill structures displayed in road cuts between Gage's Estate and the summit of the hill show that erosion and redistribution of St. George's Hill material have been widespread. Further difficulties arise from the lack of marker horizons in the pyroclast fall series which is made up of a very uniform group of beds. Not only does this prevent detailed correlation of successions at different localities but it also makes it very difficult to estimate what proportion of the original deposit is present at each locality. However, it is obvious



PLATE 11A. St. George's Hill pyroclast falls in Fort Ghaut.



PLATE 11B. Close-up of exposure shown in 11A, showing interbedded ash and hornblende-hypersthene andesite pumice lapilli. The pyroclast falls show signs of slight reworking but many of the rounded fragments are pisolites.

that the pyroclast falls are thicker on the west side of the hill than on the east side (25 ft. near Bransby Point compared with 10 ft. near Dyers Village) and they may also be thicker on the north side than on the south. Certainly there is a marked contrast between the relatively thin (20 ft.), finely-bedded ash beds in Fort Ghaut (Plate II) and the thicker (50 ft.) and coarser deposits on the north side of St. George's Hill but this might be due to the greater proximity of the latter to the eruptive vent. The much better sorting of the deposits in Fort Ghaut supports this alternative conclusion. Although the evidence is inconclusive it seems probable that the St. George's Hill pyroclast fall series was deposited under the influence of an easterly wind possibly with a southerly bias.

13.3 RELATIONSHIP OF ST. GEORGE'S HILL TO OTHER VOLCANIC CENTRES.

Sections in the south bank of Belham River where St. George's Hill pumiceous tuffs unconformably overlie Centre Hills tuffs show that St. George's Hill is a younger volcano than the Centre Hills. In addition, St. George's Hill deposits often contain fragments of Centre Hills two-pyroxene andesite lava and it appears that they were erupted through a cover of Centre Hills material.

The Bransby-Richmond ridge may be composed of Carabald Hill mudflows and agglomerates but is capped by St. George's Hill pumiceous ash fall. In addition, in the coastal cliffs west of Richmond Estate 25 ft. of pumiceous ash fall infill an erosion hollow in Carabald Hill agglomerates.

St. George's Hill pyroclast falls in Fort Ghaut and in Aymer's Ghaut are overlain unconformably by Soufriere Hills pyroclast flows containing blocks of hornblende-hypersthene andesite and are thus older than the more recent deposits of the Soufriere Hills.

However, the similarity in composition of the St. George's Hill pumices and the later hornblende-hypersthene andesite lavas and pumices of the Soufriere Hills suggests that St. George's Hill may have been active as a secondary centre on the flanks of the

Soufriere Hills during the period of formation of the hornblende-hypersthene andesite domes and pyroclast flows. Unfortunately the relationship of the St. George's Hill pyroclast falls to the two-pyroxene andesite pyroclast flows and mudflows of the Gage's Dome area could not be established so that this tentative correlation could not be definitely confirmed or disproved. There can however be little doubt that St. George's Hill is a comparatively recent centre and it is interesting to note that during the seismic crisis of 1933-36 Powell (1938) recorded several earthquakes at a depth of one to two kilometres below the hill.

CHAPTER 14.

SUMMARY OF THE VOLCANIC HISTORY OF MONTSERRAT.

The main events in the volcanic history of Montserrat are summarised in Table 3. This table also includes all the radiometric dates so far available. Since a detailed reconstruction of the histories of the older volcanic centres on Montserrat has proved to be virtually impossible, Table 3 is largely a history of two volcanoes - South Soufriere Hill (including the subsidiary Roche's Centre) and the Soufriere Hills (including the parasitic volcanic centre of St. George's Hill). Although, in general the type of volcanic activity characteristic of these two volcanoes is different, with pyroclast falls and lava flows predominant among the products of South Soufriere Hill and pyroclast flows and dome lavas being the principal products of the Soufriere Hills, late stage activity at South Soufriere Hill bears a certain resemblance to early events at the Soufriere Hills. The last events at South Soufriere Hill involved the formation of a series of lava bodies, ranging in composition from two-pyroxene basalt (oldest) to basic, two-pyroxene andesite (youngest). Their extrusion was apparently followed closely by the start of activity at the nearby Soufriere Hills where the compositional trend in the Older Andesite Domes (two-pyroxene andesite to hornblende-hypersthene andesite) could be regarded as a continuation of the trend of the late South Soufriere Hill lavas. This together with the geographical proximity of South Soufriere Hill and the Soufriere Hills suggests that the two centres may be in some way related.

Table 4 represents an attempt to estimate the approximate volumes of different rock types on Montserrat. For various reasons, e.g. uncertainty about thicknesses, the figures given in Table 4 are probably very inaccurate. In addition, they are based entirely on present day outcrop and therefore give little indication of original volumes except perhaps in the case of the most recent volcanoes. Nevertheless the figures given in Table 4 allow certain generalisations to be made concerning the relative volumes of the different rock types on Montserrat:-

TABLE 3. SUMMARY OF THE VOLCANIC HISTORY OF
MONTserrat

SOLFATARIC and SEISMIC ACTIVITY at the SOUFRIERE HILLS	Continuous in historic time with periods of exceptional activity between 1966 - 1967 1933 - 1936 1897 - 1898
LAST ERUPTION at the SOUFRIERE HILLS (MINOR PYROCLAST FLOW)	A.D. 1646 $\pm$ 54 yrs. (charcoal from the pyroclast flow)
EXTRUSION of the CASTLE PEAK HORNBLende-HYPERSTHENE ANDESITE DOME and ? BREACHING of the EAST WALL of ENGLISH'S CRATER	
FORMATION OF ENGLISH'S CRATER and ASSOCIATED PUMICE FLOW ERUPTIONS	18,390 $\pm$ 360 yrs. B.P. (charcoal from a pumice flow)
(EXTRUSION OF CHANCE'S and GALWAY'S HORNBLende-HYPERSTHENE ANDESITE DOMES and ASSOCIATED ERUPTIONS of PYROCLAST FLOWS and MUDFLOWS ((THE ST. GEORGE'S HILL HORNBLende-HYPERSTHENE ANDESITE PYROCLAST FALLS probably also belong to this period	23,568 $\pm$ 786 yrs. B.P. (Charcoal from a pyroclast flow)
EXTRUSION of the GAGE'S and PERCHE'S TWO-PYROXENE ANDESITE DOMES and ASSOCIATED ERUPTIONS of PYROCLAST FLOWS and MUDFLOWS.	
INTRUSION of the ROCHE'S TWO-PYROXENE ANDESITE LAVA	Younger than 40,000 yrs. (intruded into limestones which may be about 40,000 yrs. old)
EXTRUSION of the RASPBERRY HILL TWO-PYROXENE ANDESITE DOME	
ERUPTION of BASALTIC PYROCLAST FALLS of the WHITE RIVER PYROCLAST FALL SERIES and the EXTRUSION of OLIVINE-BASALT LAVA FLOWS	
(ERUPTION of the ANDESITIC PYROCLAST FALLS of the WHITE RIVER PYROCLAST FALL SERIES ((THE EXTRUSION of the LANDING BAY DACITE may belong to this period	0.96 $\pm$ 0.25 M. yrs. (K-Ar age)
ACTIVITY at the CENTRE HILLS and CARABALD HILL	
? PERIOD OF HIGH SEA LEVEL	
EARLY ACTIVITY at SOUTH SOUFRIERE HILL - THE EXTRUSION of OLIVINE-BASALT LAVA FLOWS	1.6 $\pm$ 0.34 M. yrs. (K-Ar age)
ACTIVITY at SILVER HILL	1.55 $\pm$ 0.21 M. yrs. (K-Ar age on late stage intrusion)
EXTRUSION of BUGBY-HARRIS TWO-PYROXENE ANDESITE LAVAS and AGGLOMERATES	4.31 $\pm$ 0.22 M. yrs. (K-Ar age on massive lava)

TABLE 4. APPROPRIATE VOLUMES (IN CUBIC MILES) OF ROCK TYPES ON MONTSERRAT

VOLCANIC CENTRE	BASALT			ANDESITE				DACITE
	LAVA FLOW	LAVA DOME	PYROCLAST FALL	LAVA DOME	PYROCLAST FALL	PYROCLAST FLOW	OTHERS	
SOUFRIERE HILLS	-	-	-	0.48	0.001	0.35	0.005	-
ST. GEORGE'S HILL	-	-	-	-	0.12	-	-	-
SOUTH SOUFRIERE HILLS	0.010	0.05	0.02	0.10	0.04	-	-	-
ROCHES	-	-	0.005	0.001	0.01	-	-	-
LANDING BAY DACITE	-	-	-	-	-	-	-	0.004
CENTRE HILLS	-	-	-	0.3	0.2	-	0.5	-
CARABALD HILL	-	-	-	-	-	-	0.10	-
SILVER HILL	-	-	-	0.17	-	-	0.02	-
HARRIS - BUGBY CENTRE	-	-	-	0.10	-	-	0.09	-
TOTAL	0.010	0.050	0.025	1.151	0.371	0.350	0.615	0.004
%	3.3			96.5				0.2

1. Andesite (96.5%) greatly predominates over basalt and dacite. Taking the island as a whole the volumes of two-pyroxene andesite and hornblende-hypersthene andesite are probably about the same, but hornblende-hypersthene andesite accounts for an estimated 67% by volume of the Soufriere Hills volcano (including St. George's Hill). Basic two-pyroxene andesites occur only at the South Soufriere Hill and Harris-Bugby centres.

2. Basalts (3.3%) are very rare on Montserrat. They occur only at South Soufriere Hill, where they make up an estimated 35% of the total volume.

3. Dacites (0.2%) are represented only by a small lava body - the Landing Bay Dacite.

Tomblin (1968) has estimated the relative abundances of rock types in the Lesser Antilles as a whole as 67% andesite, 25% basalt and 7% dacite but the proportions vary very considerably both from island to island and also from volcano to volcano. The islands of Grenada and St. Vincent at the southern end of the chain have well over 50% basalt whereas some islands e.g. Nevis and Saba are composed entirely of andesite. The islands in the middle of the Lesser Antilles - Guadeloupe, Dominica, Martinique and St. Lucia are much richer in dacite than the other islands. Individual volcanoes are usually composed entirely of andesite (e.g. Mont Pele', Martinique; La Soufriere, Guadeloupe) or of a small amount of basalt and a large amount of andesite and dacite (e.g. Qualibou, St. Lucia) but some volcanoes have erupted appreciable amounts of both basalt and andesite (e.g. Soufriere, St. Vincent; Mt. Misery, St. Kitts). Many of the latter volcanoes are also characterised by the presence of ultrabasic cumulate blocks and lavas which show a complete compositional gradation from basalt through basaltic andesite to andesite. These volcanoes may be genetically distinct from the "andesitic" Pelean type volcanoes (Rea, 1969).

It is clear that all the volcanoes on Montserrat except South Soufriere Hill are "Pelean type" volcanoes. South Soufriere Hill, with its ultrabasic blocks and basaltic

andesites is more like the Soufriere, St. Vincent, although the proportion of basalts at South Soufriere Hill is probably quite a lot lower. The possible petrogenetic significance of this is discussed more fully in chapter 17.

CHAPTER 15.

PETROGRAPHY.

15:1 CLASSIFICATION AND NOMENCLATURE.

The rocks of Montserrat, and the Lesser Antilles in general, belong to the Basalt Andesite Rhyolite Association of Turner and Verhoogen (1960, p. 272) and to the Calcic Series of Peacock (1931). Different authors have used different criteria to subdivide this suite of rocks. Criteria which have been used include the composition of plagioclase phenocrysts (see e.g. Hatch, Wells and Wells, 1961, p. 289); the abundance of normative and modal quartz (Lacroix, 1926); the nature of the ferromagnesian phenocrysts (Baker, 1963; Tomblin, 1964); the colour index of the groundmass (Kuno, 1950); and the silica content (Williams, 1942; Robson and Tomblin, 1966).

The composition of the plagioclase phenocrysts is of little use for classifying the Montserrat rocks since phenocrysts of calcic plagioclase persist throughout the entire suite and in any case oscillatory zoning makes it difficult to determine the average composition of the plagioclase phenocrysts. Criteria such as the abundance of modal and normative quartz, the nature of the ferromagnesian phenocrysts and the colour index all reflect the silica content of the rock. For this reason it is probably simpler to divide the Basalt Andesite Rhyolite Association arbitrarily on the basis of silica content. The silica percentages used by Williams (1942) to subdivide the Crater Lake lavas and by Robson and Tomblin (1966) to subdivide the Lesser Antillean lavas differ only slightly but the author has decided to use Robson and Tomblin's nomenclature for the Montserrat rocks as it is obviously useful to apply the same system of classification to all the volcanic rocks in the Lesser Antilles.

Robson and Tomblin's classification is as follows:- West Indian volcanic rocks, which contain 63% or more silica are called dacites; those with between 63 and 55% SiO_2 are called andesites; and those with less than 55% SiO_2 are called basalts. It should be noted that these silica values are not volatile-free. Thus, a lava from St. Lucia

TABLE 5. CLASSIFICATION OF THE MONTSERRAT LAVAS

ROCK TYPE	% SiO ₂	COMMON FERROMAGNETIC PHENOCRYSTS	SUBDIVISIONS of the MAIN GROUPS	DISTINGUISHING FEATURES of the SUBDIVISIONS	APPROXIMATE RANGE in SiO ₂ of the SUBDIVISIONS
Basalt	< 55%	Augite Olivine (Hypersthene)	Olivine Basalt	Phenocrysts of augite and olivine	51 - 53
			Two-Pyroxene Basalt	Phenocrysts of augite with subsidiary hypersthene Olivine rare	53 - 55
			Two-Pyroxene Andesite	Augite > Hypersthene Olivine rare Quartz absent	55 - 60
Andesite	55-63%	Hypersthene Hornblende Augite Quartz Rare Olivine	Hornblende - Two Pyroxene Andesite	Hypersthene < Augite Hornblende present Quartz rare Very few examples of this group	
			Hypersthene - Andesite	Hypersthene ≫ Augite Hornblende absent Very few examples	
			Hornblende - Hypersthene Andesite	Hornblende > Hypersthene Augite - rare as Phenocrysts Quartz - up to 2%	58 - 63
Dacite	> 63%	Hornblende Hypersthene Quartz Augite rare			

(Robson and Tomblin, 1966, Table 10, Col. 2) which contains 55.7% SiO_2 on a volatile-free basis, is referred to as a basalt.

On Montserrat, the three main groups have been subdivided on the basis of the ferromagnesian phenocryst assemblages. Thus andesites are subdivided into hornblende-hypersthene andesites, which contain phenocrysts of hornblende and hypersthene, and two-pyroxene andesites, with phenocrysts of augite and hypersthene. Rocks with phenocrysts of hornblende, hypersthene and augite are called hornblende-two-pyroxene andesites but these are rare. Andesites with phenocrysts of hypersthene but with little or no hornblende and augite are also rare. These rocks have been called hypersthene-andesites. Both the hornblende-two-pyroxene andesites and the hypersthene-andesites occur on Montserrat exclusively as pyroclastics. Basalts have been subdivided into olivine-basalts which have phenocrysts of olivine and augite and two-pyroxene basalts which have phenocrysts of augite and hypersthene. Analysed two-pyroxene basalts have between 54 and 55% SiO_2 (often over 55% SiO_2 on a volatile-free basis) and are in many ways transitional between the olivine-basalts and the two-pyroxene andesites. There would therefore be some justification for calling these rocks "basaltic andesites" but in view of the rather loose application of this term (Coats, 1968, pp. 692-693) the writer prefers the term two-pyroxene basalts.

The system of classification used for the Montserrat lavas is quite similar to that used by Tomblin for the lavas of St. Lucia (Tomblin, 1964, Table 4, p. 89). It is summarised in Table 5.

15:2 OPTICAL METHODS.

Plagioclase composition was estimated by the measurement, on the universal stage, of the maximum extinction angle in the zone perpendicular to (010) using the determinative curve of Winchell (1951, p. 262). The results are probably accurate to $\pm 5\%$ An although the relative accuracy (e.g. the range of zoning in a single crystal) is probably accurate to $\pm 2\%$ An.

The composition of the unzoned feldspars in the coarse-grained blocks was estimated from the refractive index of (001) cleavage flakes and the curves of Tsuboi (1923).

Compositions of olivine in the ultrabasic blocks were estimated by the X-ray diffraction method of Yoder and Sahama (1957). Olivine crystals were difficult to separate from the basalt lavas and their composition was estimated from the direct measurement of $2V (\pm 2^\circ)$ and the use of the tables of Tomkief (1939). These results are probably accurate to ± 5 Fo.

For the clinopyroxenes the $2V (\pm 2^\circ)$ was measured by direct rotation between the optic axes and the N_y was determined by the immersion method. Approximate compositions were then obtained from the curves of Hess (1949).

The composition of the orthopyroxenes was estimated from the measurement of N_z (by the immersion method) and $2V (\pm 1^\circ)$ (by direct rotation) using the curves of Kuno (1954, p. 40).

15:3 BASALTS.

Basaltic rocks on Montserrat occur only at the South Soufriere Hill centre. Two groups of basalt lavas:- olivine-basalts and two-pyroxene basalts have been distinguished on the basis of their phenocryst assemblages (Table 5). Both types of basalt occur as lava flows but two-pyroxene basalt also contributes to the Raspberry Hill Domes. The olivine-basalts are more basic (51-53% SiO_2) than the two-pyroxene basalts (53-55% SiO_2). Basaltic pyroclastics are also quite abundant among the products of South Soufriere Hill. The modal compositions of analysed South Soufriere Hill basalts are given in Table 6 and mineralogical data are summarised in Table 7.

15:3:1 Olivine-Basalt Lava Flows.

The olivine-basalts show a gradation from dark grey, non-vesicular types to black, vesicular types. Sometimes this gradation occurs within individual flows, which may be composed of a central area of grey, non-vesicular lava grading into black

TABLE 6. MODAL COMPOSITIONS OF ANALYSED BASALTS

TYPE	OLIVINE-BASALTS			TWO-PYROXENE BASALTS			BASALTIC PYROCLASTICS	
	146E	404	296	298	26	169	148B	333C
Field No.								
Acc. No.	18618	18657	18637	18638	18575	18623	18620	18642
Plagioclase	38.9	35.6	42.8	32.3	47.1	42.1	29.0	6.0
Olivine	1.5	5.3	3.7	0.2	-	0.6	4.0	0.6
Clinopyroxene	4.5	6.4	4.9	4.0	6.0	5.1	7.8	0.5
Orthopyroxene	-	0.3	0.4	1.3	2.4	3.6	-	-
Ore	0.7	1.4	1.9	1.9	1.1	1.4	-	0.2
Calcite	-	-	-	1.5	-	-	-	-
Groundmass	54.7 ¹	50.9	46.3	58.8	43.4	47.1	59.2	92.7

¹ The groundmass is made up as follows:-

Plagioclase	59.7
Olivine	0.6
Clinopyroxene	29.7
Ore	5.4
Glass	4.8

TABLE 7. MINERALOGICAL DATA for ANALYSED BASALTS

SPECIMEN	COMPOSITION of PLAGIOCLASE		COMPOSITION of OLIVINE	CLINOPYROXENE			ORTHOPIYROXENE		
	Core	Margin	Core	2V	Ny	Approximate Composition of Core	2V	Nz	Approximate Composition
296 Microphenocryst	An ₈₅ An ₅₇	An ₅₂	Fo ₇₃	55 (Core) -51 (Margin)	1.698	Ca ₄₅ Mg ₃₄ Fe ₂₁	60		
404 Microphenocryst	An _{83.5} An ₅₄	An ₃₈ An ₄₀	Fo ₇₇	53	1.696	Ca ₄₄ Mg ₃₆ Fe ₂₀			
146E	An ₈₅ An ₅₃	An ₄₄ An ₃₃		52-49	1.700	Ca ₄₀ Mg ₃₄ Fe ₂₁			
26 Microphenocryst	An ₈₄ An ₅₂	An ₄₂		52					
298	An ₈₅	An ₄₇		52					
333C	An ₇₅								
148B	An ₇₉	An ₅₅	Fo ₇₇	53					

scoriaceous lava at the margins (e.g. 18698). Both types of lava contain abundant white plagioclase phenocrysts and moderately abundant dark green or black clinopyroxene. The black vesicular lavas often have prominent golden phenocrysts of olivine, whereas olivine can seldom be recognised in hand specimens of the grey, non-vesicular lavas.

Plagioclase.

Plagioclase is the most abundant phenocryst in the olivine-basalts. It attains a maximum diameter of about 3 mm. and occurs either as single crystals or in glomeroporphyritic groups with olivine or clinopyroxene and ore. Plagioclase is also by far the most abundant microphenocryst in the groundmass of the olivine-basalts. In some specimens (e.g. 18618) there is a gradation in size from phenocrysts to microphenocrysts to microlites of plagioclase and a similar gradation is displayed by the other phenocrysts. The texture of these rocks may be described as seriate.

The plagioclase phenocrysts have large homogeneous cores ranging from about An_{85} to An_{80} while the rims are about An_{50-40} . Microphenocrysts are generally less calcic and have cores of about An_{55} with rims of An_{40-35} . Zoning is of normal discontinuous type although a few phenocrysts show slight oscillatory zoning. The plagioclases frequently have clouded cores and sometimes contain narrow zones of inclusions aligned roughly parallel to the crystal margins. Both clouding and compositional zoning are much better developed in plagioclases from andesites and are therefore considered in more detail in the sections (especially 15:4:1) on andesites.

Olivine.

Olivine phenocrysts are usually about 0.25 mm. in diameter but are sometimes as big as 0.5 mm. Crystals are subhedral or rounded. Olivine occurs mostly as single crystals but also in glomeroporphyritic clusters with plagioclase and iron ore and less often with clinopyroxene as well. Olivine usually occurs on the periphery of these clusters (e.g. in 18637. Plate 12A).

The olivines frequently enclose granules of iron ore, sometimes in irregular

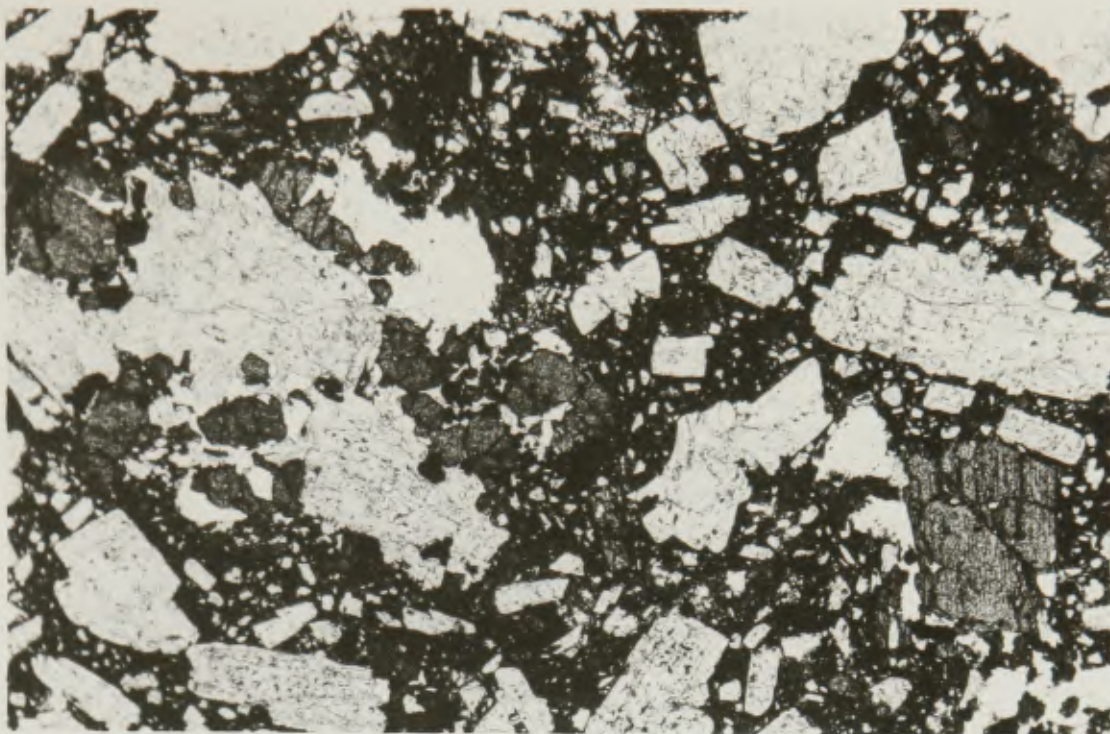


PLATE 12A. Photomicrograph of olivine-basalt lava (18637) from near Shoe Rock. Phenocrysts of plagioclase, olivine and augite (bottom *right*) in a dark microcrystalline to glassy matrix. Note the glomeroporphyritic cluster of olivine and plagioclase on the *left* of the photograph. Small crystals of olivine rim a large plagioclase crystal which itself encloses small crystals of magnetite and a single crystal of olivine. Magnification x 12.

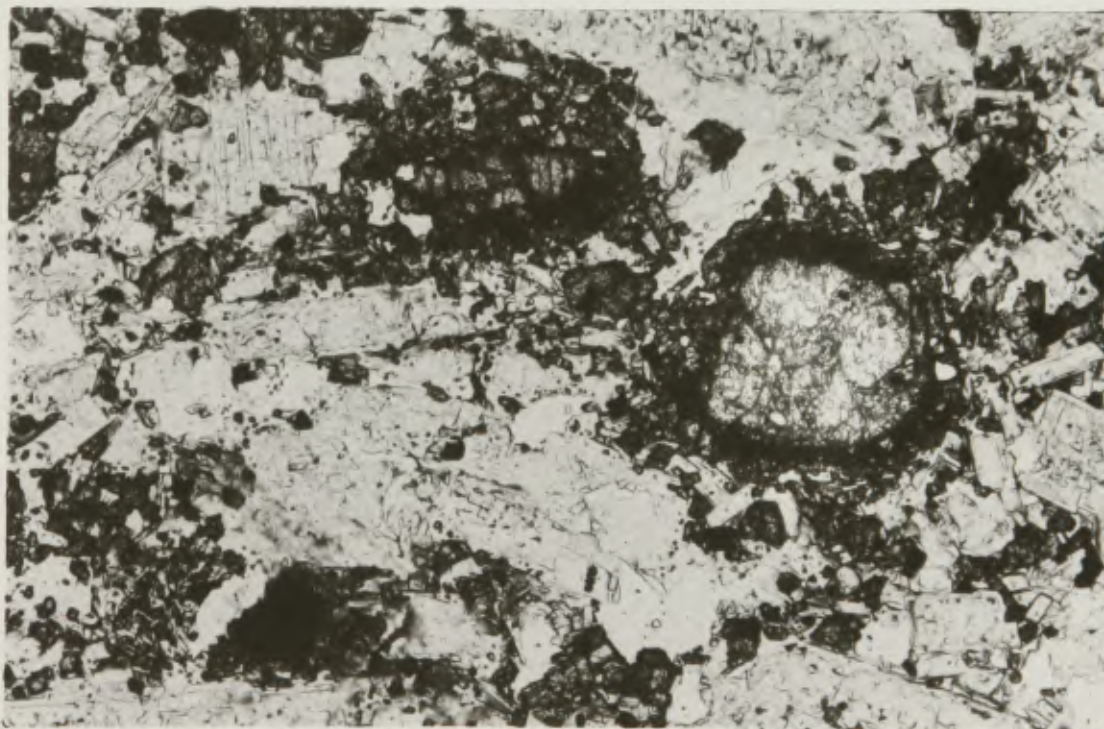


PLATE 12B. Photomicrograph of olivine-basalt lava block (18618) from near Fergus Mount Estate. Partially "iddingsitised" olivine phenocrysts are surrounded by an inner rim of magnetite and an outer rim of clinopyroxene granules. The rest of the rock is composed mainly of phenocrysts of plagioclase and augite in a fine-grained to glassy matrix which contains abundant microphenocrysts and microlites of clinopyroxene. Magnification x 48.

curved bands (Plate 13A). Olivine itself is sometimes enclosed by plagioclase or clinopyroxene phenocrysts (e.g. in 18657). More often, however, olivine is surrounded by a corona of clinopyroxene granules and in some cases (e.g. 18618) by an inner rim of magnetite and an outer rim of clinopyroxene (Plate 12B). Narrow orthopyroxene rims occur around some olivines but are much rarer than the clinopyroxene rims.

Kuno (1950, p. 971) has reported rims of orthopyroxene and more rarely of clinopyroxene around olivines in lavas from Hakone and has interpreted these rims as indicating a reaction relationship between olivine and liquid but the orthopyroxene rims could also form by the oxidation of olivine (e.g. Muir et al., 1957, p. 252). Clearly, detailed optical and chemical work on the pyroxenes which surround the olivines in the Montserrat lavas are needed before any definite conclusions can be reached regarding their origin. However, the association of clinopyroxene with magnetite in 18618 is suggestive of an oxidation reaction. Elsewhere the pyroxene rims may be produced by reaction with the liquid although crystal nucleation around olivines might be an important factor as discussed on p. 84.

Almost all the olivines in the Montserrat basalts are coated with a thin film of reddish iron oxide, which is probably "iddingsite" (Gay and Le Maitre, 1961). In general, however, the olivines in the olivine-basalts are quite fresh. Plate 13A shows a relatively fresh crystal of olivine, immediately adjacent to a cavity filled with cristobalite.

The olivines in the olivine-basalts are more or less completely unzoned and have compositions of around Fo₇₅ (Table 7).

Clinopyroxene.

Clinopyroxene is generally the most abundant ferromagnesian phenocryst in the Montserrat basalts. It often occurs in cumulophyric clusters and may enclose olivine, iron ore, or plagioclase. In general the crystals are only slightly zoned with 2Vs of up to 55° at the core compared with 49° at the rim. Very rarely clinopyroxene phenocrysts contain zones of inclusions parallel to the crystal boundaries (18637). Twinning on (100) is common but polysynthetic twinning, apparently with (001) as twin plane, also occurs.

Magnetite.

Magnetite is an important constituent of the olivine-basalts. It occurs as euhedral or subhedral phenocrysts often associated with olivine. All the other phenocryst minerals, especially clinopyroxene enclose crystals of magnetite. Magnetite is however, rarely enclosed by olivine.

Accessories.

Hypersthene may be present in small amounts in the olivine-basalts.

Groundmass.

The groundmass of the olivine-basalts contains abundant microphenocrysts and microlites of plagioclase, granules of clinopyroxene and spots of ore. Clinopyroxene may sometimes be exceptionally abundant as in 18618. Olivine is very rare or absent as a constituent of the groundmass and glass is also rare although it is more abundant in the more vesicular lavas. Abundant cristobalite is found in cavities in some of the lavas (Plate 13A).

15:3:2 Two-Pyroxene Basalts.

The two-pyroxene basalts form a transitional group between the olivine-basalts and the two-pyroxene andesites. They are restricted to the South Soufriere Hill volcano, where they occur mainly as lava flows but also contribute to the Raspberry Hill Dome.

The two-pyroxene basalts are pinky grey lavas with phenocrysts of plagioclase and clino- and ortho-pyroxene. The pyroxenes tend to occur in clusters.

Plagioclase.

Although the overall compositions are very similar (Table 7) the plagioclases in the two-pyroxene basalts are more strongly zoned than those from the olivine-basalts. Oscillatory zoning (Plate 13B) is common and the plagioclases are rich in inclusions. Usually the inclusions are very small grains of ore, pyroxene or glass and occur in bands more or less parallel to the crystal outlines. Sometimes however, the plagioclases include larger crystals of clinopyroxene in a more random orientation (Plate 14A). Zoning

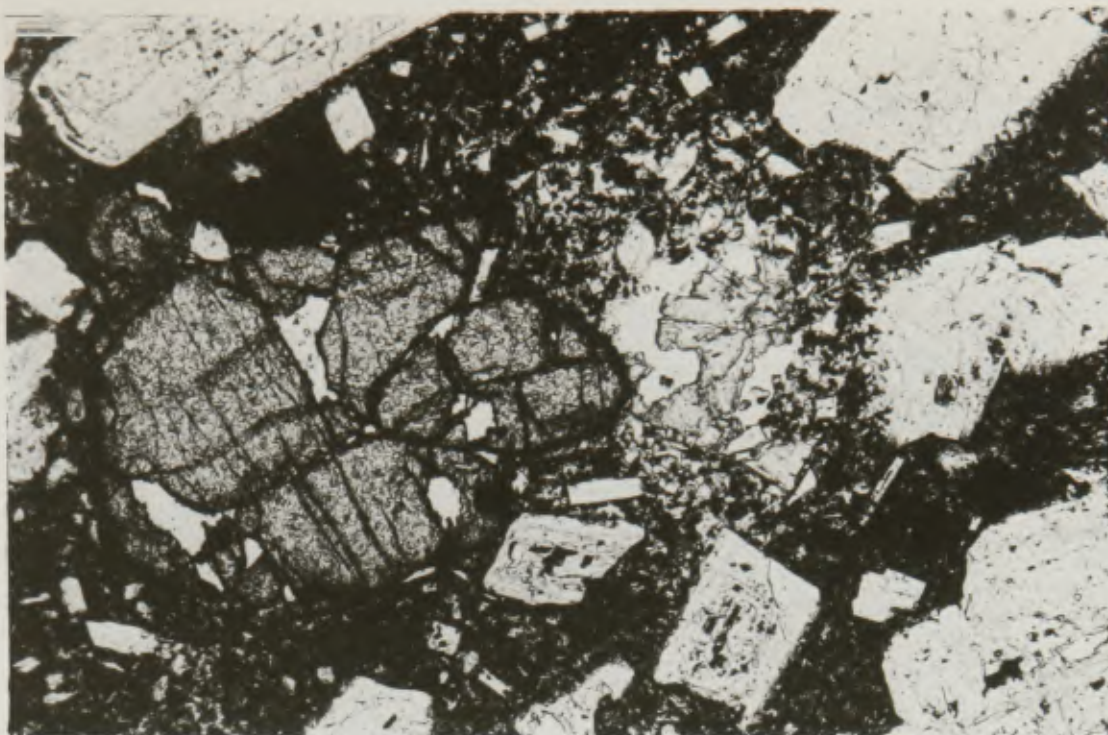


PLATE 13A. Photomicrograph of olivine-basalt lava (18657) from near Landing Bay. An olivine phenocryst (Fo_{77}) which is quite fresh apart from a narrow rim of ore, occurs next to a cavity infilled by cristobalite. Note the irregular bands composed of granules of ore within the olivine phenocryst. Magnification $\times 30$.



PLATE 13B. Photomicrograph of two-pyroxene basalt (18575) from lava flow near O'Garra's. Plagioclase phenocryst with fine-scale oscillatory zoning. The phenocryst has a small relatively homogeneous core (composition about An_{85}) which contains small inclusions of glass. Inclusions in the outer part of the crystal occur in bands parallel to the crystal outlines and are sometimes concentrated within a single compositional zone. Crossed nicols. Magnification $\times 37.5$



PLATE 14A. Photomicrograph of two-pyroxene basalt (18575) from lava flow near O'Garra's. Complex plagioclase phenocryst containing crystals of clinopyroxene in a more or less random orientation. Magnification x 30.

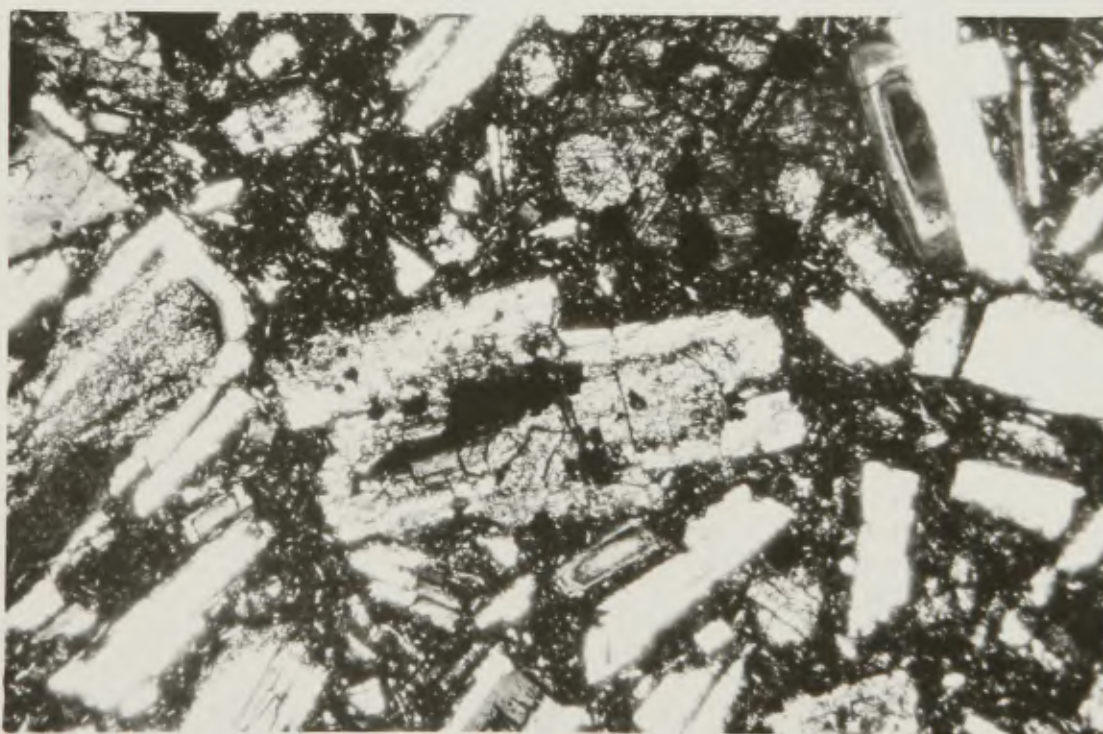


PLATE 14B. Photomicrograph of two-pyroxene basalt (18575). Clinopyroxene rimming orthopyroxene. A clinopyroxene crystal showing polysynthetic twinning occurs just above the rimmed hypersthene crystal. Crossed nicols. Magnification x 48.

and inclusions in plagioclase phenocrysts are discussed more fully in section 15:4:1.

Clinopyroxene.

Clinopyroxene occurs as single crystals, in cumulophyric groups and in glomeroporphyritic groups with orthopyroxene and ore. Compositions are similar to those in the olivine-basalts (Table 7).

Clinopyroxene shows three types of intimate association with orthopyroxene in two-pyroxene basalts and also in two-pyroxene andesites from Montserrat. It may rim orthopyroxene (Plate 14B) or be rimmed by it and sometimes clinopyroxene and orthopyroxene show parallel to sub-parallel growth along the c-axis. Similar relationships have been reported in many other calc-alkaline suites notably Hakone (Kuno, 1950). Kuno (1950, p. 991) has attributed the mutual rimming to simultaneous growth but he also suggested that the hypersthene rims on phenocrystic augite indicated a discontinuous reaction between augite and liquid to form hypersthene. In addition the rimming of hypersthene by augite was interpreted by him as resorption of hypersthene xenocrysts by the magma with precipitation of augite. Yoder and Tilley (1962, p. 353-354) have pointed out that there is no experimental evidence in synthetic systems for an equilibrium reaction relation between diopside and liquid to produce orthopyroxene so that if augite is reacting with liquid to give hypersthene the reaction is a non-equilibrium one and may indicate assimilation. Alternatively they suggest that the rimming of augite by hypersthene might be the result of oxidation.

Although detailed optical and electron microprobe examination are probably required before any final interpretation of the pyroxene relationships in the Montserrat rocks is made a few general points can be made here.

1. The occurrence of parallel growth of ortho- and clino-pyroxene in lavas from Montserrat and elsewhere in the Lesser Antilles (e.g. Baker, 1963, p. 119) almost certainly indicates simultaneous growth.
2. The rimming of orthopyroxene by clinopyroxene is by far the most common relationship observed in the Montserrat rocks. It may be significant that several other

phenocryst minerals, including olivine (p. 81), quartz (p. 97) and hornblende (p. 96) are also on occasions rimmed by clinopyroxene, and this rimming frequently occurs in lavas which contain very abundant clinopyroxene in the groundmass. It is possible, therefore that at least some clinopyroxene coronas have formed by crystal nucleation around the phenocrysts rather than as a result of a reaction relationship between the phenocryst and the magma (see also p. 118).

3. The assimilation and reaction hypothesis can probably explain only one type of pyroxene relationship at a time since it is unlikely that xenocrysts of clinopyroxene would be reacting to give orthopyroxene at the same time as orthopyroxene xenocrysts were reacting to give clinopyroxene.

Orthopyroxene.

Hypersthene is less abundant than augite in the two-pyroxene basalts. It occurs as prismatic crystals which are as much as 2 mm. long and which may occur singly or in groups associated with clinopyroxene and plagioclase. Almost invariably hypersthene encloses grains of magnetite and magnetite is often abundant near hypersthene crystals. Hypersthene is pleochroic as follows:-

X	-	pale brown
Y	-	pale yellowish brown
Z	-	pale green.

Magnetite.

Magnetite is abundant as a phenocryst mineral in the two-pyroxene basalts (Table 6). It is often closely associated with orthopyroxene.

Accessories.

Olivine is relatively rare in the two-pyroxene basalts and when it does occur it is often enclosed by clinopyroxene (e.g. 18592). Hornblende was found in only one of the two-pyroxene basalts (18699) where it showed strong pyroxenic resorption (p. 95).

Groundmass.

The groundmasses of the two-pyroxene basalts are in general quite similar to those in the olivine-basalts. They contain abundant microlites of plagioclase together with granules of clinopyroxene, orthopyroxene and magnetite. Cristobalite is very abundant in some of the rocks (e.g. 18575) where it infills cavities. Tridymite also occurs in places. In its usual form it is distinguishable from cristobalite only by the presence of arrow-head twinning and the relative paucity of cracks but sometimes it occurs as acicular needles (e.g. in 18622; see also MacGregor 1938, p. 59). A pale brown mica which may be phlogopite, was recognised in the groundmass of one specimen (18623). It occurs as abundant small flakes in the midst of finely divided quartz-rich aggregates which apparently infill cavities in the rock (see also p. 94). Calcite occurs in small patches in the groundmass of 18638.

15:3:3 Basaltic Pyroclastics.

Basaltic pyroclastics make up the whole of the Basalt Cinder Zone and the uppermost parts of the Andesite Coarse Fall Zone of the White River Pyroclast Flow Series.

The welded scoriae bed (18610) which occurs at the base of the Basalt Cinder Zone is interesting in view of its unusual mode of occurrence (p. 34), its unusual chemistry (p. 125/136) and because it is almost aphyric (Table 6). In hand specimen (Plate 20A) 18610 consists of a mass of dark vesicular fragments, which have been slightly flattened to form a coherent, but friable mass. Individual fragments contain no recognisable minerals apart from a few crystals of plagioclase.

In thin section rare phenocrysts of rather corroded plagioclase, of eu- to sub-hedral olivine and brownish corroded augite occur in a highly vesicular pale yellow-brown glass, which contains abundant tiny microlites of plagioclase and pyroxene (Plate 15A). The olivine phenocrysts are virtually unaltered and the numerous vesicles in the rock are empty.

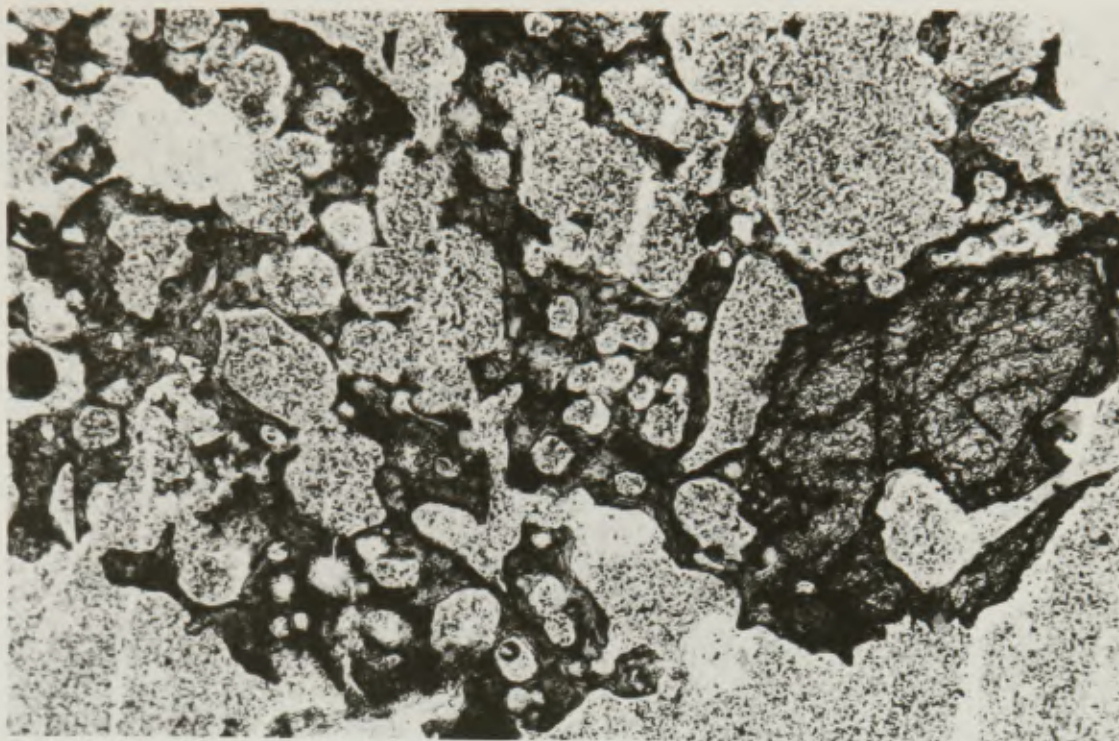


PLATE 15A. Photomicrograph of welded basaltic scoriae (18642) from White River Ghaat. A phenocryst of olivine in a highly vesicular glassy base, containing tiny microlites of plagioclase and pyroxene. Magnification x 48.

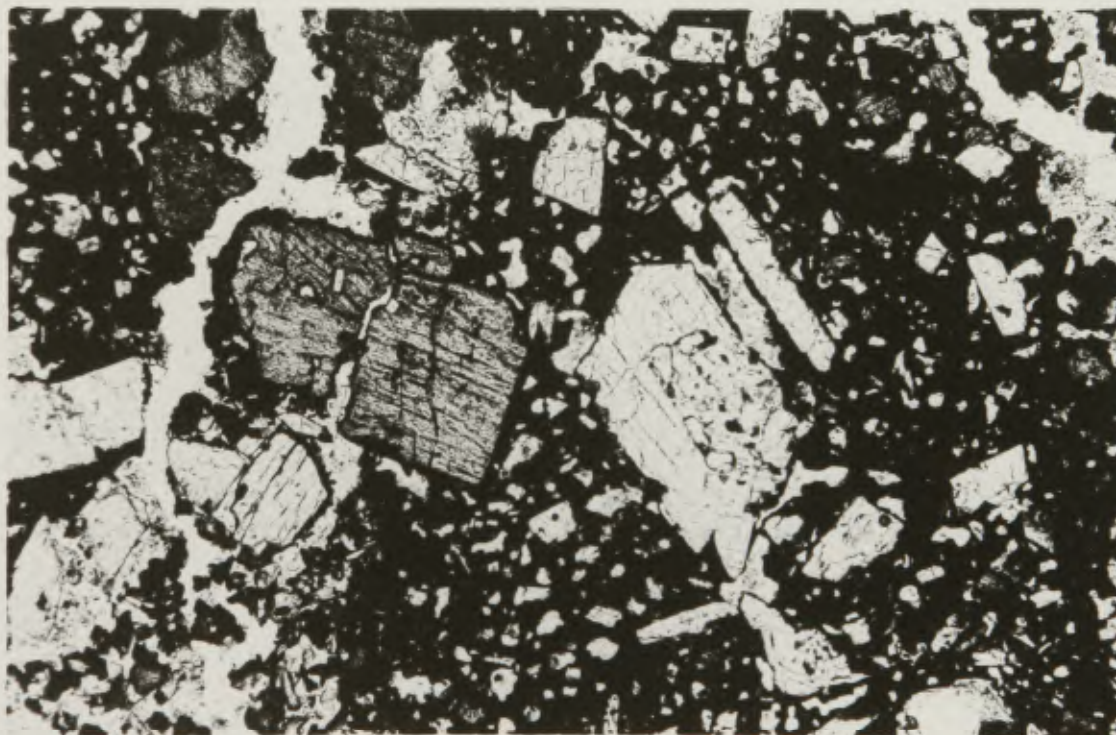


PLATE 15B. Photomicrograph of basalt cinder (18617) from Fergus Mount Estate. Phenocrysts of augite and plagioclase in a dark glassy groundmass. Magnification x 30.

The writer knows of nothing strictly comparable to 18610 in the Lesser Antilles or in other calc-alkaline suites. In some ways, it resembles the interstitial scoria in the ultrabasic blocks from Montserrat (p. 107) but it is a lot lighter in colour than these.

In general, fragments in the Basalt Cinder Zone are similar to the olivine-basalt lava flows although fragments from the very top of the zone are more like the two-pyroxene basalt flows (e.g. 18647). The cinders tend, however, to be richer in mafic phenocrysts (olivine and especially clinopyroxene) than the lava flows. They also contain a black glassy groundmass (Plate 15B) and do not contain cristobalite.

15:4 ANDESITES.

Andesites make up an estimated 96% by volume of the rocks of Montserrat. Their mode of occurrence is different from that of the basalts. The andesites are erupted typically as pyroclast flows and dome lavas, whereas the basalts are erupted as pyroclasts falls and lava flows. Andesitic pyroclast falls do however occur and are important among the products of St. George's Hill and South Soufriere Hill. Modal analyses of analysed andesites are given in Table 8 and mineralogical data in Table 9.

15:4:1 Two-Pyroxene Andesite Lavas.

The earlier Soufriere Hills' domes (Gage's Dome and Perche's Dome), the younger of the Raspberry Hill domes, the Roche's intrusion and much of the Silver Hill and Harris-Bugby centres are composed of two-pyroxene andesite lava.

The two-pyroxene andesites are quite similar in appearance to the two-pyroxene basalts. They are usually non-vesicular and light grey in colour but some of the lavas have been considerably oxidised and are noticeably pink or red (e.g. 18649). Phenocrysts of plagioclase are common and dark clots of pyroxene are recognisable in most specimens. The two-pyroxene andesite lavas sometimes contain ellipsoidal, holocrystalline cognate xenoliths. These are described in section 15:6:3.

TABLE 8. MODAL COMPOSITIONS OF ANALYSED ANDESITES

TYPE	TWO-PYROXENE ANDESITE LAVAS								HORNBLENDE-HYPERSTHENE ANDESITE LAVAS			BANDED HORNBLENDE-HYPERSTHENE ANDESITE LAVA BLOCK			ANDESITIC PYROCLASTICS				
	384	268	421	122	324	373	409	364	133	322	398	135BK	135GY	135WH	47F	195	46C	145	377A
FIELD NO.																			
ACC. NO.	18651	18634	18662	18609	18641	18649	18660	18648	18610	18640	18654	18612	18612	18612	18595	18626	18592	18615	18650
Plagioclase	33.2	32.4	41.0	30.5	28.8	33.1	43.8	39.6	30.7	36.8	21.2	28.8	27.5	29.0	24.2	9.9	19.9	27.9	14.6
Clinopyroxene	7.9	5.1	5.2	5.2	6.1	4.0	1.8	0.6	0.3	0.7	0.8	0.7	0.8	-	0.5	0.3	0.3	0.6	-
Orthopyroxene	3.1	1.3	3.4	5.2	2.2	3.0	4.1	2.5	1.8	0.9	1.5	1.4	3.1	2.0	1.3	1.3	1.8	1.4	1.6
Hornblende	-	-	-	-	tr.	-	-	-	5.6	5.3	4.6	2.5	4.4	7.4	0.5	0.7	1.3	2.1	1.7
Quartz	-	-	-	-	-	-	-	-	0.6	0.7	0.1	0.8	0.8	1.2	tr.	0.2	tr.	-	1.2
Olivine	-	-	-	0.3	2.3	-	tr.	-	-	-	-	-	-	-	-	-	0.1	-	-
Ore	1.7	0.7	0.8	0.9	1.4	6.2	1.8	0.7	1.0	0.4	0.9	0.6	0.8	1.3	0.3	0.3	0.7	0.6	0.7
Groundmass	53.9	60.5	49.6	57.9	59.1	53.7	48.6	56.6	60.0	55.2	70.9	65.2	62.6	59.1	73.2	87.3	75.8	67.4	80.2

TABLE 9. MINERALOGICAL DATA FOR ANALYSED ANDESITES

SPECIMEN	COMPOSITION of PLAGIOCLASE		CLINOPYROXENE		ORTHOPYROXENE	
	Core	Margin	2V	Ny	2V	Nz
384	An ₇₂	An ₄₂	47 (Margin)		61	
324 Micro P.	An ₈₀ An ₅₈	An ₄₁	55	1.700	58	
373	An ₇₀	An ₃₈	52			
169	An ₇₄	An ₅₂	50	1.701	64-61	
364	An ₇₈	An ₅₀			58	1.728
122	An ₇₀	An ₅₀	53		57	En ₄₅
409	An ₈₁	An ₅₄			58	
46C	An ₈₄	An ₅₆				
47F	An ₇₃	An ₃₈				
133	An ₇₁	An ₅₀	51		59	1.721
322					57	
398a	An ₈₅	An ₅₂	50		56	
145	An ₆₈	An ₅₁				
377A	An ₆₈	An ₃₅				

Plagioclase.

Various phenomena, including oscillatory zoning, clouded cores and the occurrence of bands of inclusions are better developed in plagioclase phenocrysts from the two-pyroxene andesites than in plagioclases from the other rock groups and these phenomena are therefore described in detail in this section. These features are also important in plagioclases from the hornblende-hypersthene andesites and the two-pyroxene basalts but they are less well-developed in the olivine-basalts. The zoning of plagioclase appears to be more conspicuous in andesites than basalts throughout the Lesser Antilles (Lacroix, 1904, p. 591; Baker, 1963, p. 116 and Tomblin, 1964, p. 103) and in calc-alkaline suites in general.

Plagioclase phenocrysts account for up to 42% of the two-pyroxene andesites. Plagioclase occurs as single crystals up to 5 mm. long and also in glomeroporphyritic groups with pyroxene and ore.

The overall trend in composition of plagioclase phenocrysts in the Montserrat two-pyroxene andesites is from a calcic (An_{85-70}) core to a more sodic (An_{50-40}) rim but numerous reversals may be superimposed on this general trend. Many of the plagioclase phenocrysts have unzoned cores, surrounded by a region of oscillatory zoning and a narrow normally zoned rim but there are many exceptions to this pattern and oscillatory zoning may begin at the centre of some crystals and continue right to the rim. The amount and type of zoning often vary conspicuously in plagioclase phenocrysts in the same thin section. In addition variation exists in the size of the compositional oscillation within a single phenocryst. In most cases the oscillations appear to be very small (2% An) but occasionally one zone is considerably richer in calcium ($\sim 10\%$ An) than the margin of the preceeding zone. These major reversals are sometimes accompanied by magmatic corrosion of the pre-existing crystal and may also be associated with bands of inclusions. Zoning may also be related to crystallographic directions in the plagioclase phenocrysts since some zones parallel to the short direction of plagioclase crystals appear to be absent parallel to the long direction

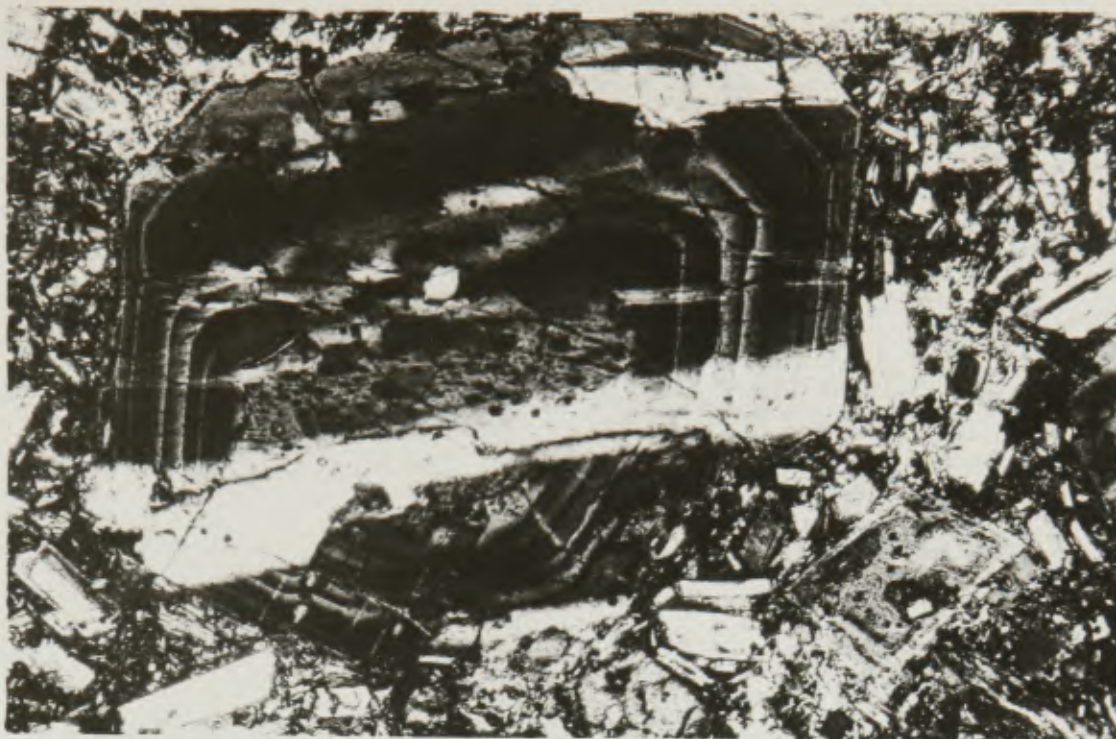


PLATE 16A. Photomicrograph of two-pyroxene andesite lava (18662) from intrusion ? near Harris Village. Fairly large plagioclase phenocryst with a calcic core (An_{82}) containing glass inclusions. The core is surrounded by an area of oscillatory zoning which extends right to the edge of the crystal. The oscillatory zoning is better developed parallel to the short axis of the crystal. Crossed nicols. Magnification x 30.

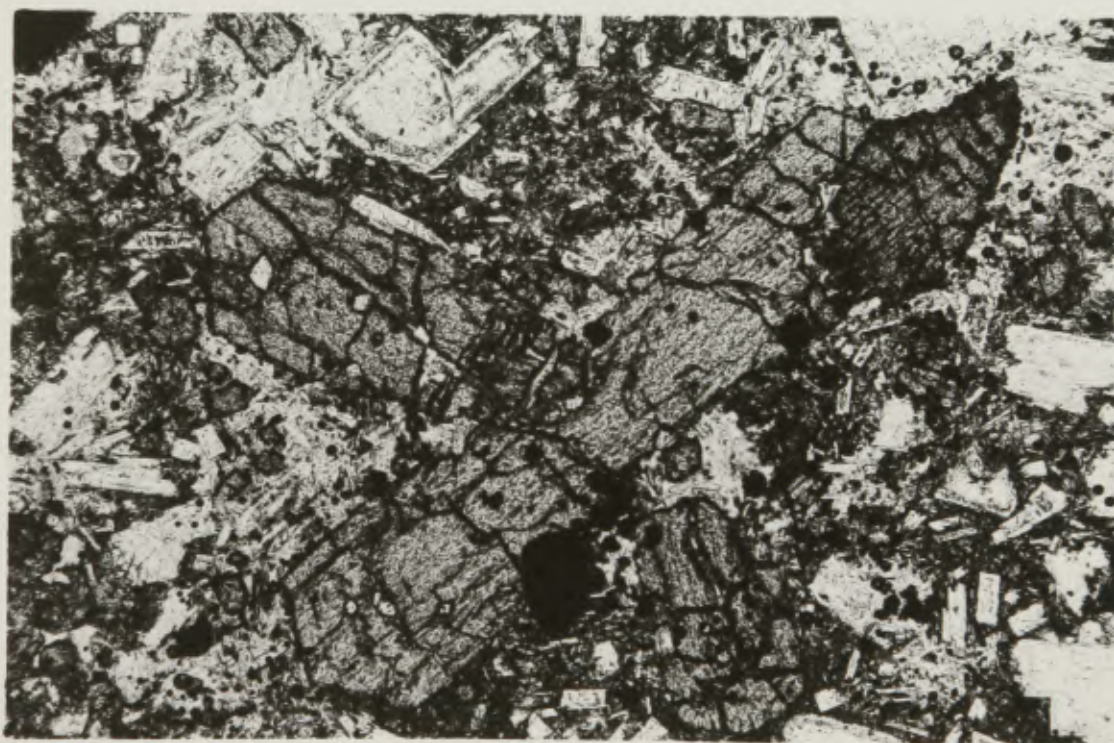


PLATE 16B. Photomicrograph of two-pyroxene andesite lava (18662). Aggregate of clinopyroxene, orthopyroxene (bottom and top right) and magnetite in a microcrystalline groundmass of plagioclase, pyroxene and ore. Magnification x 30.

(Plate 16A).

In general microphenocrysts have much less conspicuous zoning than the phenocrysts and sometimes show only normal zoning. The microphenocrysts are usually less calcic than the phenocrysts by as much as 20% An. This is in accord with the difference in phenocryst and groundmass plagioclase compositions from basalt lava flows (Hoffer, 1966).

Plagioclase phenocrysts in the two-pyroxene andesites are often clouded by numerous small inclusions. The inclusions are often of brownish glass but small crystallites of pyroxene and opaque oxide are also found, along with a large number of tiny indeterminate particles. The unzoned cores of plagioclase phenocrysts are often completely clouded in this way (Plate 16A) and narrow, inclusion-rich bands may occur between the core and the rim parallel to what may be inferred to have been the crystal-liquid interface during some stage of growth.

The relationship of the inclusions to compositional zoning is complex and varies considerably in different rocks and even in phenocrysts from the same rock. Quite often, however, bands of inclusions coincide with a single compositional zone, which is usually of more sodic composition. In many cases, however, the inclusions do not follow compositional zones at all.

Compositional zoning and, to a lesser extent, the nature of the inclusions in plagioclases, represent potentially useful records of changes in the physical and chemical environment during crystallisation, provided that the processes giving rise to these phenomena are understood. Unfortunately this is far from being the case.

Tuttle and Bowen (1953, p. 69) have stressed the importance of pressure changes, which alter the water content of a magma, in producing compositional zoning in plagioclases. Both the rise and fall of andesitic magma during seismic crises (p. 66) and the loss of volatiles during eruptions will result in large scale changes of pressure (and in the former case temperature as well) and there can be little doubt that these events have given rise to large-scale compositional breaks in the Montserrat plagioclases.

Ewart (1963) has related major compositional breaks in plagioclase from pumice ash in the Taupo area, New Zealand to specific volcanic events (eruptions). It has not been possible however to correlate the major compositional breaks in the Montserrat plagioclases with specific eruptions or seismic crises partly because of the variable pattern of zoning in plagioclase phenocrysts from the same rock and partly because the volcanic history is not well enough known. Nevertheless it may be possible in a general way to relate some of the features seen in the plagioclases to volcanic events. Tomblin (1964, p. 106) has suggested that the continuous glass bands in plagioclases from St. Lucia represent liquid that was chilled on the outside of the growing phenocryst and this explanation presumably implies rapid transfer to a low temperature environment - perhaps during a seismic crisis. Where the glass band is associated with a major break in composition the evidence is strongly in favour of such a mechanism.

The clouded cores in the Montserrat plagioclases may have a similar origin. MacGregor (1938, p. 50) suggests that the "spongy" cores found in many Montserrat plagioclases are the result of magmatic corrosion of early-formed plagioclase phenocrysts under changed physiochemical conditions, followed by the infilling of cavities left by corrosion by residual magmatic liquid.

Although major changes in physical conditions provide a likely explanation for some of the major compositional breaks in plagioclases it is unlikely that the fine-scale oscillatory zoning can be explained in terms of changes of this magnitude. Oscillatory zoning has been ascribed to several different processes (Vance, 1962, p. 750-751) and the possible effectiveness of some of these in producing fine-scale oscillatory zoning in the Montserrat plagioclases is discussed below.

Tuttle and Bowen (1958, p. 69) have shown that small-scale changes in the water vapour pressure of a magma may cause oscillatory zoning in plagioclase. Such changes could be related to small scale rises and falls of magma, or perhaps seasonal variation in soufriere activity but there is little or no evidence for either of these processes. Furthermore these changes should give rise to a uniform pattern of zoning in neighbour-

ing crystals. On the other hand the migration of water through a magma as suggested by Kennedy (1955; see also this volume p. 172) will certainly give rise to changes in water vapour pressure and might conceivably result in a rather variable pattern of zoning but there is no reason why it should produce oscillatory zoning unless the migration is cyclical.

Another possible explanation of oscillatory zoning is repeated differential movement between plagioclase and a thermally or compositionally heterogeneous melt (Bowen, 1928, p. 275). Leedal (1952) has attributed oscillatory zoning in plagioclases in trondhjemitic rocks to circulation in a magma chamber with the deposition of sodic zones as the crystal rises followed by resorption as the crystal sinks and Carr (1954) has attributed the occasional oscillatory zoning in plagioclase from the Skaergaard to a similar mechanism. The effectiveness of this mechanism in viscous andesitic melts has been questioned (e.g. Tomblin, 1964, p. 104) especially as zoning is relatively inconspicuous in plagioclases in basalts, where a more mobile magma would probably have facilitated circulation.

Another possible explanation of oscillatory zoning in plagioclase (Harloff, 1927) involves the interplay of diffusion and plagioclase growth rate in two stages as follows:-

- 1) Rapid growth of plagioclase with resultant reduction of the Ca content near the crystal so that subsequent crystallisation results in precipitation of progressively An-poor plagioclase and
- 2) The decreasing Ca content of the liquid in the immediate vicinity of the growing plagioclase crystal reduces the degree of supersaturation of the liquid relative to the plagioclase and consequently the growth rate decreases. At this stage a diffusional flux of Ca towards the interface replenishes the melt near the growing crystal and stage (1) begins again.

Recently, Bottinga et al. (1966) have shown, by measurements of concentration gradients in the boundary layers adjacent to plagioclase volcanic glass interfaces that plagioclase crystallisation rate is diffusion controlled during certain stages of growth. Bottinga et al. (op. cit., pp. 800-802) were particularly concerned with the

problem of the transition from the end of one cycle to the beginning of the next, during which diffusion must be proceeding at a greater rate than crystal growth. It is not at all obvious why crystal growth should either slow down or stop altogether. Instead, the attainment of a steady state regime in which growth and diffusion rates are equal appears to be more likely. Bottinga et al. consider that crystal growth may cease partly as a result of decreasing supersaturation and partly because the crystal-liquid interface reaches a state in which it presents no energetically favourable sites for crystallisation.

The Harloff-Bottinga theory explains a number of the features seen in the Montserrat plagioclases e.g. the development of more zones along the length of plagioclase crystals than along the width (Bottinga et al., 1966, p. 803). In addition a diffusion-supersaturation mechanism might account for the differences in the pattern of zoning in neighbouring crystals in the same rock (Tomblin, 1964, p. 105) in so far as rates of diffusion will depend on factors like the number of centres to which diffusion takes place and may vary considerably throughout a magma. Furthermore, the enrichment of Fe and Mg in the boundary layer adjacent to growing plagioclase crystals (Bottinga et al., 1966, p. 799) suggests a possible explanation for the inclusion of mafic microlites in plagioclase crystals. Bottinga et al. consider that the boundary layer is, in certain cases, sufficiently rich in Fe and Mg to cause nucleation of minerals rich in these elements and these minerals are trapped by the rapidly growing plagioclase.

However, one thing the Bottinga-Harloff theory does not explain adequately is the occurrence of oscillatory zoning in plagioclases in some rocks and its absence from others. According to this theory plagioclase crystallising from any magma should be oscillatorily zoned unless it is removed from contact with the liquid or for some reason the rate of diffusion has never exceeded the rate of crystal growth. Why diffusion rates should exceed crystal growth rates in viscous intermediate lavas rather than in mobile basic ones is by no means clear.

From the foregoing discussion it is clear that the origin of the oscillatory zoning in the Montserrat plagioclases is still uncertain. None of the suggested mechanisms can account satisfactorily for all the features seen in the Montserrat plagioclases and all these mechanisms may have contributed something to the final pattern of zoning. The diffusion - supersaturation mechanism of Harloff and Bottinga explains most of the observed features and may be of prime importance.

Clinopyroxene.

Clinopyroxene (Plate 16B) is abundant in the two-pyroxene andesites and usually accounts for about 5% of the rock although exceptionally it makes up as much as 8% (e.g. in 18651). It is very similar in composition to the clinopyroxene found in the olivine-basalt and two-pyroxene basalts. The $2V$ ($\pm 2^\circ$) for clinopyroxene cores ranges from $50-55^\circ$ and N_y is about 1.700. Some crystals are slightly zoned. The clinopyroxene is very light brown or green but is non-pleochroic. In the andesites clinopyroxene may enclose ore, plagioclase and olivine and it shows the same associations with orthopyroxene as it does in the two-pyroxene basalts (p. 83).

Orthopyroxene

In the two-pyroxene andesites hypersthene usually occurs in more or less equal amounts to clinopyroxene, though it is less abundant than clinopyroxene in the more basic varieties (e.g. 18651, 18641) and is more abundant in the more acid two-pyroxene andesites (e.g. 18648, 18660). The properties of hypersthene in the two-pyroxene andesites are similar to those described for hypersthene in the two-pyroxene basalts (p. 84). In the two-pyroxene andesites $2V$ ($\pm 1^\circ$) ranges from $57-64^\circ$ and N_z is about 1.728. Some crystals are slightly zoned.

Iron Oxides.

Magnetite, which is often associated with hypersthene is quite abundant as a primary mineral in some of the two-pyroxene andesites (e.g. 18622). Secondary oxides - probably a mixture of magnetite and haemetite are exceptionally abundant in some of the

dome lavas. In the Perche's Dome lava (18649), for instance, the mafic minerals (clinopyroxene and hypersthene) have been very extensively altered. Sometimes the pyroxenes are rimmed with oxide but more often the alteration has completely obliterated the original crystal. Microphenocrysts of pyroxene have been similarly affected.

Accessories.

Olivine is quite abundant in some of the more basic two-pyroxene andesites. In the Gage's Dome lava (18641) for instance it is as abundant as hypersthene. The olivine phenocrysts in the Gage's Dome lava are generally quite fresh apart from a small amount of "iddingsitisation" and narrow rims of orthopyroxene. In weathered, reddened samples of the Gage's Dome lava (e.g. 18652) the edges of olivine crystals have often been completely replaced by iron oxide and the crystal contains numerous small crystals of oxide. Hornblende is exceptionally rare in the two-pyroxene andesites but two phenocrysts of hornblende were seen in the Gage's Dome lava (18641). They are irregular in shape and have an inner rim of magnetite and an outer rim of clinopyroxene, plagioclase and magnetite. Pleochroism is according to the scheme

X	-	yellow-brown
Y	-	brown
Z	-	orange-brown.

Groundmass.

The groundmass of the two-pyroxene andesites is usually composed of microphenocrysts of the main phenocryst minerals together with microlites of plagioclase and granules of clinopyroxene and ore. Hypersthene is much less abundant than clinopyroxene as a constituent of the groundmass. Glass is rare as a groundmass constituent but cristobalite occurs in most specimens and is very abundant in some of the lavas (e.g. 18649 and 18641). In a few cases (notably 18662 but also 18651) the groundmass contains patches which are composed of a fine-grained, more or less equigranular, quartz-rich aggregate together with some tiny flakes of mica (Plate 17^A). These patches are

apparently infilling cavities in the lava. The mica is probably phlogopite. It occurs as small flakes about 0.1 mm. long and is pleochroic according to the following scheme:-

- X - very pale yellow
- Z - orange, pale orange

If the mica is phlogopite and not biotite this is the only known occurrence of this mineral in Lesser Antillean lavas. Phlogopite is also very rare in volcanic rocks in general but it has been reported from a San Juan rhyolite (Deer, Howie and Zussman, 1962, vol. 3, p. 52) where it was originally described as biotite (Larsen et al., 1937).

The mode of occurrence of the quartz-mica aggregates is similar to that of cristobalite or tridymite in the other lavas and this suggests that the quartz-mica aggregates may have formed in much the same way as the tridymite and cristobalite, i.e. from late-stage fluids (see p. ///).

15:4:2 Hornblende-Hypersthene Andesite Lavas.

The younger domes of the Soufriere Hills (Chance's, Galway's and Castle Peak) are composed of hornblende-hypersthene andesite lava. The dome lavas are a light, sometimes pinky grey in colour and contain abundant phenocrysts of plagioclase and hornblende. Hypersthene phenocrysts also occur but are difficult to distinguish from small hornblende phenocrysts in hand specimen. The Castle Peak Dome lava contains very large hornblende phenocrysts up to 2 cm. long. The Chance's Dome lava is slightly banded with fairly regular reddish and grey bands and the Galway's Dome lava contains abundant holocrystalline inclusions.

The banded blocks of hornblende-hypersthene andesite lava from Pea Ghaut may also have been derived from a Soufriere Hills dome (p. 6/). These blocks are composed of irregular bands of white, grey and black lava (Plate 20B).

Plagioclase.

The mode of occurrence and properties of plagioclase in the hornblende-hypersthene andesites and in the two-pyroxene andesites are very similar. The range of composition

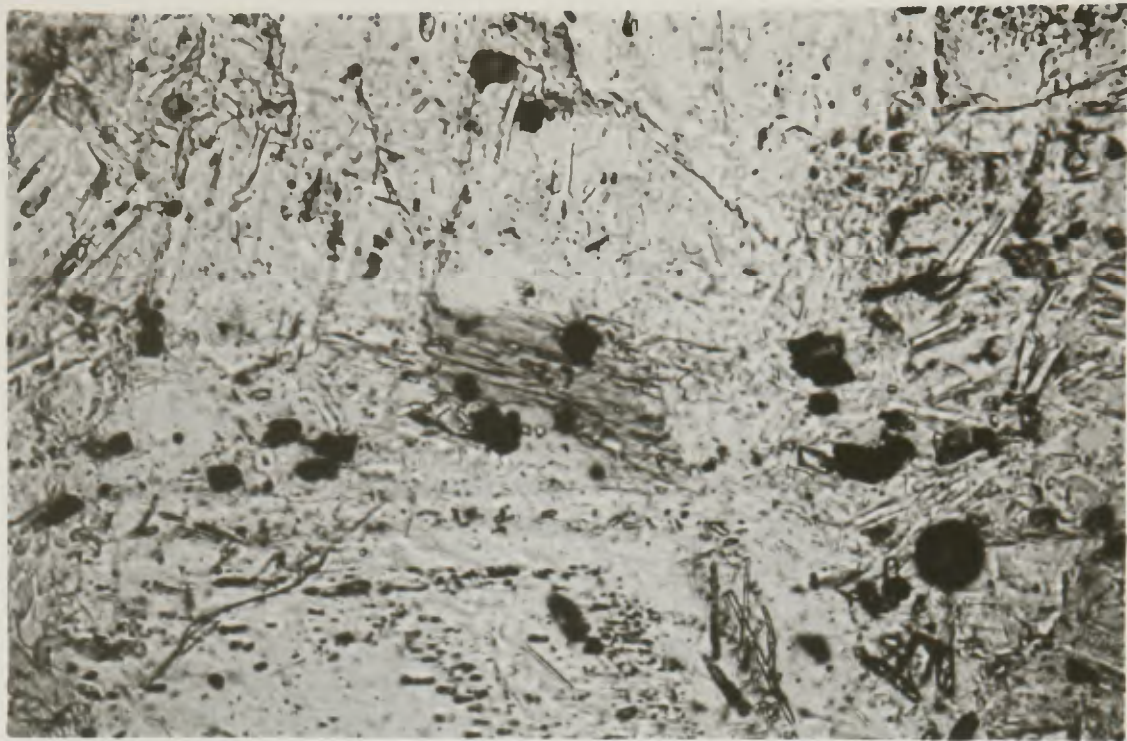


PLATE 17A. Photomicrograph of two-pyroxene andesite lava (18662) from intrusion ? near Harris Village. Small flake of mica which is probably phlogopite in a quartzose aggregate containing tiny laths of pyroxene ? and granules of magnetite. Magnification x 189.

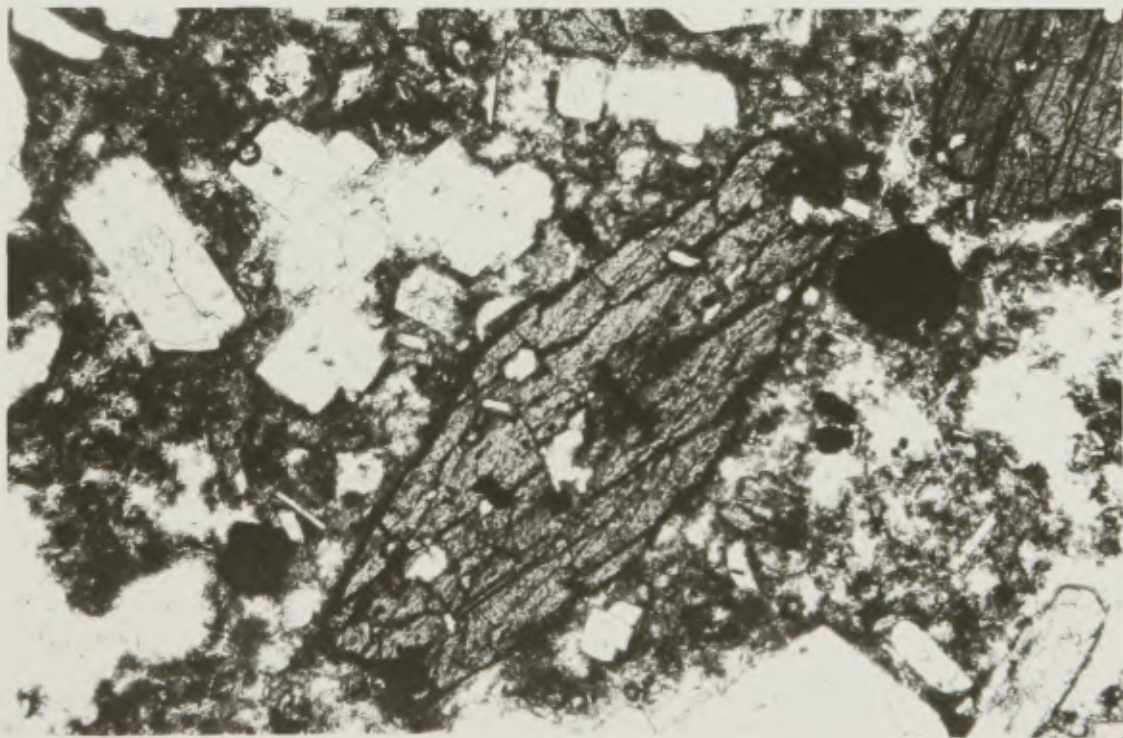


PLATE 17B. Photomicrograph of hornblende-hypersthene andesite (18640) from Chance's Dome. Hornblende phenocryst with a narrow resorption rim of magnetite. Magnification x 30.

of plagioclase phenocrysts is also similar in the two groups although slightly more calcic core compositions (up to An_{66}) were recorded in the hornblende-hypersthene andesites.

Oscillatory zoning and inclusions are probably less conspicuous than in the two-pyroxene andesites. Normally zoned rims, on the other hand, are more noticeable. Complex intergrowths of plagioclase crystals (p. 102) are common.

Hornblende.

Hornblende is abundant in some of the dome lavas (e.g. 18610). It occurs as single crystals up to 2 cm. long. Hornblende often encloses plagioclase and sometimes magnetite and very rarely hypersthene (18654). In the dome lavas, pleochroism is usually according to the following scheme:-

- X - pale yellow brown or greenish yellow
- Y - brown
- Z - dark brown or dark red brown (in oxidised lavas).

Values of $Z^{\wedge}C$ range from about 5° - 12° . The lowest values were obtained from the red brown hornblendes in oxidised lavas.

Hornblende phenocrysts in the dome lavas always show signs of resorption. In some cases (e.g. 18640, Plate 17B) the hornblendes are relatively fresh and resorption is confined to a narrow rim of iron oxide around the edges of the crystal. In others (e.g. 18610) the hornblendes are almost completely replaced by dark iron oxide ("black" resorption of MacGregor, 1938, p. 54). It is also noticeable that the phenocrysts in a single thin section often show a range in the extent and sometimes also in the type of resorption. Thus, in 18640 one or two of the hornblende phenocrysts have been replaced by a fine aggregate of orthopyroxene and clinopyroxene with subsidiary iron oxide ("pyroxenic" resorption of MacGregor 1938, p. 54). This type of resorption is rare in the hornblende-hypersthene andesite dome lavas but is more common in pumice fragments, although very often hornblendes in the pumices are not resorbed at all (p. 101).

Washington (1896) suggested that "black" resorption of hornblende results from decreased pressure, occurring under conditions of slow cooling in a magma close to the surface. It may be however that the decrease in water vapour pressure during an eruption is of greater importance than the decrease in total pressure though the two factors are obviously related. Thus pumice, which is erupted early from a volatile-rich melt will contain largely unresorbed hornblende whereas dome lava erupted from a late stage volatile-poor melt will contain hornblende that has been resorbed under conditions of low water vapour pressure. In addition, the rapid cooling of the pumice means that the time available for resorption to occur is short.

Pyroxenic resorption of hornblende is more or less restricted to glassy or semi-glassy rocks throughout the Lesser Antilles and Lacroix (1904, p. 507) and MacGregor (1938, p. 54) consider that this type of alteration takes place at greater depths than that producing the "black" resorption. It is possible however that in certain cases where "pyroxenic resorption" is restricted to the presence of a corona of pyroxene around a hornblende phenocryst the "resorption" is in fact a crystal nucleation effect (p. 84).

Hypersthene.

Hypersthene is abundant in the hornblende-hypersthene andesites. It usually occurs as single laths up to 5 mm. long. Hypersthene almost invariably includes magnetite or else abundant magnetite occurs nearby in the groundmass. Hypersthene shows pleochroism according to the following scheme.

X	-	pale pink or brown
Y	-	pale brown
Z	-	pale green

Optical data and inferred compositions for hypersthene in the hornblende-hypersthene andesites are given in Table 9.

Quartz.

A small amount of quartz is usually present in the hornblende-hypersthene andesites. The quartz crystals are often rounded and embayed (Plate 18A) and may be fractured as well. These features indicate magmatic resorption. In many of the rocks (e.g. 18610) quartz is mantled by abundant prisms of pale green augite but both rimmed and unrimmed crystals may occur in the same thin section. In 18692 a rounded quartz crystal is separated from a rim of small clinopyroxene crystals by an irregular zone of glass (Plate 18B).

The presence of rounded and resorbed crystals in andesites and dacites from other areas has been cited as evidence for assimilation (e.g. Larsen and Irving, 1938, p. 253). Furthermore, the clinopyroxene mantles around quartz crystals in basic lavas have been regarded as evidence for reaction with the groundmass (Lacroix, 1893) and glass zones as indicating transfusion of quartz by the acquisition of alkalis from the enclosing magma (Holmes, 1936). The writer considers, however, that the clinopyroxene mantles may be due to rapid nucleation around a pre-existing phenocryst. The fact that rocks which contain mantled quartz crystals usually contain abundant clinopyroxene microlites in the groundmass and may also contain "mantled" orthopyroxene and hornblende phenocrysts (as e.g. in 18610) supports this assumption (see also p. 84).

It is also possible that the rounded quartz crystals represent phenocrysts which were precipitated from an andesitic magma under certain physical conditions and were later resorbed under changed physical conditions. Thus T. H. Green and Ringwood (1968, p. 155) have pointed out that the reduction of load pressure may bring about resorption of early-formed quartz crystals. In addition experimental studies of the Ab-Or-Qz-H₂O system (Tuttle and Bowen, 1958) show clearly that the crystallisation field of quartz is greatly increased at high water vapour pressures, so that lowering of water vapour pressure may result in the resorption of quartz. It has been suggested earlier that the water vapour pressures of andesitic magma may fluctuate dramatically - during seismic crises or eruptions - and resorption phenomena and compositional zoning in other pheno-



PLATE 18A. Photomicrograph of hornblende-hypersthene andesite (18640) from Chance's Dome. Slightly rounded, embayed and fractured quartz crystal and oscillatorily zoned crystals of plagioclase in a fine-grained to glassy matrix. Crossed nicols. Magnification x 18.9

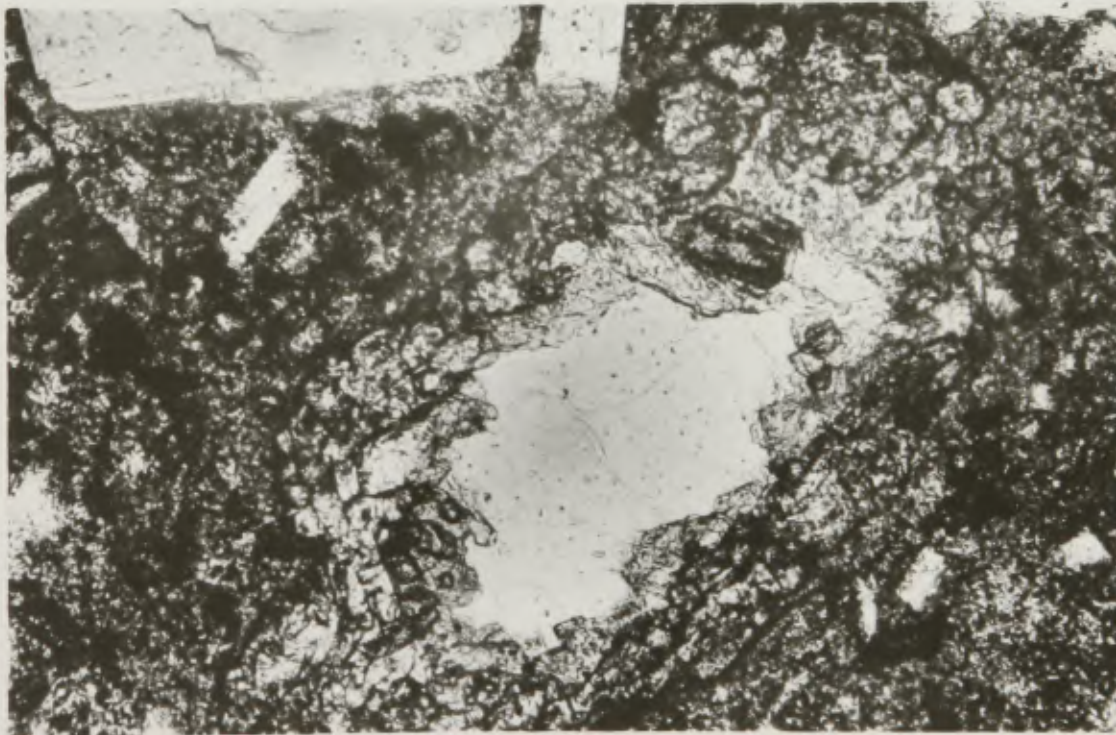


PLATE 18B. Photomicrograph of hornblende-hypersthene andesite lava block (18692) from pyroclast flow near St. Patricks. Quartz crystal surrounded by an irregular zone of glass which is itself surrounded by a "corona" of small clinopyroxene crystals. Magnification x 120.

crysts (notably plagioclase) in andesites have probably been caused by these changes. Tomblin (1964, pp. 120-121) has suggested that rounded quartz crystals in dacites from St. Lucia represent phenocrysts precipitated from dacitic magma at depth, under conditions of high water vapour pressure and later resorbed nearer the surface under conditions of reduced water vapour pressure and the writer suggests a similar origin for the rounded quartz crystals in the Montserrat andesites. The fact that quartz in pumices, from which presumably there was very late separation of the volatile phase, are less rounded and embayed than quartz in the dome lavas (p. 101), supports this assumption.

The glass zone surrounding the quartz crystal in 18692 is difficult to explain. Holmes (1936, p. 409) considers that the glass zones around quartz crystals in basic lavas from Uganda are not produced by fusion followed by rapid cooling but result from the transfusion of quartz by the introduction of various oxides (notably Al_2O_3 , K_2O and H_2O) from the enclosing basic magma. The introduced oxides (especially the alkalis) act as fluxes and convert the quartz to a glass. The writer is at present unable to suggest a more convincing explanation than this for the example of "fused" quartz from Montserrat.

Magnetite.

Magnetite is considerably less abundant in the hornblende-hypersthene andesites than in the two-pyroxene andesites or the basalts. Both hornblende and hypersthene phenocrysts may include crystals of magnetite.

Accessories.

Clinopyroxene is rare as a phenocryst in the hornblende-hypersthene andesite lavas although it may be prominent constituent of the groundmass (p. 98).

Relatively fresh olivine crystals occur in some of the lavas, notably 18654.

Groundmass.

Microphenocrysts of plagioclase, microlites of clinopyroxene and granules of

magnetite are the principal constituents of the groundmass of the hornblende-hypersthene andesites. Cristobalite and sometimes tridymite also occur, apparently infilling cavities. Glass occurs rarely.

15.4.3 Andesitic Pyroclastics.

This group is large and varied and includes among others:- the hornblende-hypersthene andesite pyroclast flows and pumice flows, the two-pyroxene andesite pyroclast flows and the hypersthene-andesite pumice falls of the Soufriere Hills; the Andesite Lapilli and Ash Zone and the Andesite Coarse Fall Zone of the White River Pyroclast Fall Series of South Soufriere Hill; the andesite tuffs of Roche's; the hornblende-hypersthene andesite pyroclast falls of St. George's Hill; and various pyroclast flows, pyroclast falls and agglomerates of the Centre Hills, Carabald Hill, Silver Hill and the Harris-Bugby Centre. Many of the non-vesicular fragments in these deposits bear a close petrographic resemblance to lava units which have been described above and these are not described in much detail. The pumiceous fragments, however, frequently show quite distinct petrographic characteristics and some of these are described in detail below.

Fragments in Pelean type Pyroclast Flows.

Many of the fragments in the Pelean type pyroclast flows are derived from lava domes (p. 19) and are similar petrographically to dome lavas of approximately the same composition. Fragments in the pyroclast flows, however, are usually more vesicular than the dome lavas and some of the minerals in these fragments may show properties that are gradational between those shown by the mineral in dome lava and pumice. Thus, hornblende in blocks from the pyroclast flows may be green in colour and pyroxenic resorption may be more common than black resorption. Fragments in the pyroclast flows also tend to be more glassy than the dome lavas.

Soufriere Hills Pumice.

18615 is typical of the pumice fragments in the widespread pumice flows which are believed to have accompanied the formation of English's Crater. It is a cream-

coloured, slightly pink, relatively non-vesicular pumice with prominent phenocrysts of plagioclase (up to 5 mm. long) and hornblende (up to 1 cm. long) together with small phenocrysts of hypersthene.

Plagioclase is abundant in 18615. The amount and type of zoning varies from crystal to crystal but oscillatory zoning is not as prominent as in plagioclases from the hornblende-hypersthene andesite dome lavas. The composition of plagioclase cores, estimated from extinction angle measurements is about An_{70} and rim compositions are about An_{50} . The contents of CaO (12.00%) and Na_2O (5.45%) in analysed plagioclase phenocrysts separated from 18615 indicate an average composition of An_{55} .

Hornblende occurs as large single crystals often including small plagioclases. One crystal includes a small patch of fresh brown glass. The hornblendes are very fresh and resorption is limited to narrow magnetite rims. Pleochroism is according to the following scheme:-

X - pale yellow green

Y - yellow brown

Z - dark green

and $Z \wedge C$ is about 10° .

Hypersthene occurs in 18615 as single crystals usually associated with magnetite and clinopyroxene occurs as microphenocrysts. Quartz is apparently absent.

The groundmass of 18615 is a dirty black colour. It is glassy and very finely vesicular. Microphenocrysts of the phenocryst phases occur, together with small crystals of clinopyroxene.

St. George's Hill Pumice.

Pumice falls believed to have been derived from St. George's Hill are widespread in the south and west of Montserrat (p. 70). The pumice found in these deposits contains phenocrysts of plagioclase, hypersthene, augite, hornblende and sometimes quartz as well. Many of these phenocrysts are euhedral but angular in shape apparently having been

broken during eruption so that the texture of these pumices may be described as proto-clastic (e.g. 18650, Plate 19A). In some rocks extreme fragmentation of phenocrysts has produced a granulated texture. In the St. George's Hill pumices hornblende is green and relatively unresorbed but quartz crystals are sometimes minutely embayed, indicating some magmatic resorption.

Other Pumices.

These pumices, from the Centre Hills, Carabald Hill and the Harris-Bugby Centre will not be described in detail but a few general points will be made.

The pumices vary considerably with respect to the size, type and relative amounts of phenocrysts present, vesicularity, colour, amount of glass etc. Many of the pumice fragments are characterised by a protoclastic texture.

Plagioclase is the most abundant phenocryst in all the pumices which were examined by the writer. Typically the cores of the plagioclases are rather ^{less} calcic and the total range of composition within a single crystal is not so great as in plagioclases from the lavas. Oscillatory zoning is also rather less pronounced, but the pattern of oscillatory zoning in many of the plagioclase crystals indicates clearly that they are broken fragments derived from larger crystals.

Hornblende is almost invariably present in pumiceous rocks, being totally absent in only two pumice specimens out of the 45 or so specimens which were examined by the writer. Hornblende and clinopyroxene phenocrysts quite often occur together in pumiceous rocks whereas they occur together in very few non-vesicular lavas. Hornblende in the pumices is very fresh and rarely shows much sign of resorption. Pyroxenic resorption is more common than black resorption. The hornblende in the pumices is invariably green.

Quartz crystals in the pumices in general show less sign of resorption than quartz crystals from the lavas and mantled quartzes do not occur. Quartz is also less resorbed in pumice than in lavas from St. Lucia (Tomblin 1964, pp. 122 and 133). The fact that quartz, hornblende and plagioclase crystals are less resorbed in pumices than

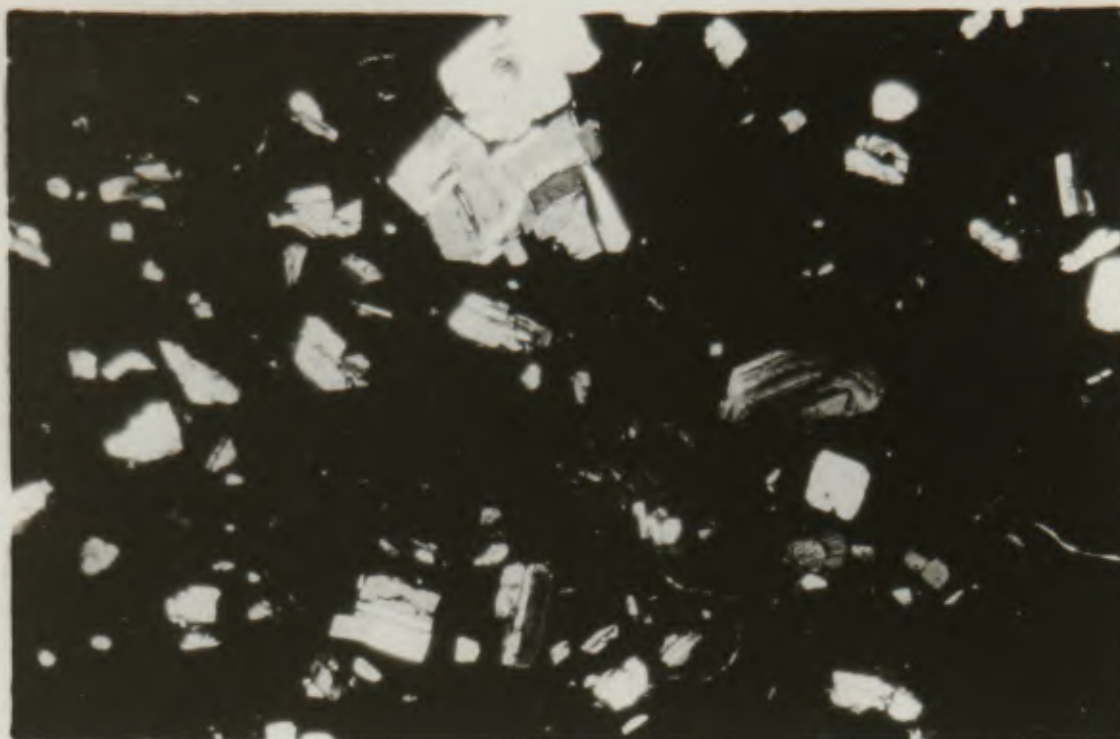


PLATE 19A. Photomicrograph of hornblende-hypersthene andesite pumice (18650) from St. George's Hill. Irregular, broken phenocrysts mostly of plagioclase occur in a glassy matrix. The pattern of zoning in the plagioclase crystal in the middle right of the photograph indicates quite clearly that it is a fragment from a larger crystal. Crossed nicols. Magnification x 15.

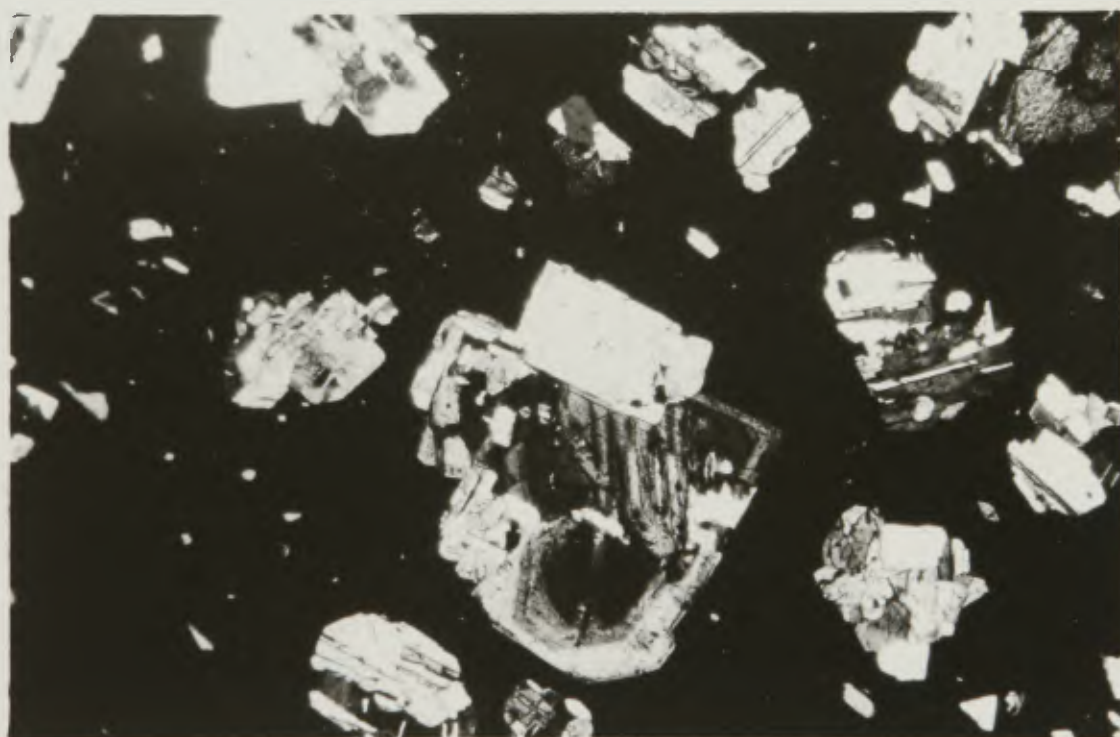


PLATE 19B. Photomicrograph of andesitic fragment (18594) from the White River Pyroclast Fall Series. Very irregular intergrowths of plagioclase occur in a glassy matrix. These intergrowths appear to be made up of plagioclase crystals which have grown together during later stages of growth (p. 102). Crossed nicols. Magnification x 15.



0 2 4 6
C/Ms.

PLATE 20A. Welded basaltic scoriae (18642) from the White River Pyroclast Fall Series. This rock is composed of lapilli of highly vesicular, almost aphyric basalt, which have been slightly flattened and lightly welded into a coherent mass.



PLATE 20B. Banded hornblende-hypersthene andesite lava block (18612) from Pea Ghaut. The block is composed of black, grey and white bands which are slightly contorted and swell and pinch out irregularly.

in lavas may be due to the late escape of volatiles from the latter (e.g. p. 96).

Other phenocrysts in the pumices include hypersthene, augite and magnetite. The properties of these minerals are similar to their properties in the lavas.

The groundmass of the pumices is glassy and ranges from finely to coarsely vesicular. The glass ranges in colour from pale grey or brown to black. The groundmass contains varying amounts of opaque oxide.

Andesitic Pyroclastics of the White River Pyroclast Fall Series.

Blocks from the andesitic zones of the White River Pyroclast Fall Series are quite uniform petrographically and the uniformity is very marked in blocks from the same horizon. In general the blocks are notably glassy but nevertheless quite rich in phenocrysts. Plagioclase crystals often form complex intergrowths (Plate 19B). These growths are made up of two or more crystals and often the whole group is characterised by a similar pattern of zoning and inclusions around the margins so that it appears that the whole mass has grown as a single (though very irregular) unit during later stages of growth. The original intergrowth may have resulted from the resorption of an early-formed plagioclase crystal followed by the crystallisation of plagioclase of a somewhat different composition in the embayed portion of the original crystal and in many cases around the original crystal as well. Similar plagioclase intergrowths also occur in certain lavas (p. 95) but why they should be particularly abundant in andesitic fragments from the Coarse Fall Zone is not immediately apparent.

Clinopyroxene and hornblende crystals occur together in many of these fragments. Other phenocrysts include hypersthene and magnetite. Quartz is apparently absent.

15:5 DACITES.

The Landing Bay Dacite is the only dacite lava known to occur on Montserrat. In many ways it closely resembles the hornblende-hypersthene andesites of the Soufriere Hills. In hand specimen the Landing Bay Dacite is a pale grey lava containing smallish phenocrysts of plagioclase and hornblende. The rock also contains some fine-grained

inclusions composed of plagioclase and a mafic mineral.

In thin section the Landing Bay Dacite is seen to consist of phenocrysts of zoned plagioclase, brownish hornblende with black magnetite rims, hypersthene, rounded quartz and rare augite in a microcrystalline groundmass of plagioclase, ore and pyroxene.

15:6 XENOLITHS.

Xenoliths found in lavas and pyroclastics from Montserrat can be divided into four main groups on the basis of their mineralogy and mode of occurrence.

1. Ultrabasic cumulate blocks which occur within andesitic pyroclast falls of the White River Pyroclast Fall Series.
2. Doleritic blocks, which have the same occurrence as group 1.
3. Cognate inclusions, of basaltic composition, which occur within andesite dome lavas and andesitic lava and pumice fragments from pyroclast flows.
4. Meta-sedimentary and meta-volcanic blocks which have been found in a variety of deposits including lava flows and pyroclast falls from South Soufriere Hill and pyroclast flows from the Soufriere Hills.

Petrographical and mineralogical characteristics of these groups are outlined below. Modal analyses of some of the xenoliths are given in Table 10.

15:6:1 Ultrabasic Cumulate Blocks.

Ultrabasic blocks are quite abundant in the block fall at the base of the Andesite Coarse Fall Zone of the White River Pyroclast Fall Series. They are apparently confined to this horizon although an inclusion of olivine and calcic plagioclase in pumice (18700) from the Andesite Lapilli and Ash Zone may represent part of a cumulate block.

The blocks are more or less ellipsoidal in shape but may have somewhat angular margins. The largest block found by the writer measured approximately 12 cm. x 8 cm. x 5 cm. but the blocks are normally quite a bit smaller than this and sometimes even single crystals of amphibole or plagioclase can be found. The blocks are notably

TABLE 1L. CHEMICAL and OPTICAL DATA ON MINERALS in the ULTRABASIC BLOCKS

	PLAG	OL	MAG ⁿ .	HORNBLLENDE		HORNBLLENDE ANALYSES RECALCULATED ON BASIS of 24 (0, OH, F)		
	47C	47D(2)	47C	47C	47D(2)		47C	47D(2)
SiO ₂				40.39	40.68	Si	5.907	5.983
TiO ₂				1.80	1.63	Al ⁴⁺	2.093	2.017
Al ₂ O ₃				14.88	14.64	Al ⁶⁺	0.473	0.521
Fe ₂ O ₃	0.70	1.45		4.42	5.00	Ti	0.198	0.181
FeO		25.39		7.06	6.81	Fe ³⁺	0.487	0.559
MnO		0.40		0.14	0.15	Mg	3.543	3.470
MgO		37.5		16.26	15.83	Fe ²⁺	0.864	0.838
CaO	17.74			11.80	11.76	Mn	0.018	0.019
Na ₂ O	1.30			2.39	2.48	Na	0.678	0.698
K ₂ O	-			0.22	0.20	Ca	1.849	1.853
P ₂ O ₅	0.01			0.01	0.01	K	0.040	0.038
H ₂ O				1.15	0.97	OH	1.122	0.950
F				0.06	0.06	F	0.028	0.028
TOTAL				100.58	100.19	Z	8.000	8.000
-O ≡ F				0.03	0.03	Y	5.583	5.588
				100.55	100.16	X	2.567	2.589
V		187	2760	938		100 Mg Mg + Fe ²⁺ + Fe ³⁺ + Mn		
Cr		3	125	5		72.1	71.0	
Composition from Chemical Data	An ₈₉	Fo _{72.5}						
R.I. n_z , (001) $\pm$.002	1.581							
Composition from Optical or X-ray Data	An ₉₁	Fo ₇₄						

NOTES:-

1. ANALYSTS MAJOR ELEMENTS
cols. 4 and 5 :-
MRS. J. WIGLEYMAJOR ELEMENTS cols. 1
and 2 and MINOR ELEMENTS:-
MR. R. FUGE2. METHODS See p. 119, 132

coarse-grained and consist mainly of crystals of amphibole (up to 5 cm. long) and plagioclase with small amounts of magnetite (Plate 21A). Round, reddened crystals of olivine are recognisable in one of the blocks (18593, Plate 21B). Patches of brownish fine-grained vesicular material occur interstitially in many of the blocks. Many of the blocks show a well-defined texture with large amphibole crystals aligned roughly parallel to the c-axis (Plate 21A). Rhythmic layering is however absent although this might be partly a result of the small size of the blocks. Distinctly plagioclase-rich and amphibole-rich patches occur in some of the blocks (e.g. 18592).

Plagioclase.

Plagioclase accounts for an average 43% of the mode of the Montserrat cumulates. It occurs as single crystals, which occasionally contain slightly rounded crystals of olivine. The plagioclase crystals range from 1 mm. up to about 2 cm. in length. Twinning is according to the albite or pericline laws with the rare development of Carlsbad twins. The crystals appear to be compositionally quite homogeneous but very narrow normally zoned margins are common. Some of the plagioclases in 18687 however have quite broad, normally zoned rims in which very fine-scale oscillatory zoning can be detected. Tiny inclusions, which are mostly of magnetite or glass occur in almost all the plagioclases.

Some chemical data on plagioclase separated from a plagioclase-amphibole-magnetite cumulate (18592) are given in Table II. These data indicate a composition of An_{89} , whereas the composition inferred from the measurement of the refractive index of (001) cleavage flakes and the determinative curves of Tsuboi (1923) is An_{91} . Refractive index measurements on plagioclase from 18593 which is a plagioclase-amphibole-olivine-magnetite cumulate indicate a composition of An_{93} . Lewis (1964, p. 38) found a range in composition in plagioclase from the St. Vincent blocks of An_{96} to An_{89} . Plagioclases from the plagioclase-amphibole cumulates had the lowest anorthite contents.

An interesting feature of the chemistry of the Montserrat plagioclase is the relatively high content of Fe_2O_3 . Part of this is no doubt due to the small inclusions

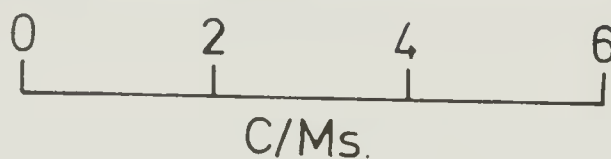


PLATE 21A. Anorthite-amphibole-magnetite cumulate block (18687) from White River Pyroclast Fall Series. Large amphibole crystals which are up to 3 cm. long are arranged approximately parallel to one another. ? Crescumulate texture.

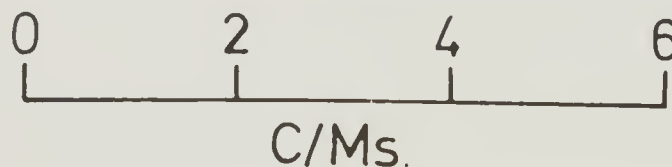


PLATE 21B. Anorthite-amphibole-olivine cumulate block (18593) from the White River Pyroclast Fall Series. More or less equigranular aggregate of anorthite, amphibole and olivine. The olivines are enclosed by the amphibole crystals.

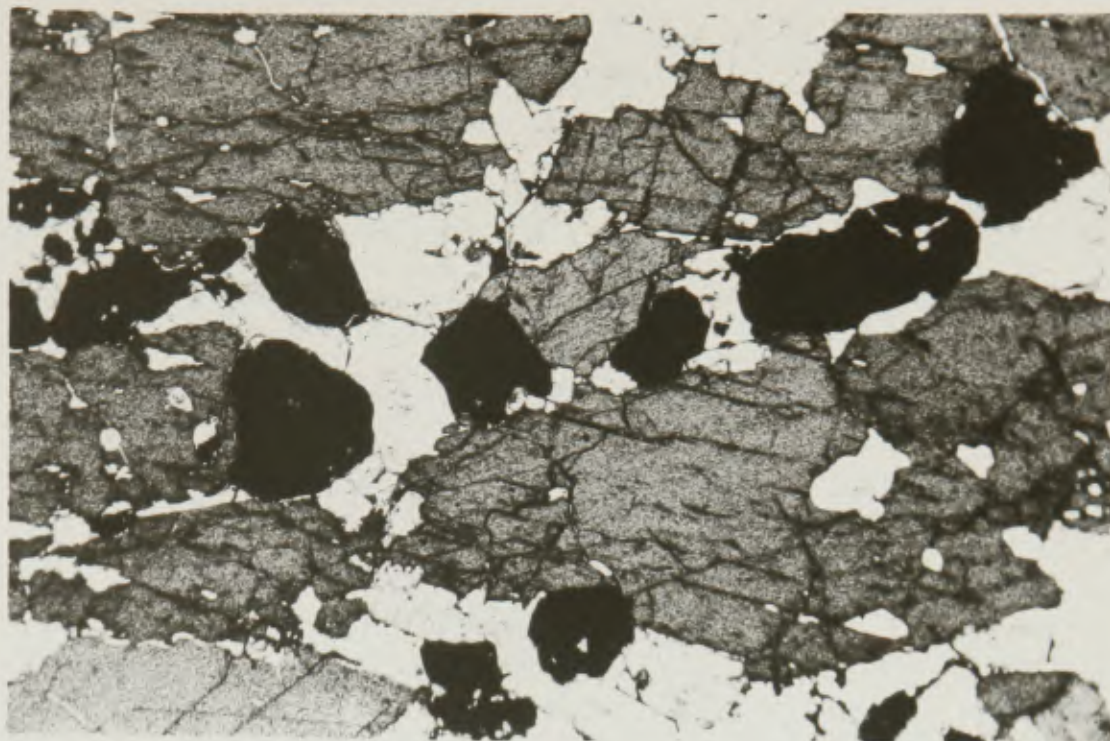


PLATE 22A. Photomicrograph of anorthite-amphibole-magnetite cumulate block (18687) from the White River Pyroclast Fall Series. Note the roughly parallel alignment of the amphibole crystals. Magnification x 12.

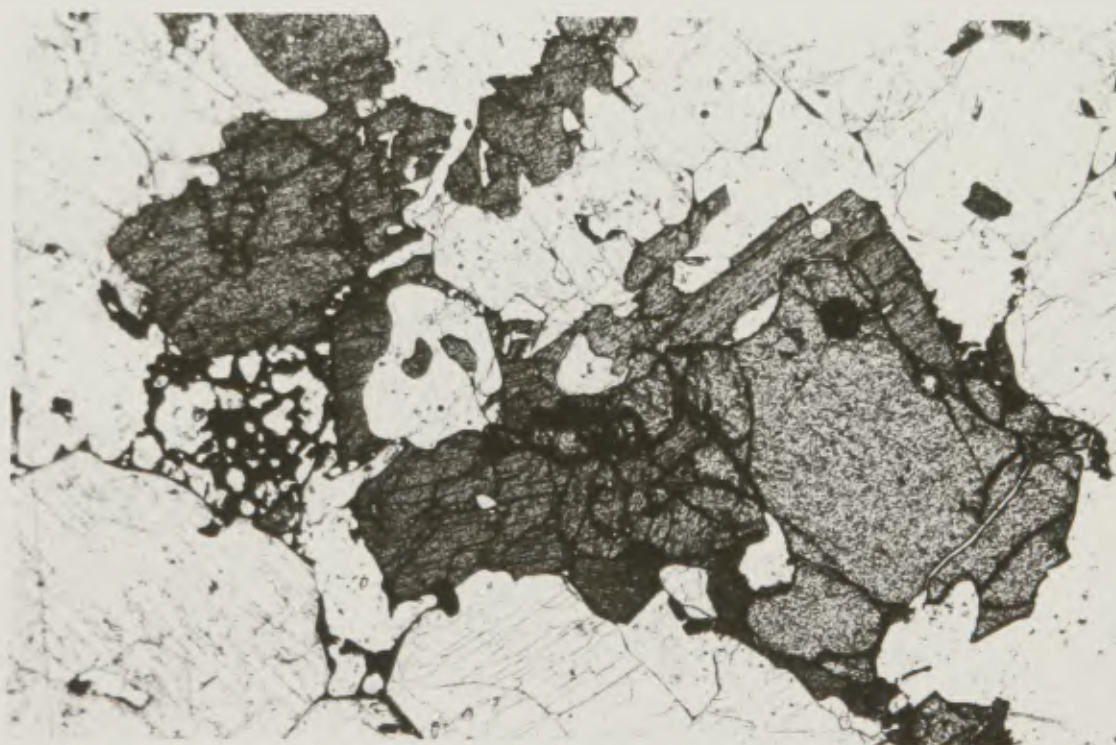


PLATE 22B. Photomicrograph of anorthite-amphibole-olivine cumulate block (18593) from the White River Pyroclast Fall Series. Amphibole surrounds an olivine crystal and a plagioclase crystal (centre of picture), which itself contains two overgrowths of amphibole. A patch of interstitial scoria occurs on the left of the picture and also forms a thin film around some of the crystals. Magnification x 18.9

in the plagioclase crystals but some Fe^{3+} probably replaces Al^{3+} in the plagioclase lattice. The value of Fe_2O_3 found in the Montserrat plagioclase is higher than values recorded from plagioclase from the St. Vincent blocks but closely resembles values obtained for anorthite crystals in Japanese volcanics (Sen, 1960).

Amphibole.

Amphibole is extremely abundant in the Montserrat ultrabasic blocks. It accounts, on average for a little over 43% and sometimes for as much as 60% of the total volume of the blocks. The amphibole crystals are large, ranging up to 5 cm. in length and they are often aligned roughly parallel to one another (Plate 22A). The crystals may enclose olivine (Plate 22B) or more rarely plagioclase.

Unlike the hornblendes in the lavas the amphiboles in the blocks are extremely fresh and show no sign of resorption. Pleochroism is according to the scheme:-

X - pale yellow

Y - green

Z - brownish green

and $\angle C$ was 13° in all the amphiboles measured.

Compositionally the Montserrat amphiboles (Table 11) are very similar to amphiboles from the St. Vincent blocks (Lewis, 1964, Table 28). They are rich in CaO and belong to the general group of calciferous amphiboles. Using the system of classification of calciferous amphiboles adopted by Deer, Howie and Zussman (1963, Vol. 2, p. 272) the Montserrat amphiboles, like those from the St. Vincent blocks are tschermakitic hornblendes grading into hastingsites.

The Montserrat amphiboles contain the maximum theoretical substitution of Al for Si of 2 atoms in the Z group and more than the theoretical maximum of 5 ions in the Y group (Table 11). Part of this discrepancy may be due to analytical error but it is worth noting that the majority of magnesian calciferous amphiboles have more than 5 ions in the Y group when the number of ions are distributed according to the

form adopted in Table 11.

Other noteworthy chemical features of the amphiboles from the Montserrat ultra-basic blocks include their high $\text{Fe}^{3+}/\text{Fe}^{2+}$, Mg/Fe and Al/Si ratios. The Al/Si ratios, which are even higher than those in amphiboles from the St. Vincent blocks, indicate high temperatures of crystallisation (see e.g. Lewis, 1964, p. 111, 112 and 114). Amphibole from 18592 is also rich in V, probably reflecting the high Fe^{3+} content of this mineral. The value of V is higher than in most amphiboles but is very similar to that found in an amphibole from the calcic hornblende gabbro of the Southern Californian Batholith (Sen et al., 1959, Table 4 No. 3). Amphiboles from the calcic hornblende gabbro show close chemical similarities with amphiboles from the St. Vincent blocks (Lewis, 1964, p. 107).

Olivine.

Olivine occurs in only one of the blocks (18593) collected by the writer. No anorthite-olivine blocks, like those which are common on St. Vincent or St. Kitts were found. The olivine in 18593 occurs as rounded to subhedral crystals, up to 2 mm. in diameter. The olivines are invariably enclosed by large amphiboles (Plate 22B). The olivines are somewhat altered, being coated by a thin film of red-brown oxide, which also penetrates the olivine crystals along cracks. The oxide has similar properties to the "iddingsite" which is replacing olivine phenocrysts in the basalt lavas. The occurrence of "iddingsite" is usually confined to volcanic or hypabyssal rocks (Gay and LeMaitre, 1961) so that its occurrence in these "plutonic" blocks is unusual. Gay and LeMaitre consider that "iddingsitisation" occurs at low pressures and intermediate temperatures, under strongly oxidising conditions.

The composition of the olivines from 18593 calculated from chemical data is $\text{Fo}_{72.5}$ whereas the value obtained by X-ray diffraction using the d_{130} method of Yoder and Sahama (1957) was Fo_{74} . This composition is similar to that of olivine from amphibole-bearing blocks from St. Vincent and also to the composition of olivine phenocrysts in the Montserrat basalts (Table 7). The Fe_2O_3 content of the olivine is

quite high probably due to the relative abundance of "iddingsite". Vanadium, which normally replaces Fe^{3+} in minerals is also quite high. Possibly some of the vanadium is present in the olivine crystal lattice, with the V^{3+} ion (ionic radius $0.74\text{\AA}$) substituting for the Fe^{2+} ion ($0.74\text{\AA}$).

Magnetite.

Magnetite is quite abundant in the Montserrat cumulates. It occurs in all the blocks which were examined in this section, except for 18593. Magnetite occurs as subhedral to rounded, apparently homogeneous crystals up to 2 mm. long. It is sometimes enclosed by amphibole.

V and Cr determinations were made on magnetite from 18592. The V content is over twice as great as that found in magnetites from St. Vincent (Lewis, 1964, Table 33). The method for vanadium determination used in the present investigation (p. 133) is probably more reliable than Sandell's method which was used by Lewis (Fuge, 1969, p. 33). Vanadium is considerably less abundant in the Montserrat magnetite than in magnetites from andesite and dacite for Mt. Edgecumbe, New Zealand (Duncan and Taylor, 1968).

Interstitial Scoria.

Filling the interstices between minerals grains in the Montserrat blocks is some scoriaceous, glassy material (Plate 22B), which is believed to represent the liquid from which the minerals separated at depth. The amount of this material varies both from block to block and also within individual blocks where it may occur in patches up to 1 cm. across or in very thin films around mineral grains. The proportion of interstitial scoria is particularly low in the crescumulates (see below). Sometimes (e.g. in 18592) the interstitial scoria contains abundant microphenocrysts of plagioclase, green hornblende and ore but normally the interstitial scoria is a dark brown, vesicular glass with occasional microlites of plagioclase. Unfortunately, it was not possible to separate enough of the interstitial scoria from any of the blocks for chemical analysis.

Textures.

Although rhythmic layering does not occur in the Montserrat ultrabasic rocks, these blocks show various properties which are best explained in terms of crystal settling from a basaltic magma. The blocks often have an equigranular mosaic texture, which might possibly be due to deformation and recrystallisation but as none of the blocks shows any evidence of deformation and amphibole is never distorted this explanation is considered to be very unlikely. Using the nomenclature, suggested by Wager and Brown (1968, pp. 553-555) the Montserrat blocks include mesocumulates (e.g. 18592, 18689, 18690), heteradcumulates (e.g. 18593) and crescumulates (18687, 18688).

The textural relations between minerals in the Montserrat blocks are such that amphibole cannot have crystallised before olivine, plagioclase or magnetite. The rather inconclusive evidence from the pumice specimen (18700, p. 103) suggests that olivine sometimes crystallises before plagioclase. It is probable however, that olivine and plagioclase crystallised together in 18593 and that amphibole, plagioclase and magnetite crystallised simultaneously in the other blocks.

Comparisons.

Ultrabasic cumulate blocks have been found at several localities in the Lesser Antilles. These include the Soufriere volcano, St. Vincent (Lewis, 1964) Mt. Misery, St. Kitts (Baker, 1968, pp. 132-135), Grenada and Carriacou in the Grenadines (Jackson, 1970). Anorthite-olivine cumulates also occur in andesitic volcanics from Japan (Kuno, 1950) and the South Sandwich Islands (Tomblin, in press) but the occurrence of amphibole in ejected blocks from these areas has not been reported.

The Montserrat blocks differ from the other Lesser Antillean ultrabasic cumulates in a number of ways. Anorthite-olivine blocks have not been found on Montserrat and clinopyroxene does not occur in the Montserrat blocks. On the other hand, amphibole is more abundant in the Montserrat cumulates than in those from other islands. The probable conditions of formation of the Montserrat ultrabasic blocks and their role in the petrogenesis of the Montserrat lavas is discussed in chapter 17.

15:6:2 Dolerite Blocks.

Blocks which may be classified as dolerites occur within the block fall at the base of the Andesite Coarse Fall Zone of the White River Pyroclast Fall Series, both as individual fragments (18597) and as inclusions within blocks of scoriaceous andesite (e.g. 18596).

These blocks consist very largely of plagioclase (Plate 26A) with cores of about An_{80} and rims of An_{40} . Zoning is predominantly of normal-discontinuous type but slight oscillatory zoning is also developed. Pyroxene is also quite abundant. 2Vs of 66° for orthopyroxene and 45° for clinopyroxene were measured. In places clinopyroxene is surrounded by narrow rims of green hornblende which is apparently replacing it (see also p. 117). The only other commonly occurring mineral is magnetite.

Two generations of crystals appear to exist in the dolerites. The larger crystals of 1-2 mm. diameter are equidimensional and often euhedral. Between these large crystals, patches containing small crystals of plagioclase, pyroxene, magnetite, hornblende and quartz occur.

15:6:3 Cognate Basaltic Inclusions.

Small ellipsoidal inclusions are common in almost all the Montserrat dome lavas and also occur in lava and pumice blocks in pyroclast flows. Similar inclusions have been found in lavas from almost all the islands in the Lesser Antilles and they also occur in many other calc-alkaline provinces. Various criteria, including the mineralogy of the inclusions (Baker, 1963, Tomblin, 1964) and the composition of the host rock (MacGregor, 1938) have been used to subdivide the inclusions in lavas from other islands in the Lesser Antilles but in view of the fact that all the Montserrat inclusions apparently have a common origin, no such subdivisions are used in the following account. In general, the Montserrat inclusions belong to Lacroix's (1904) class - "enclaves homogènes pléiomorphes".

The cognate inclusions represent accumulations of those minerals, which occur as

phenocrysts or microphenocrysts in the host rock although the relative proportions of the minerals in the inclusion and the host rock may be radically different. A cognate xenolith in a hornblende-hypersthene andesite lava, will probably consist of crystals of plagioclase, hornblende, hypersthene and magnetite. In a few cases, not all the minerals, which occur as phenocrysts and microphenocrysts in the host rock are present in the cognate inclusion but minerals which do not occur in the host rock are never found in the inclusion.

Three generations of minerals occur in the cognate inclusions:-

1. The oldest group consists of large extensively resorbed crystals usually of plagioclase (Plate 23A) or hornblende (Plate 23B) but occasionally of pyroxene, olivine or quartz. These minerals resemble the large phenocrysts in the enclosing rock but are more extensively resorbed. In addition, the large hornblendes in the inclusions have undergone "pyroxenic" resorption, whereas hornblende in the host rock may have undergone "black" resorption.

2. The second group of minerals normally makes up 75% or more of the inclusion. It is made up of a more or less equigranular mass of eu- to subhedral crystals (Plate 25B) which closely resemble microphenocrysts in the enclosing rock, with respect to size, optical properties and types of resorption. Thus extinction angle measurements indicate plagioclase compositions of about An_{55-60} in the inclusions compared with values of around An_{55} for microphenocrysts and An_{85} in phenocryst cores in the enclosing lava.

3. Most of the inclusions, but particularly those in the lavas have an extremely open texture, with extremely abundant vugs up to a few millimetres across. These vugs are sometimes filled with brownish glass but more often contain tridymite or cristobalite. Occasionally glass and a silica polymorph occur together. Acicular tridymite is found in some inclusions (cf. Plate 25A) and arrow-head twins of tridymite (Plate 24) were also seen but "tiled" patches of cristobalite are the most common infilling. Quartz-mica aggregates, which fill vesicles in certain lavas and are thought to have had a

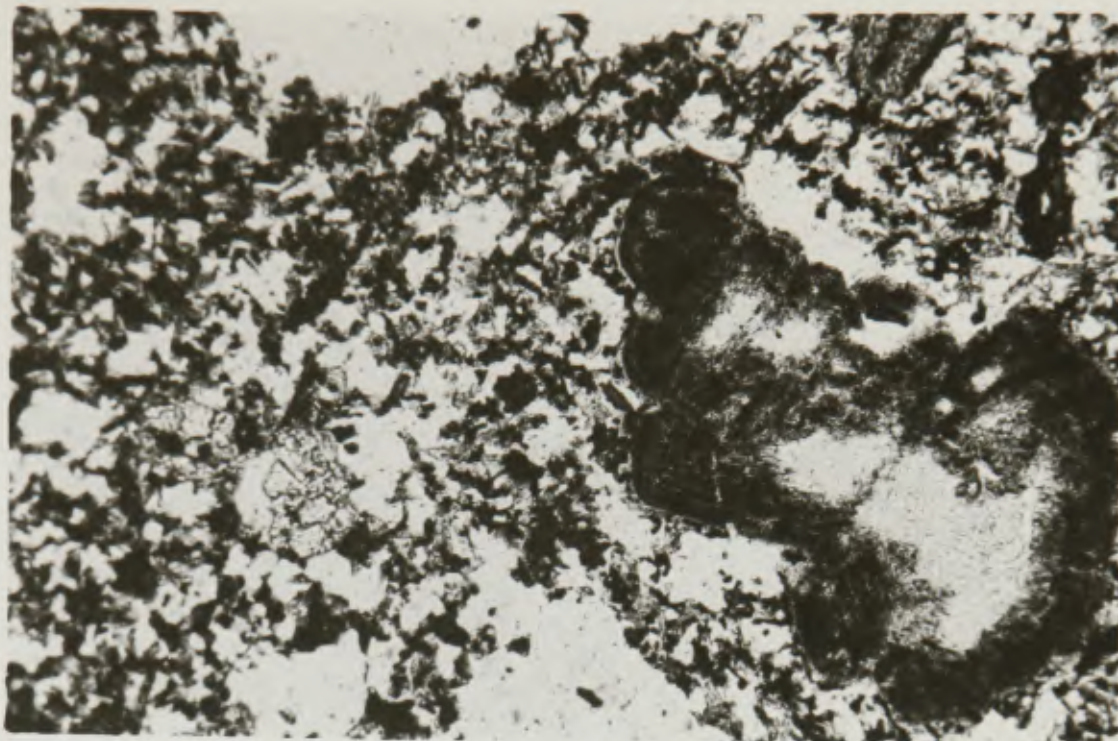


PLATE 23A. Photomicrograph of cognate inclusion in hornblende-hypersthene andesite lava (18627) from Carabald Hill. A rounded crystal of plagioclase, clouded with inclusions of ore and glass, occurs in a fine-grained aggregate which consists of laths of plagioclase, pyroxene, hornblende and ore. The hornblende shows "black" resorption similar to that shown by microphenocrysts in the host rock. Note the open texture of the inclusion and the large patch of cristobalite (bottom left) which infills one of the numerous cavities. Magnification x30.

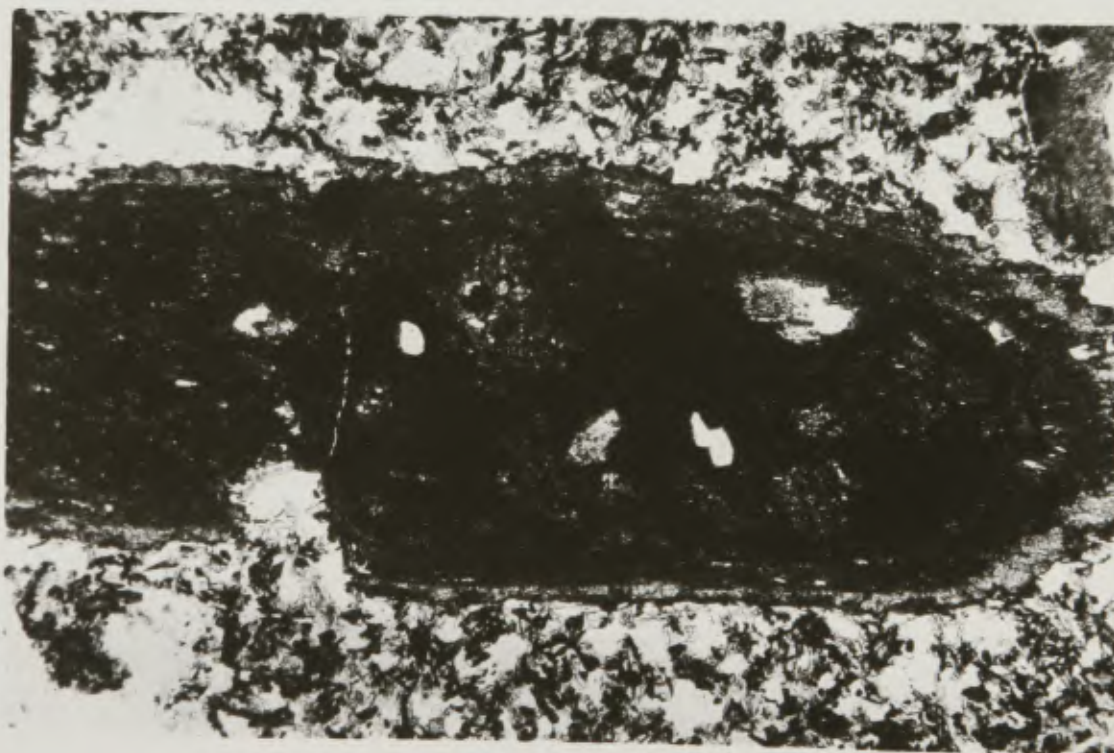


PLATE 23B. Photomicrograph of 18627. Large crystal of hornblende showing "pyroxenic" resorption. The numerous small laths in the rest of the inclusion show "black" resorption. Magnification x 12.

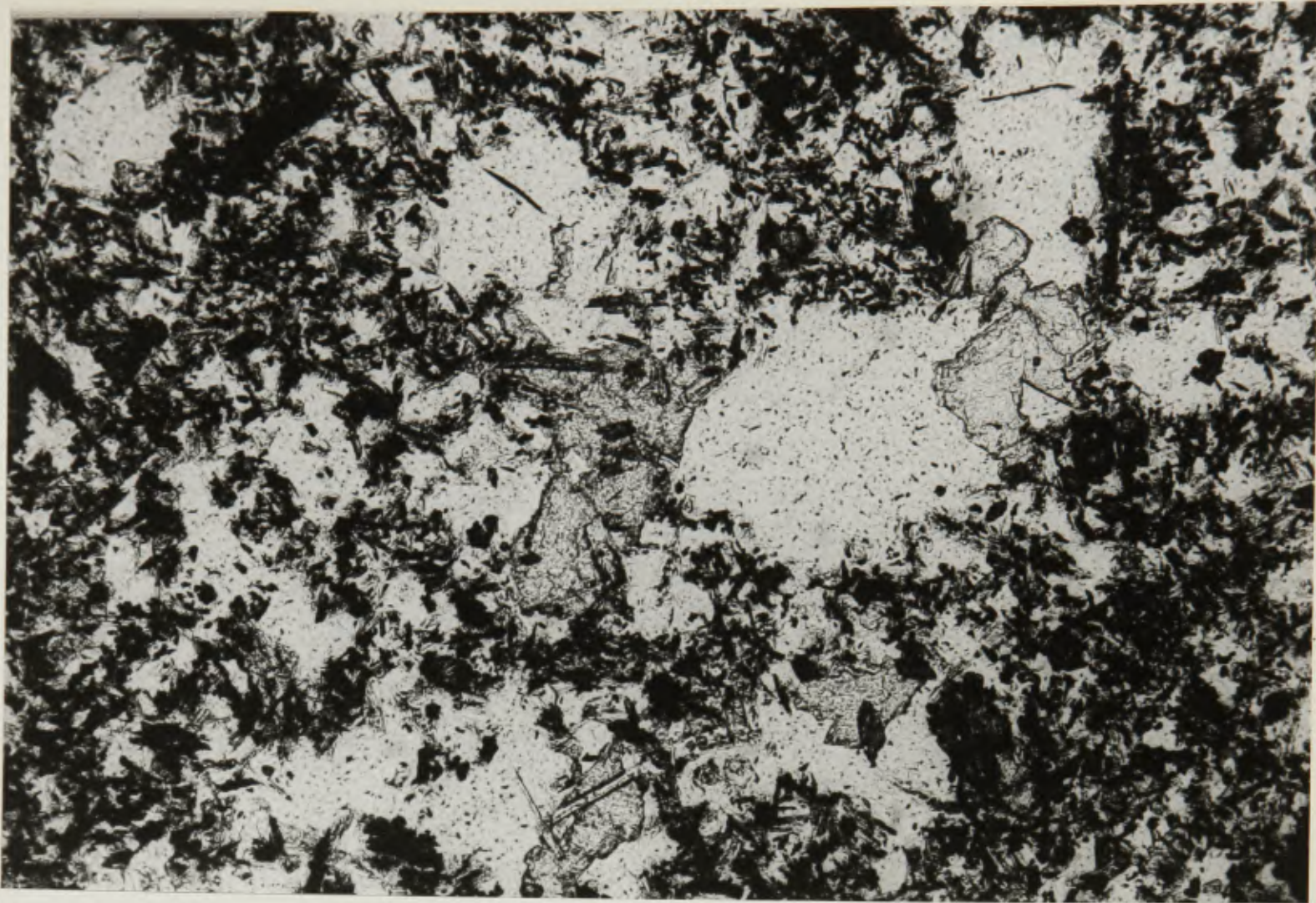


PLATE 24A. Photomicrograph of cognate inclusion in hornblende-hypersthene andesite lava (18627) from Carabald Hill, showing patches of "tiled" interstitial material which appears to be cristobalite. Magnification x15.



PLATE 24B. Same view as 24A but under crossed nicols. The presence of arrow-head twinning indicates that the silica polymorph on the right of the photograph is actually tridymite. Magnification x15.



PLATE 25A. Photomicrograph of two-pyroxene andesite lava block (18701) from east coast of Montserrat, near Mulcare's, showing vesicles containing acicular tridymite. Magnification x 94.5

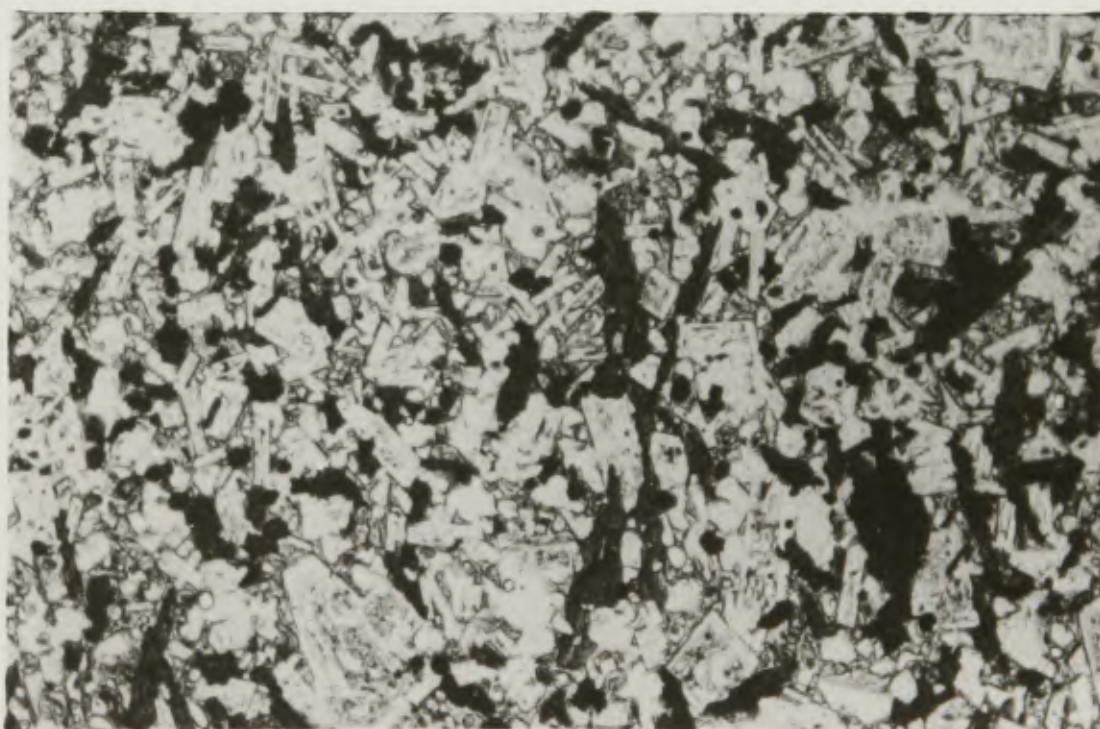


PLATE 25B. Photomicrograph of cognate inclusion in hornblende-hypersthene andesite pumice (18702) from pumice flow near Galway's Soufriere. The inclusion is made up of a roughly equigranular aggregate of plagioclase, hornblende, magnetite and orthopyroxene with a little interstitial glass. The hornblende in the inclusion, like that in the host rock is green and unresorbed. Magnification x 19.2

similar origin to the tridymite and cristobalite in other lavas (p. 94), were not found in any of the cognate xenoliths.

Tridymite and cristobalite in cognate inclusions and lavas from Montserrat infill cavities and have apparently crystallised from late stage fluids. Lacroix (1905) noted that rocks collected from Mont Pelé soon after the eruption of 1902, contained no tridymite or cristobalite, but that tridymite began to appear in the rocks about six months after their eruption. It seems therefore that much of the tridymite and cristobalite and probably the quartz-mica aggregates as well, may have crystallised after eruption, from magmatic fluids trapped in the lavas at the time of eruption. In any case, it is obvious that tridymite and cristobalite have formed far outside their normal stability fields. There are two possible reasons for this.

(a) Rapid cooling. This is an unlikely explanation if, as seems to have been the case in many of the Lesser Antillean lavas, cristobalite and tridymite have formed after eruption.

(b) The substitution of Al^{3+} for Si^{4+} in the cristobalite or tridymite structure, together with the inclusion of other ions, notably Na^+ , K^+ and Ca^{2+} in spaces in the cristobalite or tridymite lattice may considerably affect the stability range of tridymite and cristobalite (see e.g. Deer, Howie and Zussman, 1962, Vol. 4, p. 192-193 and 199-200). Experimental work has shown that tridymite and cristobalite precipitate most readily from alkali-containing systems (e.g. Tokuda, 1957) and that the presence of water is a considerable advantage in the precipitation of cristobalite (Carr and Fyfe, 1958). The presence of metal cations may well be a crucial factor in the stability of tridymite and cristobalite in the Antillean lavas. If as seems likely, the tridymite and cristobalite in the Montserrat lavas are equivalent to the quartz-rich, mica-bearing aggregates, it is expected that the tridymite and cristobalite contain appreciable amounts of Al_2O_3 , K_2O , Na_2O , CaO , MgO and perhaps also some Fe_2O_3 .

15:6:4 Metasedimentary and Metavolcanic Blocks.

Metamorphic blocks are found in lava flows and pyroclast falls from South Soufriere Hill and in pyroclast flows from the Soufriere Hills. Although these blocks vary greatly in chemical (Table 12, Nos. 51 and 52) and mineralogical composition they are quite uniform in hand specimen. They are a bluish to greyish green in colour and have a fine-grained, hornfelsic texture. Some of the blocks (e.g. 18613) show crude banding and many of the blocks have irregular light and dark patches. Individual minerals are very difficult to recognise in hand specimen. Under the microscope, however, the "metamorphic" blocks are seen to be very varied both with respect to their mineralogy and the amount of recrystallisation they have undergone. Modal analyses of two of the blocks are given in Table 10. In view of the extremely fine grain-size of the blocks it is often difficult to distinguish small crystals of quartz and plagioclase in 18576 so that the accuracy of this modal analysis is questionable.

Plagioclase.

Plagioclase is abundant in most of the blocks. It usually occurs as very small irregular grains but in 18590 discrete sub- to an-hedral crystals up to 2 mm. in diameter can be recognised. Plagioclase compositions are very difficult to determine but it appears that the plagioclase in 18590 ($\sim \text{An}_{80-90}$) is considerably more calcic than that in the other blocks ($\sim \text{An}_{50}$). Compositional zoning is inconspicuous although some crystals have narrow normally zoned rims. Many plagioclases contain small inclusions of pyroxene, magnetite or glass.

Quartz.

Quartz occurs in all the blocks (except 18590) and is the major constituent in 18576. The quartz in 18576 occurs mostly in rounded patches consisting of several small fragments of quartz. Sometimes these patches are surrounded by a rim of small green pyroxene crystals giving a texture which resembles the "mantled" quartzes in some of the Montserrat lavas (p. 97). Veins, composed of rather coarser crystals of quartz cut some

of the blocks.

Clinopyroxene.

Two types of clinopyroxene have been recognised in the metamorphic blocks. Colourless clinopyroxene occurs in two blocks (18685 and 18590). It is probably diopside or augite. Green clinopyroxene, which may be slightly pleochroic to brownish green occurs in 18513 and 18576. Apart from the colour the optical properties of the two clinopyroxenes are similar and the green variety may simply be slightly richer in iron than the colourless variety (cf. Sandra, 1949, p. 376-377). In 18590 a gradation is seen from distinct single crystals of pyroxene to a densely packed brown, columnar aggregate composed of very fine grains.

Orthopyroxene.

Hypersthene occurs in only one of the blocks (18686).

Amphibole.

Brown hornblende is abundant in 18685 and pale brown hornblende occurs in 18686.

Accessories.

Magnetite occurs as small crystals in most of the blocks and interstitial glass is also quite common. Calcite occurs in patches in 18576.

Textures.

The blocks are mostly hornfelsic being composed of a fine grained roughly equigranular mosaic. The patchy appearance seen in hand specimen in many of the blocks is due to local concentrations of mafic minerals (Plate 26B) and the crude banding seen in 18613 also results from a variation in the proportion of mafic minerals in different parts of the rock. Two blocks have unusual textures. 18590 is composed of dense fibrous aggregates of clinopyroxene which grade into individual crystals of clinopyroxene at the edges. The patches of clinopyroxene are separated by irregular bands composed almost exclusively of calcic plagioclase. Only one block (18686) shows good evidence of relict texture. Here granulation and recrystallisation are affecting a two-pyroxene



PLATE 26A. Photomicrograph of doleritic block (18597) from the White River Pyroclast Fall Series. The rock consists mainly of plagioclase with minor pyroxene and ore. The plagioclase which has cores of about An_{80} and rims of about An_{40} shows zoning predominantly of normal discontinuous type but slight oscillatory zoning also occurs. Crossed nicols. Magnification x 18.9.

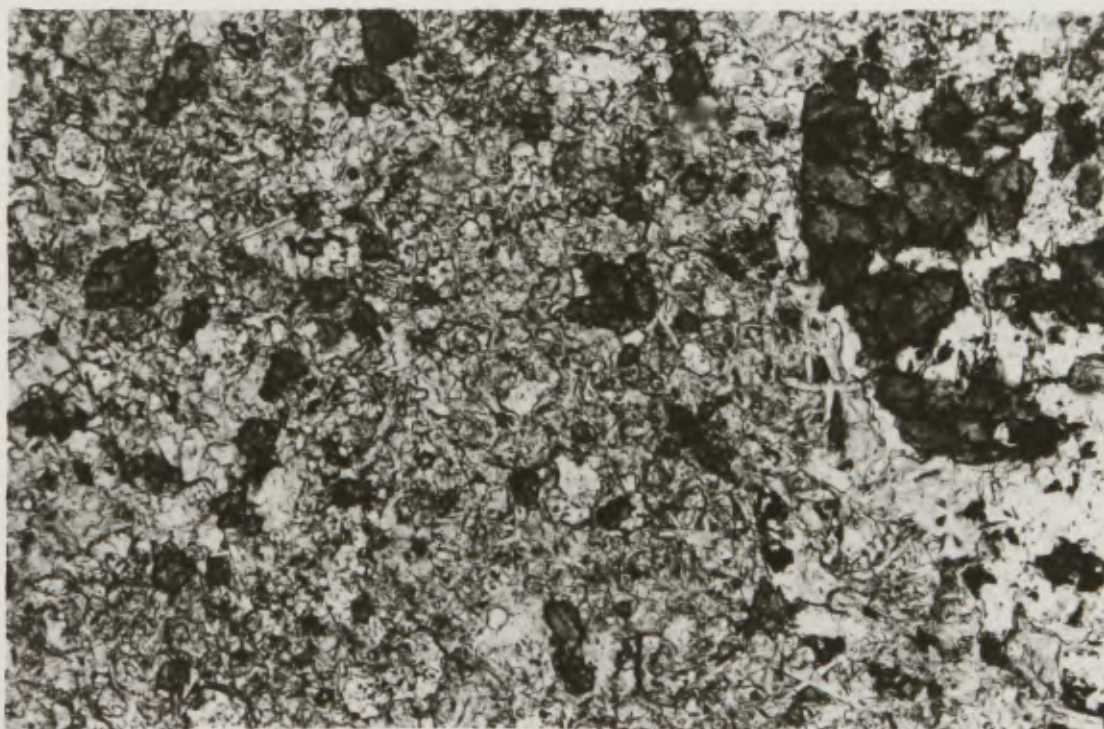


PLATE 26B. Photomicrograph of metasedimentary inclusion (18576) from a basalt lava flow near O'Garra's. Hornfelsic rock composed mainly of quartz and green clinopyroxene with subordinate plagioclase, magnetite and glass. An aggregate of clinopyroxene occurs on the right hand side of the photograph. Magnification x 120.

andesite lava in which primary igneous textures (phenocrysts and small inclusions) are clearly distinguishable.

Comparisons.

"Metasedimentary" calcareous blocks have also been described from the Soufriere volcano, St. Vincent by Lacroix (1904), Flett (1908) and Sandrea (1949). Flett (1908) recognised 3 types of calcic blocks:- impure siliceous limestones, quartzites and albite - augite bearing blocks while Sandrea (1949) has described in some detail the anorthite-bearing metasediments. From these descriptions it is clear that in general the Montserrat blocks are richer in quartz and with the exception of 18590 contain considerably more sodic plagioclase than the St. Vincent blocks. The mafic minerals in the two sets of blocks appear, however, to be very similar except that wollastonite, which is common in the St. Vincent blocks does not occur in the Montserrat blocks. Metasediments from St. Lucia (Tomblin, 1964, pp. 144-146) appear to be quite different from those found on Montserrat.

Origin.

The hornfelsic textures of the Montserrat metamorphic blocks suggest that they are the product of contact metamorphism. Sandrea (1949) concluded, on the basis of the high temperature mineralogy of the St. Vincent "enclaves calcaires" that these blocks cannot have been metamorphosed by contact with any of the St. Vincent lavas. He suggested that the agent of metamorphism might have been the St. Vincent ultrabasics. In this connection it may be significant that the only anorthite-bearing "metamorphic" block found on Montserrat (18590) occurs together with ultrabasic blocks in a particular horizon within the White River Pyroclast Fall Series. In general, however, the Montserrat blocks have a lower temperature mineralogy than the St. Vincent "metamorphics" so that in this case basaltic or andesitic magma could have been the agent of metamorphism. However, the fact that those blocks (e.g. 18576) which occur as inclusions in basalt lava flows, show no sign of any reaction with the host rock suggests that these blocks may have been metamorphosed before their inclusion in the lavas.

The original nature of the Montserrat "metamorphics" is by no means clear except in the case of 18686 which is almost certainly an altered two-pyroxene andesite lava. The other blocks cover a very wide range of compositions (Table 12, Nos. 51 and 52) and the chemical analyses suggest that these blocks are unlikely to have been volcanic. They are more likely to have been derived from a heterogeneous suite of sediments and the fact that they resemble, in hand specimen, rocks from Eocene flysch deposits on Grenada and Barbados (J. F. Tomblin, pers. comm.) may be significant. The large amount of plagioclase in the blocks further suggests that these sediments may have been volcanoclastic.

15:7 SUMMARY OF PETROGRAPHY.

The Montserrat lavas and the Lesser Antillean lavas in general are simple in the sense that they are composed of a limited number of mineral species but these minerals often show evidence of complex crystallisation histories. Compositional zoning and resorption phenomena are common but different crystals of the same mineral in the same lava may show widely different patterns of zoning and resorption.

Because some of the minerals e.g. plagioclase seem to have crystallised throughout virtually the entire cooling history of most of the lavas it is difficult to work out an order of crystallisation. In addition there may be at least three different generations of crystals in many of the lavas, each of which has formed under different physico-chemical conditions and the order of crystallisation may be different at the different stages. The three main groups of crystals in the Montserrat lavas are thought to be as follows:-

1. Crystals that have formed relatively deep in the crust. Most of the phenocrysts in the lavas belong to this group. Many of these phenocrysts, but especially the plagioclases, are characterised by complex compositional zoning and resorption phenomena which suggests that they have been affected by large-scale changes in their physico-chemical environment. Indeed, the widespread resorption of some of these cryst-

als might indicate that they are xenocrysts but it is considered that in most cases their instability is due to changed physical conditions affecting the magma from which they crystallised rather than to their incorporation in a different magma (e.g. p. 98).

The exact physical conditions under which these crystals formed is not known. However, certain phenocrysts in the basalts, notably olivine and to a lesser extent plagioclase (cores only), clinopyroxene and magnetite have similar compositions to crystals in the Lesser Antillean ultrabasic blocks, which may have formed at depths of about 6-8 km. under high water vapour pressure. The phenocrysts in the lavas differ in many ways from the crystals in the ultrabasic blocks but many of these differences may be due to the fact that crystals in the blocks did not undergo reaction with the magma, under changed physical conditions subsequent to their formation.

As one might expect hypersthene and quartz which occur as phenocrysts in andesite lavas are not present in the ultrabasic blocks and the composition of hornblende phenocrysts in the andesites is very different from that of amphibole in the blocks (R. Goodman, pers. comm.). Nevertheless, the phenocrysts in the andesites especially quartz (p. 98) and the calcic plagioclase cores may have originally crystallised under high water vapour pressure, relatively deep in the crust.

The following generalisations can be made regarding the order of crystallisation among crystals of group one as indicated by textural evidence. Olivine was the first phenocryst to form in the basalts but may have crystallised together with plagioclase, magnetite and clinopyroxene during later stages of crystallisation. There is some evidence of a reaction relation between olivine and liquid to produce hypersthene (p. 81) as suggested by Kuno (1950, p. 971) but olivines are more often surrounded by clinopyroxene coronas than by hypersthene rims (p. 81).

Magnetite which is much more abundant in the basalts than the andesites may also have been an early phase to separate. Pyroxene phenocrysts in the basalts and two-pyroxene andesites show complex interrelationships (p. 83) and slight changes in the physico-chemical environment may have been sufficient to reverse the order of

crystallisation of these phases. There is no evidence to suggest a reaction relationship between augite and liquid to give hypersthene (cf. Kuno, 1950). Instead clinopyroxene probably reacts with liquid to give hornblende in the more acid lavas. There is not much positive evidence for this reaction although hornblende is apparently replacing clinopyroxene in the doleritic block (18597) from the White River Pyroclast Fall Series (p. 109). The consumption of clinopyroxene in the formation of hornblende will also account for the antipathetic relationship between hornblende and clinopyroxene phenocrysts in the Montserrat lavas.

The textural evidence shows that plagioclase, clinopyroxene and magnetite in the basalts, plagioclase, augite and hypersthene in the two-pyroxene andesites and plagioclase and hypersthene in the hornblende-hypersthene andesites have in many cases crystallised together.

2. Crystals which belong to the second group of crystals in the lavas are believed to have crystallised near the surface, shortly before eruption. Crystals of this group include microphenocrysts in the lavas and are the main constituents of the cognate inclusions in the lavas. These crystals are relatively unzoned and unresorbed and may be different in composition from group one crystals e.g. plagioclase microphenocrysts are less calcic than plagioclase phenocrysts. The microphenocrysts are believed to have crystallised at pressures approaching one atmosphere i.e. at depths of less than 3 km.

Most of the group two crystals, which include labradorite, clinopyroxene, orthopyroxene, hornblende and magnetite but not olivine or quartz appear to have crystallised simultaneously. Clinopyroxene, which may be very abundant, and hornblende are not apparently antipathetic at this stage.

Phenocrysts of group one may undergo resorption and/or additional crystallisation at this stage e.g. resorption of calcic plagioclase, together with the growth of normally zoned rims of labradorite or andesine may occur. Many phenocrysts should therefore be considered to be mixtures of group one and group two crystals. It is

possible also that some so called "resorption" effects may be the result of rapid nucleation of group two crystals especially clinopyroxene around phenocrysts (e.g. p. 84).

3. The third group is made up of crystals which have formed after extrusion. It includes much of the groundmass and probably some microphenocrysts as well. The late stage tridymite, cristobalite and the quartz-rich mica-bearing aggregates also belong to this group.

The division of the constituents of the lavas into three groups, as outlined above is undoubtedly an oversimplification, since it takes no account of constituents of intermediate type or of those complex constituents that may have risen and fallen in the crust more than once before being erupted. It is however, considered that most of the constituents of the lavas and also of the cognate xenoliths in the lavas (p. 109) can be assigned to these groups. The relative importance of the different groups is different in the lavas where group one crystals may account for up to 50% of the total and in the cognate inclusions where group two crystals ($\sim 75\%$) are predominant. Group three crystals appear to be quite important in both lavas and cognate inclusions but tridymite and cristobalite are more conspicuous in the latter.

Finally the importance of water in the formation of the Montserrat lavas as indicated inter alia by the high An contents of plagioclase phenocrysts (p. 95) and the abundance of hornblende is stressed. In addition many of the nonequilibrium petrographic features seen in the lavas e.g. major compositional zoning in plagioclase (p. 89) and resorption of quartz (p. 96) and hornblende (p. 98) may be caused by fluctuations in water vapour pressure.

CHAPTER 16.

PETROCHEMISTRY.

16:1 MAJOR ELEMENTS.

52 major element analyses of Montserratian rocks are presented in Table 12 and specimen descriptions are given in Table 13. With the exception of analyses numbers 48-50 which are analyses of different bands in a banded lava block and analysis number 47 which is of the glassy groundmass of a hornblende-hypersthene andesite pumice all the analyses in Table 12 are whole rock analyses. Seven of these analyses have been published before (Mac-Gregor, 1938) but the rest are new analyses.

16:1:1 Analytical Methods.

Of the 45 new analyses presented in Table 12 one analysis (number 47) was obtained by X-ray fluorescence spectroscopy. The other 44 analyses were made by Mr. R. Fuge of the Geology Department, University College of Wales, Aberystwyth using the following methods. SiO_2 and Al_2O_3 were determined on solution A, prepared according to the method of Riley (1958). Silica was determined using the method of Abdullah and Riley (1966) slightly modified for use on the Technicon AutoAnalyser. This method involves the measurement of the yellow complex of molybdo-silicic acid on the spectrophotometer. Al_2O_3 was measured by automated colorimetric analysis using the Eriochrome cyanine - R method (Dabin, 1965). All other major elements except FeO and H_2O were measured on solution B. MnO and total iron (as Fe_2O_3) were measured directly on solution B by atomic absorption analysis on the Unicam SP 90 Atomic Absorption Spectrophotometer and MgO and CaO were measured by the same method, using a lanthanum buffer (Walsh and Howie, 1967). Na_2O and K_2O were determined on the SP 90 by flame emission using $(\text{NH}_4)_2\text{SO}_4$ as a spectroscopic buffer and no ion exchange. TiO_2 was measured using Riley's (1958) colorimetric method modified for use on the Technicon AutoAnalyser (Dabin, 1965) and P_2O_5 was determined by the measurement on the AutoAnalyser of the blue reduced phospho-molybdic acid complex using SnCl_2 as reducing agent (R. Fuge, pers. comm.) FeO

TABLE 12. CHEMICAL ANALYSES OF ROCKS FROM MONTERRAT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	
SiO ₂	42.3	43.2	49.3	50.1	52.0	52.00	52.2	52.64	53.3	53.5	53.5	53.5	53.8	54.1	54.9	55.5	55.6	56.3	56.5	56.75	57.0	57.6	57.9	58.0	58.3	58.3	58.36	58.5	58.7	59.2	59.5	59.5	59.68	59.8	60.0	60.0	60.0	60.0	60.08	60.8	61.3	61.4	62.5	62.5	62.8	63.0	64.21	71.75	57.5	57.9	61.6	48.6	77.7
TiO ₂	0.82	0.80	0.84	0.86	0.79	0.63	0.80	0.86	0.81	0.91	0.60	0.75	1.58	0.69	0.69	0.53	0.74	0.64	0.48	0.71	0.53	0.44	0.62	0.57	0.40	0.38	0.43	0.48	0.35	0.46	0.38	0.55	0.46	0.47	0.58	0.55	0.58	0.45	0.52	0.53	0.47	0.49	0.49	0.41	0.45	0.34	0.42	0.60	0.61	0.40	0.54	0.13	
Al ₂ O ₃	25.0	22.7	20.0	19.8	18.8	19.22	19.8	19.52	18.9	19.9	18.8	18.4	17.2	19.0	18.9	18.6	19.0	18.0	18.8	18.36	18.7	19.6	17.8	17.4	19.0	19.5	18.57	18.8	19.3	19.3	18.2	17.6	18.23	18.0	18.2	17.8	18.0	18.03	18.3	17.6	17.0	17.3	17.0	16.6	16.8	16.83	14.00	18.0	18.8	17.4	15.0	10.4	
Fe ₂ O ₃	4.07	3.65	4.51	2.54	3.58	2.73	4.60	2.85	3.79	3.93	6.40	3.27	5.11	3.13	3.79	4.02	5.82	4.00	6.07	2.53	4.07	2.98	4.39	3.52	4.86	2.82	2.30	2.11	2.35	2.25	2.41	3.22	2.44	2.75	6.13	4.14	3.25	2.24	4.30	2.90	2.60	3.11	3.09	1.95	2.85	3.74	2.31	2.88	2.96	2.11	0.86	0.81	
FeO	3.61	4.51	5.22	6.20	5.22	5.61	4.47	5.78	4.96	5.02	2.27	4.94	4.24	5.55	4.20	4.17	2.34	3.74	1.96	4.96	3.38	3.42	2.72	3.40	8.98	3.03	4.36	3.67	3.53	3.49	3.62	3.37	4.37	3.36	0.69	2.87	3.98	4.09	2.17	3.29	3.71	2.85	2.86	3.07	2.93	1.77	4.14	4.03	2.95	1.89	2.11		
MnO	0.09	0.12	0.19	0.18	0.19	0.11	0.18	0.17	0.18	0.19	0.18	0.19	0.16	0.19	0.19	0.21	0.17	0.18	0.25	0.16	0.15	0.21	0.15	0.18	0.15	0.15	0.13	0.18	0.18	0.17	0.18	0.19	0.17	0.19	0.19	0.19	0.19	0.16	0.17	0.18	0.19	0.15	0.17	0.11	0.08	0.18	0.17	0.15	0.28	0.10			
MgO	6.92	7.50	5.66	5.71	5.21	5.54	4.74	3.76	4.50	3.82	4.85	4.82	4.34	4.48	4.08	3.83	3.96	3.20	2.25	3.73	3.83	2.59	3.69	4.61	1.93	2.33	3.26	2.27	2.38	2.16	2.52	2.92	2.82	2.52	3.04	3.05	2.92	3.04	2.04	2.92	2.52	2.52	2.26	3.37	2.39	2.22	1.03	3.33	3.35	2.22	8.98	0.81	
CaO	14.30	13.68	10.81	11.20	10.00	10.58	10.05	9.68	9.13	8.92	9.13	9.23	7.74	9.29	8.61	8.27	9.29	8.07	7.31	8.62	8.24	7.31	8.48	7.44	7.34	7.31	7.85	7.50	7.31	7.31	6.84	7.26	7.52	6.99	7.07	7.26	7.39	7.44	6.90	6.46	5.76	5.96	6.35	5.76	6.24	6.03	5.20	8.16	8.20	6.40	21.30	6.84	
Na ₂ O	1.81	2.02	2.29	3.25	3.05	2.53	3.04	3.23	3.28	3.23	2.80	3.53	3.05	3.06	3.73	3.47	3.12	3.21	3.53	2.72	3.06	3.18	3.24	3.63	4.40	3.79	2.28	3.95	3.75	3.94	3.42	3.40	3.07	3.68	3.74	3.42	3.52	2.91	3.69	3.69	3.17	4.00	3.36	3.64	3.79	3.40	3.40	3.49	3.48	4.10	0.24	1.59	
K ₂ O	0.10	0.10	0.50	0.44	0.55	0.76	0.78	0.99	0.60	0.80	0.45	0.73	0.88	0.70	0.60	0.55	0.80	0.45	0.50	0.72	0.65	0.50	0.65	0.82	0.80	0.70	0.87	0.75	0.80	0.75	0.75	0.83	0.65	0.74	0.75	0.80	0.73	0.97	0.75	0.85	0.80	1.00	1.00	1.17	1.20	1.09	1.75	0.76	0.83	1.09	0.00	0.05	
H ₂ O ⁺	0.71	0.53	0.91	0.33	1.40	0.35	0.89	0.59	1.00	0.15	0.75	1.16	1.37	0.41	0.15	0.29	0.18	0.48	1.70	0.67	0.88	2.30	0.68	0.34	0.77	1.21	1.30	0.90	0.84	0.73	1.63	0.20	0.26	1.35	0.27	0.56	0.19	0.64	0.75	0.52	2.35	0.95	0.81	1.81	0.22	0.37	-	0.50	0.43	0.64	2.28	0.29	
P ₂ O ₅	0.01	0.02	0.05	0.12	0.10	0.11	0.11	0.12	0.17	0.11	0.07	0.20	0.20	0.08	0.13	0.17	0.07	0.10	0.12	0.09	0.10	0.18	0.10	0.11	0.19	0.18	0.00	0.17	0.19	0.18	0.16	0.11	0.11	0.14	0.10	0.11	0.11	0.11	0.09	0.09	0.05	0.13	0.10	0.10	0.09	0.09	0.06	0.18	0.12	0.12	0.10	0.05	
S	0.03	0.01	-	N.D.	0.09	-	-	-	0.05	-	0.03	0.97	-	0.01	-	-	0.10	-	-	-	-	-	-	-	-	-	0.20	-	-	-	0.17	-	0.01	-	-	-	-	-	-	-	0.21	-	-	-	-	-	-	-	0.01	N.D.	0.01	0.24	0.04
TOTAL	99.77	98.84	100.48	100.73	100.96	100.17	100.86	100.19	100.87	100.48	99.83	101.69	99.67	100.69	99.97	100.61	101.29	98.37	99.47	100.02	100.36	100.31	100.42	99.92	99.12	99.80	99.89	99.28	99.68	100.12	99.61	99.16	99.78	99.99	100.76	100.85	100.86	100.16	100.69	100.33	100.10	100.99	100.01	100.83	100.13	100.20	100.00	99.73	100.88	99.19	100.31	100.92	
Niggli Norms																																																					
qu	-	-	2.37	-	3.39	3.13	.91	3.21	5.61	6.00	9.92	3.82	10.67	5.94	6.41	8.82	10.17	19.70	15.13	12.39	12.98	14.86	14.10	11.42	18.08	13.38	17.05	12.12	12.91	13.00	16.35	15.84	16.51	16.67	15.65	16.57	15.11	16.86	18.38	16.79	20.45	17.68	20.95	17.92	18.49	23.23	11.47	11.06	15.72	1.53	52.18		
ocr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
or	0.59	0.60	2.99	2.35	3.28	4.52	4.60	5.92	3.58	4.76	2.71	4.34	5.37	4.16	3.66	3.26	4.73	2.75	3.07	4.34	3.89	3.06	3.89	4.88	4.82	4.23	5.29	4.52	4.81	4.49	4.67	5.01	3.81	4.47	4.46	4.77	4.33	5.83	4.50	5.07	5.52	5.96	6.04	7.01	7.17	6.54	4.56	4.92	6.56	-	0.31		
ab	7.83	11.18	20.77	28.97	27.59	22.79	27.21	29.26	29.69	29.11	28.59	31.83	28.22	27.55	33.60	31.20	27.98	29.76	32.87	34.83	27.67	29.38	29.39	31.86	40.22	34.69	21.84	36.13	34.17	35.75	31.57	31.12	28.00	33.71	33.69	38.82	31.69	26.51	33.56	33.40	29.48	36.10	30.79	33.07	34.31	30.83	31.76	31.25	37.42	2.20	14.84		
an	59.83	52.98	43.26	37.98	36.26	38.97	37.95	36.15	35.36	37.58	38.07	32.34	31.57	36.13	33.16	36.33	35.43	34.48	35.23	38.36	35.78	37.77	32.44	29.36	30.26	34.79	38.81	31.83	33.86	33.10	32.99	30.89	34.56	31.02	38.75	31.33	31.24	33.76	31.55	29.18	30.05	26.43	28.93	25.80	25.49	27.80	31.62	33.23	26.28	40.64	20.90		
ne	5.06	4.26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
di	8.98	12.32	8.56	13.20																																																	

TABLE 13. DETAILS OF ANALYSED ROCKS

1. Anorthite - amphibole - magnetite cumulate, 18592 (47C); ejected block. White River Pyroclast Fall Series. White River Ghaut. 450 ft. a.s.l.
2. Anorthite - amphibole - olivine cumulate, 18593 (47D(2)); ejected block. White River Fall Series. White River Ghaut. 450 ft. a.s.l.
3. Basaltic cinders, 18620 (146); White River Pyroclast Fall Series. Near Fergus Mount Estate. 350 ft. a.s.l. Plagioclase, augite and olivine crystals in a dark scoriaceous matrix.
4. Olivine - basalt, 18618 (146E); ejected block. White River Pyroclast Fall Series. Near Fergus Mount Estate. 200 ft. a.s.l. Plagioclase, augite, olivine and magnetite phenocrysts in a relatively coarse-grained matrix of plagioclase, augite, olivine and ore.
5. Basaltic lapilli, 18647 (362); White River Pyroclast Fall Series. Near Fergus Mount Estate. 700 ft. a.s.l. Plagioclase, augite, hypersthene and rare olivine in a dark brown glassy matrix.
6. Olivine basalt, lava flow. O'Garra's (MacGregor, 1938, p. 74, no. vii) Anal. Herdsman.
7. Olivine basalt, 18657 (404); lava flow. 100 yds. NE of Triangle Rock. 10 ft. a.s.l. Plagioclase, augite, olivine and magnetite phenocrysts in a fine-grained matrix of plagioclase, augite, ore and cristobalite.
8. Olivine basalt, lava flow. Near Shoe Rock (MacGregor, 1938, p. 74, no. VI). Anal. Herdsman.
9. Two-pyroxene basalt, 18638 (298); lava flow. 400 yds. W of Shoe Rock. 5 ft. a.s.l. Plagioclase, augite, hypersthene magnetite and rare olivine phenocrysts in a fine-grained matrix of plagioclase, pyroxene and ore. Calcite is present in the groundmass.
10. Olivine basalt, 18637 (296); lava flow. 500 yds. W of Shoe Rock. 20 ft. a.s.l. Plagioclase, augite, olivine, magnetite and rare hypersthene phenocrysts in a fine-grained, somewhat glassy matrix of plagioclase, pyroxene and ore.
11. Cognate basaltic inclusion in hornblende-hypersthene andesite lava, 18627 (205B). Cork Hill Village. 275 ft. a.s.l. Rare corroded crystals of plagioclase, hornblende and olivine in a holocrystalline network of plagioclase, hornblende, hypersthene, magnetite and augite. Abundant interstitial cristobalite with some tridymite.

TABLE 13 (continued)

12. Scoriaceous basalt, 18595 (333B); fragment from lapilli. White River Pyroclast Fall Series. White River Ghaut. 250 ft. a.s.l. Plagioclase, augite and magnetite phenocrysts in a dark brown glassy matrix.
13. Welded basaltic scoriae, 18642 (333C). White River Pyroclast Fall Series. White River Ghaut. 250 ft. a.s.l. Rare plagioclase, olivine, augite and magnetite phenocrysts in a light brown glassy base.
14. Two-pyroxene basalt, 18623 (159); loose boulder on Raspberry Hill Dome. NE of summit of South Soufriere Hill. 1,800 ft. a.s.l. Plagioclase, augite, hypersthene, magnetite and olivine phenocrysts in a fine-grained matrix of plagioclase, pyroxene and ore.
15. Two-pyroxene basalt, 18575 (26); lava flow. 1,100 yds. W of Shoe Rock. 10 ft. a.s.l. Plagioclase, augite, hypersthene and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene, ore and cristobalite.
16. Dolerite, 18597 (47H); ejected block. White River Pyroclast Fall Series. White River Ghaut. 450 ft. a.s.l. Plagioclase, augite, hypersthene, hornblende, quartz and magnetite.
17. Two-pyroxene andesite, 18634 (250); lava from intrusion. Roche's Bluff Point. 15 ft. a.s.l. Plagioclase, augite, hypersthene and magnetite phenocrysts in a fine-grained groundmass of plagioclase, pyroxene, ore and cristobalite.
18. Two-pyroxene andesite, 18651 (384); massive lava, part of Raspberry Hill Dome? Dry Ghaut. 700 ft. a.s.l. Plagioclase, augite, hypersthene and magnetite phenocrysts in a very fine-grained matrix of plagioclase, ore, pyroxene and cristobalite.
19. Andesitic tuff, 18587 (46A). White River Pyroclast Fall Series. White River Ghaut. 550 ft. a.s.l. Crystals of plagioclase hornblende, augite, hypersthene and magnetite.
20. "Labradorite-dacite"; lava from intrusion. WNW of Tuitts (MacGregor, 1938, p. 74, no. 5). Anal. Herdsman.
21. Two-pyroxene andesite, 18662 (421); lava from intrusion. 400 yds NW of Harris Village. 720 ft. a.s.l. Plagioclase, hypersthene, augite and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene, magnetite and some interstitial quartz and phlogopite?

TABLE 13 (continued)

22. Andesitic lapilli, 18691 (51B); White River Pyroclast Fall Series. Gingoe's Ghaut. 600 ft. a.s.l. Plagioclase, augite, hornblende, hypersthene, magnetite in a reddish-brown glassy matrix.
23. Two-pyroxene andesite, 18608 (122); lava from intrusion. Farm River. 150 ft. a.s.l. Plagioclase, augite, hypersthene and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene, magnetite and cristobalite.
24. Two-pyroxene andesite, 18541 (324); dome lava. S flank of Gage's Mountain. 1700 ft. a.s.l. Plagioclase, augite, hypersthene, olivine and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene, magnetite and cristobalite.
25. Two-pyroxene andesite, 18598 (47I); vesicular block from White River Pyroclast Fall Series. White River Ghaut. 450 ft. a.s.l. Plagioclase, augite, hypersthene and magnetite phenocrysts in a highly vesicular red brown glassy matrix.
26. Two-pyroxene andesite, 18596 (47G); vesicular block from White River Pyroclast Fall Series. White River Ghaut. 450 ft. a.s.l. Plagioclase, augite, hypersthene, magnetite, hornblende and rare quartz phenocrysts in a brown, glassy matrix.
27. "Labradorite-dacite"; Silver Hill. (MacGregor, 1938 p. 74 no. IV). Anal. Herdsman.
28. Two-pyroxene andesite, 18595 (47F); vesicular block from White River Pyroclast Fall Series. White River Ghaut. 450 ft. a.s.l. Plagioclase, hypersthene, augite, hornblende, magnetite and quartz phenocrysts in a brown glassy matrix.
29. Hypersthene-andesite, 18594 (47E); vesicular block from White River Pyroclast Fall Series. White River Ghaut. 450 ft. a.s.l. Plagioclase, hypersthene, magnetite and hornblende phenocrysts in a dark glassy base.
30. Two-pyroxene andesite, 18593 (46D); lava block from White River Pyroclast Fall Series. White River Ghaut. 550 ft. a.s.l. Plagioclase, hypersthene, augite, magnetite and hornblende phenocrysts in a brown glassy matrix.
31. Andesitic pumice, 18591 (46B); White River Pyroclast Fall Series. White River Ghaut. 550 ft. a.s.l. Plagioclase, hypersthene, hornblende, augite, magnetite and quartz phenocrysts in a dark glassy matrix.

TABLE 13 (continued)

32. Hornblende-hypersthene andesite, 18572 (15); lava block from flow? N of summit of St. George's Hill. 800 ft. a.s.l. Plagioclase, hornblende, hypersthene and magnetite phenocrysts in a fine-grained matrix of plagioclase, hornblende, augite, hypersthene and ore.
33. "Labradorite-dacite". Castle Peak. (MacGregor, 1938 p. 74 no. III). Anal. Herdsman.
34. Andesitic pumice, 18592 (46C); White River Pyroclast Fall Series. White River Ghaut. 550 ft. a.s.l. Plagioclase, hypersthene, hornblende, augite and magnetite phenocrysts in a dark glassy base.
35. Two-pyroxene andesite, 18649 (373); dome lava. E flank of Perche's Dome. 2,250 ft. a.s.l. Plagioclase, augite, hypersthene and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene, ore and cristobalite.
36. Two-pyroxene andesite, 18660 (409); lava block from agglomerate. W of Richmond Estate. 75 ft. a.s.l. Plagioclase, hypersthene, augite and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene, ore and cristobalite.
37. Hornblende-hypersthene andesite, 18610 (133); dome lava. SE of summit of Castle Peak. 2,275 ft. a.s.l. Plagioclase, hornblende, hypersthene and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene and ore.
38. "Labradorite-dacite". Old Fort Point. (MacGregor, 1938, p. 74 no. II). Anal. Herdsman.
39. Two-pyroxene andesite, 18648 (364); lava from intrusion? Cliffs N of Yellow Hole. 15 ft. a.s.l. Plagioclase, hypersthene, augite and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene, ore and cristobalite.
40. Hornblende-hypersthene andesite, 18640 (322); dome lava. WSW of summit of Chance's Dome. 2,575 ft. a.s.l. Plagioclase, hornblende, hypersthene, quartz and magnetite phenocrysts in a fine-grained matrix of plagioclase, pyroxene, ore and glass.
41. Andesitic pumice, 18626 (195); block from pumice fall? ENE of Harris Village. 950 ft. a.s.l. Plagioclase, hypersthene, hornblende, augite, magnetite and quartz phenocrysts in a finely vesicular glassy base.

TABLE 13 (continued)

42. Hornblende-hypersthene andesite, 18654 (398); dome lava. SSW of summit of Galway's Dome. 2,030 ft. a.s.l. Plagioclase, hornblende, hypersthene, magnetite and quartz phenocrysts in a fine-grained to glassy matrix of plagioclase, augite, hypersthene, cristobalite and ore.
43. Hornblende-hypersthene andesite pumice, 18615 (145); block from pumice flow. Paradise Estate. 975 ft. a.s.l. Plagioclase, hornblende, hypersthene, magnetite and augite phenocrysts in a dark glassy base.
44. Hornblende-hypersthene andesite pumice, 18650 (377A); block from pumice fall? E of summit of St. George's Hill. 800 ft. a.s.l. Plagioclase, hornblende, hypersthene, quartz and magnetite in a dirty glassy base.
45. Hornblende-hypersthene dacite, 18656 (400); lava from intrusion? 200 yds. S of Landing Bay. 20 ft. a.s.l. Plagioclase, hornblende, hypersthene, magnetite and quartz phenocrysts in a fine-grained matrix of plagioclase, augite, hypersthene, ore and a little glass.
46. "Labradorite-dacite", near Landing Bay. (MacGregor, 1938, p. 74 no. I). Anal. Herdsman.
47. Glassy matrix from hornblende-hypersthene andesite pumice, 18615 (no. 43). Anal. R. Goodman (X.R.F.).
48. Black portion of banded hornblende-hypersthene andesite lava block, 18612 (135 BK.); loose lava block. Pea Ghaut. 350 ft. a.s.l. Plagioclase, hypersthene, hornblende, quartz and magnetite phenocrysts in a dark brown, fine-grained matrix of plagioclase, augite, hypersthene and ore.
49. Grey portion of 18612 (135 GY.). Plagioclase, hypersthene, hornblende, quartz and magnetite phenocrysts in a fine-grained matrix of plagioclase, augite, hypersthene and ore.
50. White portion of 18612 (135 WH.). Plagioclase, hornblende, hypersthene, quartz and magnetite phenocrysts in a fine-grained to glassy matrix of plagioclase, augite, hypersthene and ore.
51. Fine-grained metasedimentary? block, 18590 (47A). White River Pyroclast Fall Series. White River Ghaut. 450 ft. a.s.l. Clinopyroxene and calcic plagioclase.

TABLE 13 (continued)

52. Fine-grained metasedimentary? block, 18576 (28); inclusion in olivine-basalt lava flow. 400 yds. E of O'Garra's. 5 ft. a.s.l. Quartz, clinopyroxene (diopside?) and plagioclase with accessory calcite, magnetite and glass. Fine-grained, hornfelsic texture.

NOTES.

1. Analysts S by Dr. G. Holland

H₂O and FeO (cols. 1, 7, 9-11, 15, 18, 23, 26, 28, 20, 32, 34-37, 40, 42, 44, 48-52) by Mr. W. J. Rea.

All other determinations by Mr. R. Fuge, except where stated otherwise in TABLE 13.

For details of analytical techniques see p. 119

2. The analyses relate to the different volcanic centres as follows:-

Harris Bugby Centre:- nos. 20, 21, 23, 41.

Silver Hill:- nos. 27, 39.

Carabald Hill:- nos. 11, 36.

South Soufriere Hill:- nos. 6-10, 14, 15, 18, 52.

including White River Pyroclast Fall Series:- nos. 1-5, 12, 13, 16, 19, 22, 25, 26, 28-31, 34, 51.

Roche's:- nos. 17, 45, 46.

Soufriere Hills:- nos. 24, 33, 35, 37, 38, 40, 42, 43, 47, 48-50.

St. George's Hill:- nos. 32, 44.

3. Using the system of classification outlined in TABLE 5 MacGregor's analysed specimens are classed as follows:-

nos. 6 and 8 olivine-basalts

nos. 20 and 27 two-pyroxene andesites

nos. 33 and 38 hornblende-hypersthene andesites

no. 46 hornblende-hypersthene dacite

4. Analyses nos. 7, 39 and 48 are averages of 2 analyses each. See Appendix 1, Table 1.

5. For details of the method used in the calculation of the norm see Appendix 2A, p. 179

was measured by the dichromate method (analyst - R. Fuge) or the permanganate method (analyst - W. J. Rea). All the samples were dried overnight at 110°C . before analysis and H_2O^+ was determined using a modified Penfield Tube method.

16:1:2 Reproducibility and Accuracy of the Analyses.

Duplicate analyses, made at different times, by the methods outlined above show good agreement and results obtained, during the present investigations, for U.S.G.S. standard rocks and for the Aberystwyth Department of Geology standard GD.1 are in good agreement with the published results (Appendix 1, Table 1). The totals of all but four of the new analyses fall between 99% and 101% which is considered to be an acceptable range for analyses made by "rapid" methods (Maxwell, 1968, p. 15). The tendency for most of the totals to be high may in part be explained by the difficulty of measuring small concentrations of SiO_2 and Al_2O_3 in reagent blanks. Two analyses (Table 12, numbers 12 and 18) have totals which fall far outside the acceptable range and these analyses must be considered suspect.

Replicate analyses of Montserrat rocks by other methods are also available (Appendix 1, Tables 2 and 3). The writer determined major elements in 20 rocks from Montserrat and SiO_2 , Na_2O and K_2O in a further 7 rocks. These analyses were carried out at the Department of Geology and Mineralogy, Oxford University and the following methods were used:-

SiO_2 , CaO - gravimetric analysis.

Total iron (as Fe_2O_3), TiO_2 , P_2O_5 and MnO - colorimetric analysis (Riley, 1958).

Na_2O , K_2O - flame photometry

MgO , Al_2O_3 - atomic absorption spectroscopy. (These analyses were carried out by the writer using the Unicam SP 90 at the Geology Department, Kings College, London).

FeO - permanganate method

$\text{H}_2\text{O}_{\text{TOT}}$ - Penfield tube.

With a few exceptions the results obtained by these methods (Appendix 1, Table 2) are in reasonably good agreement with the results shown in Table 12 and the agreement

is improved by recalculating both sets of analyses to 100%, water free. Values of CaO determined gravimetrically by the writer are however consistently higher than those determined by Mr. H. Fuge using Atomic Absorption Spectroscopy. In view of the good agreement of CaO contents in standard rocks, analysed by the latter method, with the accepted values (Appendix 1, Table 1) the CaO values given in Table 12 are preferred. A possible explanation of the high values of CaO determined gravimetrically is that some Mg oxalate was precipitated and weighed along with the Ca oxalate.

Dr. G. Holland of the Department of Geology, Durham University analysed 18 Montserratian rocks by X-ray fluorescence spectroscopy and these analyses are given in Appendix 1, Table 3. These analyses do not show particularly good agreement with the other analyses and the values of MgO and total iron are consistently low and values of SiO₂ are high compared with values obtained by other methods. As all the XRF results are calculated to 100%, water free the low values of MgO and total iron and of course the non-determination of water will have the effect of increasing the apparent silica content but these effects are insufficient to account for the whole discrepancy. In view of the above reservations it is clear that care must be taken in comparing the only XRF analysis given in Table 13 (No. 47) with the other analyses.

Finally, it is clear from the descriptions of analysed rocks in MacGregor's (1938) account of the geology of Montserrat that some of these rocks are from the same localities as rocks analysed in the course of the present study. Thus in Table 12 analyses No. 33 and No. 37 are both of the Castle Peak Dome lava and analyses 45 and 46 are both of the Landing Bay Dacite. In addition, analyses 20 and 21 are both of lavas from the Harris-Bugby Centre. All three pairs of analyses are remarkably similar and the minor differences could be due as much to chemical inhomogeneity within the three lava bodies as to analytical discrepancies.

16:1:3 Variation of Major Elements with Silica.

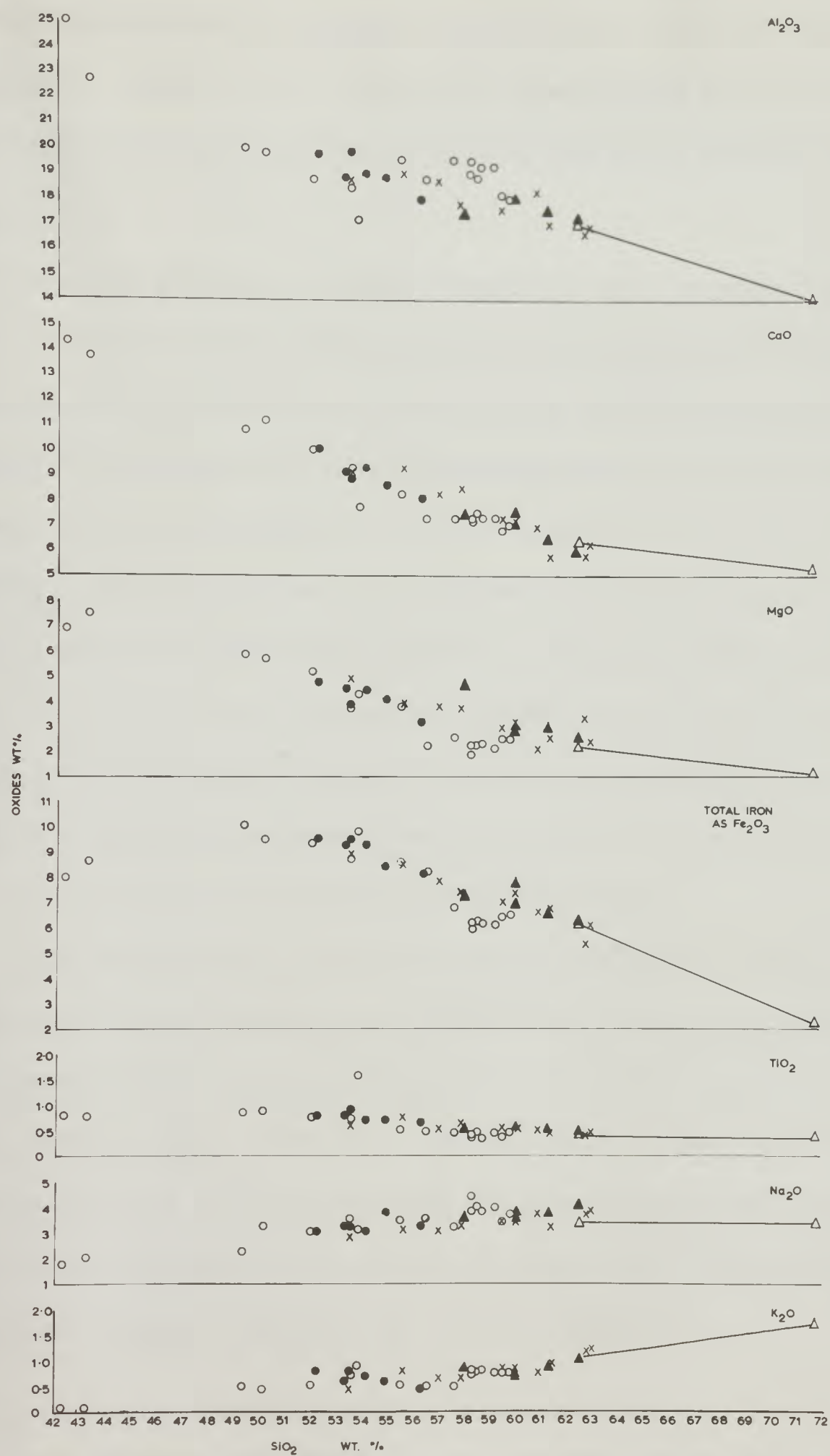
Chayes (1962, 1964 p. 235) has emphasized that the silica variation diagram is "of little use in discriminating between the effects of nearly all the processes thought

to be of major importance in the differentiation of volcanic rocks." It does however provide a simple method of illustrating graphically the proportions of major elements in a group of rocks. The variation of Al_2O_3 , CaO , MgO , total iron (as Fe_2O_3), TiO_2 , Na_2O and K_2O with SiO_2 in rocks from Montserrat is shown in Fig. 18. For the sake of the clarity of the diagrams not all the analyses given in Table 12 have been plotted in Fig. 18 or in other major element variation diagrams. Only the analyses determined during the present study have been plotted and of these, the analyses of the banded lava block (Table 12, numbers 48-50) and the metamorphic blocks (Table 12, numbers 51 and 52) have been omitted.

A few general points can be made about Fig. 18 before discussing the behaviour of the individual oxides in more detail.

1. Despite a certain amount of scatter the points for the various oxides fall on fairly regular curves. Nevertheless, for many of the oxides e.g. total iron, the rocks of South Soufriere Hill, or more particularly the White River Pyroclast Fall Series diverge slightly from the main trend. Fig. 18 also brings out quite clearly the close chemical similarity between the five lava blocks (Table 12 numbers 25, 26, 28-30) collected from the bottom of the Andesite Coarse Fall Zone of the White River Pyroclast Fall Series (see Fig. 7). Although these specimens are somewhat different in hand specimen e.g. they have different colours, they may be regarded as chemically identical, within the limits of analytical error.
2. There is a more or less continuous gradation in the silica content of the analysed rocks from 49.4% SiO_2 to 63% SiO_2 . Only the two ultrabasic blocks lie outside this range. The gaps in silica content which occur between 50.1% and 52% and between 52.2% and 53.3% SiO_2 are so small as to be virtually insignificant and there is no gap between the basalts and the andesites like those found for analysed lavas from St. Lucia (54.5% to 59% SiO_2 ; Tomblin, 1964, Table 12) or St. Kitts (53.3% to 56.6% SiO_2 ; Baker, 1968 Table 6). It must be remembered, however, that with the single exception of the basaltic cognate xenolith from Carabald Hill (Table 12 No. 11) all those lavas with less than

FIGURE 18. SILICA VARIATION DIAGRAM OF MONTSERRAT ROCKS.



KEY :- ○ WHITE RIVER PYROCLAST FALL SERIES
● OTHER SOUTH SOUFRIERE HILL LAVAS
▲ SOUFRIERE HILLS DOME LAVAS
△ OTHER SOUFRIERE HILLS LAVAS
x ALL OTHER LAVAS

TIE LINE JOINS 18615 WHOLE ROCK AND GROUNDMASS
NOTE - THIS KEY IS USED IN ALL MAJOR ELEMENT
VARIATION DIAGRAMS

57% SiO_2 belong to the South Soufriere Hill centre.

3. There is a pronounced concentration of analyses in the range 58-60% SiO_2 and a smaller concentration with between 53 and 54% SiO_2 . The numbers of analyses however, bear very little relationship to the estimated relative abundances of rock types shown in Table 4. Thus, about a quarter of the analyses in Table 12 are of basalts whereas basalt accounts for an estimated 3.3% of the total volume of rock on Montserrat.

Alumina.

Alumina decreases rather irregularly with increasing silica in the Montserrat rocks. There is quite a sharp decrease in Al_2O_3 between the ultrabasic blocks and the basalts and Al_2O_3 also falls quite rapidly with increasing SiO_2 at the acid end of the series. The decrease in Al_2O_3 between the basalts and the andesites is not however very marked. In addition there is a considerable scatter of alumina values in the range 54-60% SiO_2 . This scatter can be explained partly in terms of variation in the amount of modal plagioclase (see Tables 6 and 8). Thus, the almost aphyric basaltic scoriae (18642, Table 12, No. 13) has an exceptionally low Al_2O_3 content (17.2%). However, the andesite blocks from the Andesite Coarse Fall Zone of the White River Pyroclast Fall Series have relatively high Al_2O_3 contents even though they contain small amounts of modal plagioclase and there are many other similar exceptions.

The range of Al_2O_3 contents in the Montserrat andesites and basalts (16.6 - 20.0%) is similar to that found in rocks from Mount Misery, St. Kitts (17.1 - 20.4%, Baker 1968, Table 6) but Al_2O_3 values are rather higher than in lavas from St. Lucia (15.2 - 18.8%, Pomblin 1964, Table 12). The St. Lucian lavas also differ from the St. Kitts and Montserrat suites in that the andesites are richer in alumina than the basalts. Relative to world-wide calc-alkaline suites the Montserrat lavas and Lesser Antillean lavas in general are slightly enriched in Al_2O_3 . (Table 16).

Lime.

CaO contents fall fairly regularly from the basic to the acid end of the Montserrat

series. Although there is a good deal less scatter than in the case of the Al_2O_3 curve, CaO shows a rough positive correlation with Al_2O_3 . Contents of CaO in the Montserrat lavas appear to be quite similar to those in other lavas from the Lesser Antilles and from calc-alkaline suites in general (Table 16).

Magnesia.

Magnesia decreases quite regularly with increasing SiO_2 . A few lavas plot a little off the main trend. For example the Gage's Dome lava (18641, Table 12, No. 24) which contains abundant clinopyroxene and olivine has a rather high MgO content, whereas andesites from the White River Pyroclast Fall Series have relatively low contents. Values of MgO in the Montserrat lavas are very similar to those in other lavas from the Lesser Antilles, but the Lesser Antillean lavas contain rather less MgO than many calc-alkaline suites (Table 16).

Total Iron.

Total iron which is plotted in Fig. 18 as Fe_2O_3 shows a fairly regular decrease between the Montserrat basalts and andesites but the basalts are enriched in iron with respect to the ultrabasic blocks, in which the cumulative mafic minerals have high Mg:Fe ratios (Table 11). There is, however, little or no tendency for total iron to increase with increasing SiO_2 in the basalts, as it does in several calc-alkaline suites including Mount Misery, St. Kitts (Baker, 1968); Soufriere, St. Vincent (Lewis, 1964); Newberry Volcano (Williams, 1935) and Medicine Lake Highlands (Anderson, 1941). Andesites from the White River Pyroclast Fall Series are slightly depleted in iron relative to other Montserrat andesites.

Although values of total iron in the Montserrat lavas are comparable with amounts in other calc-alkaline rocks the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios are slightly high compared with calc-alkaline lavas from the Lesser Antilles and elsewhere. The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios also vary considerably in the Montserrat lavas and this variation cannot be correlated with the mode of eruption or water content of the specimens. Watkins et al. (1970, Fig. 6) have reported a fluctuation of over 500% in the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio within a lava flow from

Iceland and they have attributed this to variation in oxygen fugacity within the lava flow during cooling. The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio shows a direct correlation with the inferred temperature distribution throughout the flow probably because high temperatures promote the dissociation of water and subsequent diffusion of hydrogen, leading to high oxygen fugacities. Irregular temperature distribution during cooling might also explain some of the variation in the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios in the Montserrat lavas though variation in the amount of surficial oxidation is also likely to have been important.

Titania.

TiO_2 shows a slight rise from the ultrabasic blocks to the basalts but otherwise decreases steadily with increasing SiO_2 throughout the Montserrat series. Only one rock - the almost aphyric welded basaltic scoriae (18642, Table 12, No. 13) which has an exceptionally high TiO_2 content (1.58%) lies off the main trend. The relationship of TiO_2 and SiO_2 in the Montserrat lavas is similar to that found in lavas from other islands in the Lesser Antilles and other calc-alkaline suites, but the Montserrat lavas are a little poor in TiO_2 compared with world-wide calc-alkaline suites.

Soda.

Na_2O shows an irregular increase with increasing SiO_2 throughout the Montserrat rocks but the groundmass of 18615 does not appear to be enriched in soda relative to the whole rock. Andesites from the White River Pyroclast Fall Series are slightly enriched in soda compared with the other andesites. Values of soda are similar to those from St. Kitts but slightly high compared with St. Lucia.

Potash.

The potash curve for Montserrat rises somewhat irregularly with increasing SiO_2 . The Montserrat basalts have a large range in K_2O (0.44 to 0.88%) and are generally rather richer in K_2O than basalts from other islands in the Lesser Antilles, even those from St. Lucia where K_2O is exceptionally high in andesites and dacites. Potash is slightly higher in the Montserrat andesites than in andesites from St. Kitts and St.

Vincent but is lower than in the St. Lucian andesites.

The Lesser Antillean lavas as a whole are poor in potash compared with world-wide calc-alkaline suites but there is considerable variation throughout the arc. This variation occurs on different scales. The variation among basalts of the South Soufriere Hill volcano, Montserrat, mentioned above is an example of variation in the rocks of a single volcano, but variation also exists on an inter-volcano and an inter-island scale. Thus, lavas from St. Kitts are notably poor in K_2O whereas lavas from St. Lucia and Grenada are exceptionally rich in K_2O . Dickinson and Hatherton (1967) and Hatherton and Dickinson (1969) have shown that the K_2O content in calc-alkaline volcanics is directly related to the depth of the Benioff Zone beneath the volcano from which they were erupted. However, the variation of potash values in the Lesser Antilles is unlikely to be related to this factor since the depth of the Benioff Zone beneath different volcanoes in the Lesser Antilles is more or less constant and in any case it is virtually impossible to explain the variation of K_2O contents in the rocks of a single volcano in these terms. It is also difficult to account for the variation of potash values in the Lesser Antilles in terms of variation in the amount of sedimentary contamination. Although contamination by potassic sediments might explain the high potash values in andesites and dacites from St. Lucia it cannot explain the high potash contents (over 1.0% compared with the Lesser Antillean average of about 0.5%) in basalts from Grenada unless the sediments involved are very low in silica, which is unlikely (Rea, in press).

In a recent paper, Watkins et al. (1970) have attributed the large variations of potash within a single olivine basalt lava flow from Iceland to variations in the abundance of an interstitial, K-bearing phase (K feldspar) which is detectable only under electron-microprobe examination. Variation in the abundance of a minor, K-bearing phase would also seem to be a possible explanation for the variation in K_2O contents in Lesser Antillean lavas as a whole and especially for the variation in the lavas at a single volcano. Electron microprobe examination of the Lesser Antillean lavas has not yet been carried out but the mica which occurs interstitially in some of the Montserrat lavas

(p. 94) is probably rich in K_2O and tridymite and cristobalite which are abundant in the Lesser Antillean lavas may also be rich in K_2O (p. ///). In addition, the potash contents of analysed groundmasses of Lesser Antillean lavas are high though variable (J. F. Tomblin, pers. comm.) so that a detailed chemical and mineralogical investigation of groundmasses of Lesser Antillean lavas may well provide an explanation of many of the apparent anomalies in K_2O distribution in the Lesser Antilles (see also p. 171).

MnO.

MnO is low in the ultrabasic blocks but otherwise is approximately constant in the Montserrat lavas. Values are similar to those recorded from the other calc-alkaline lavas.

P₂O₅.

P₂O₅ is very low in the ultrabasic blocks. Contents of P₂O₅ in the lavas fluctuate erratically between 0.05 and 0.20% and show no correlation with SiO₂.

H₂O.

Water is significantly higher in pyroclastics than in lavas from Montserrat. Values are very low compared with lavas from St. Lucia and probably slightly low compared with most calc-alkaline lavas.

Sulphur.

Sulphur occurs in significant amounts only in lavas which are near active or extinct soufrieres. Pyroclastics from the White River Pyroclast Fall Series are relatively rich in sulphur which is hardly surprising considering their proximity to Galway's Soufriere. As far as can be seen, from the rather limited data available there is a rough positive correlation between vesicularity and sulphur content.

16:1:4 The Alkali-Line Index.

The alkali-like index which was used by Peacock (1931) to subdivide igneous rocks into four series is the silica percentage at which total alkalies ($Na_2O + K_2O$) equal CaO.

It is not possible to determine the alkali-lime index for the Montserrat rocks exactly but an estimate based on compositional trends in the lavas suggests a value of 66. If however, the analysis of the groundmass of 18615 is a reliable indication of the extension of compositional trends of the lavas at higher SiO_2 values this estimate is too low as this analysis shows $\text{CaO} > \text{Na}_2\text{O} + \text{K}_2\text{O}$ which would give an alkali-lime index greater than 71.75. As the reliability of this analysis is in doubt (p. 12) the first estimate is preferred and this is closely comparable with alkali-lime indices for St. Lucia (68), Martinique (66) and St. Vincent and St. Kitts (both 65). The values are rather high compared with the indices of other calc-alkaline volcanic suites, reflecting the relative paucity of alkalis in the Lesser Antillean lavas. Any volcanic series with an alkali-lime index greater than 61 belongs to Peacock's (1931) calcic class.

16:1:5 $\text{FeO} : \text{MgO} : (\text{Na}_2\text{O} + \text{K}_2\text{O})$ Ratios.

Plotted on the $\text{FeO} : \text{MgO} : (\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagram (Fig. 19) the Montserrat lavas show very little enrichment in FeO relative to MgO and alkalis. The andesites fall on a short trend showing a slight increase in alkalis relative to MgO and FeO in the more acid rocks and an indication of the extension of this trend is given by plotting the groundmass of 18615. A few rocks plot away from the main trend. These include the Gage's Dome lava (18641) which has a high MgO : FeO ratio, probably because it contains cumulative clinopyroxene. The reasons for the abnormalities of 18587, a Soufriere Hills ash, which has a high FeO/MgO ratio and of 18650, a St. George's Hill pumice which has a low FeO/MgO ratio are not immediately apparent. The ultrabasic cumulates which contain cumulative hornblende and olivine are enriched in MgO compared with the South Soufriere Hill basalts.

The trend shown by the South Soufriere Hills lavas and ultrabasics is similar to that shown by lavas and ultrabasic blocks from the Soufriere, St. Vincent though the iron enrichment of basalts relative to ultrabasic blocks is slightly more marked in the latter case. Lavas from the other Montserrat volcanoes follow a similar trend to that

Fig. 19. F.M.A. DIAGRAM FOR MONTSERRAT ROCKS.

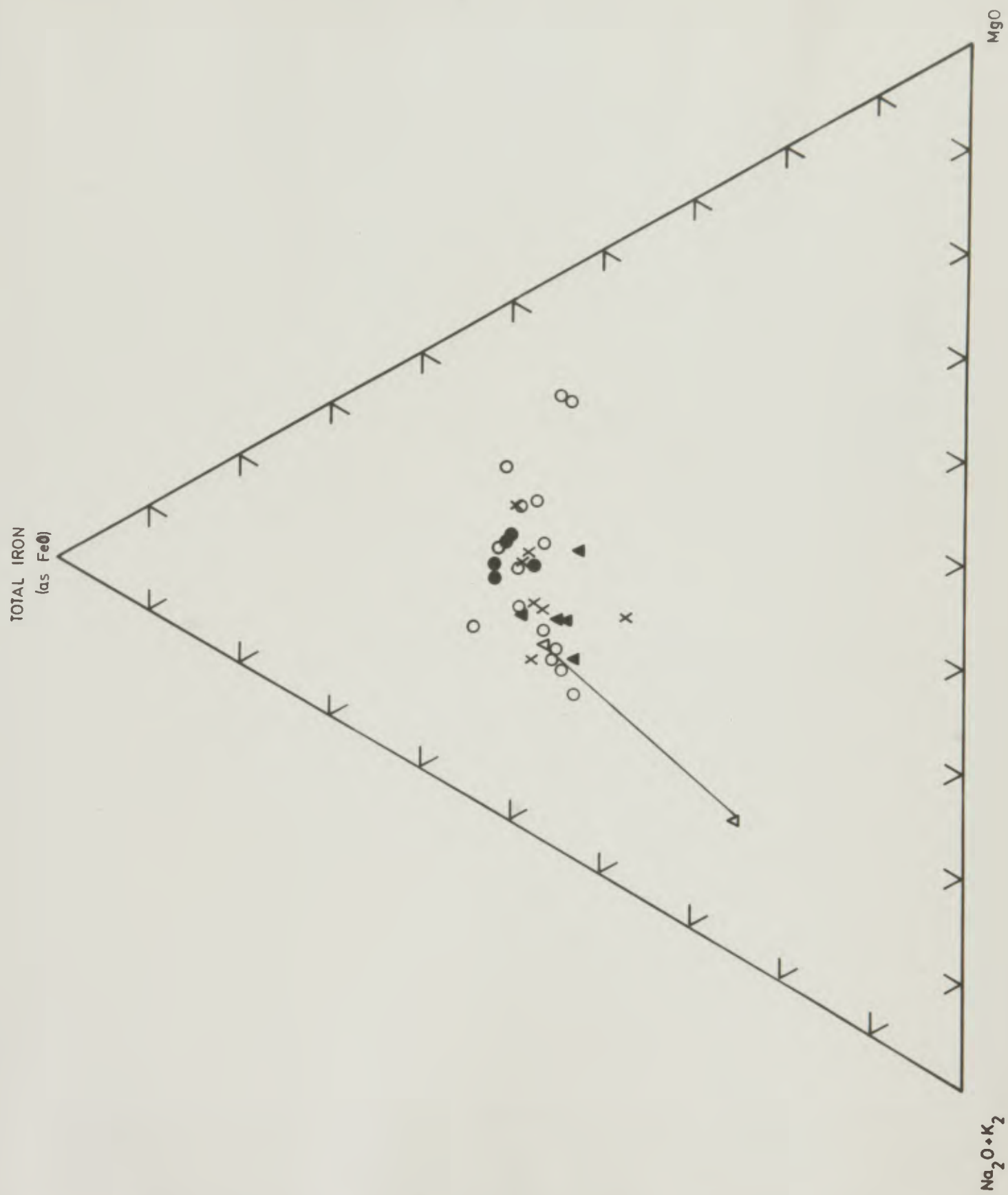
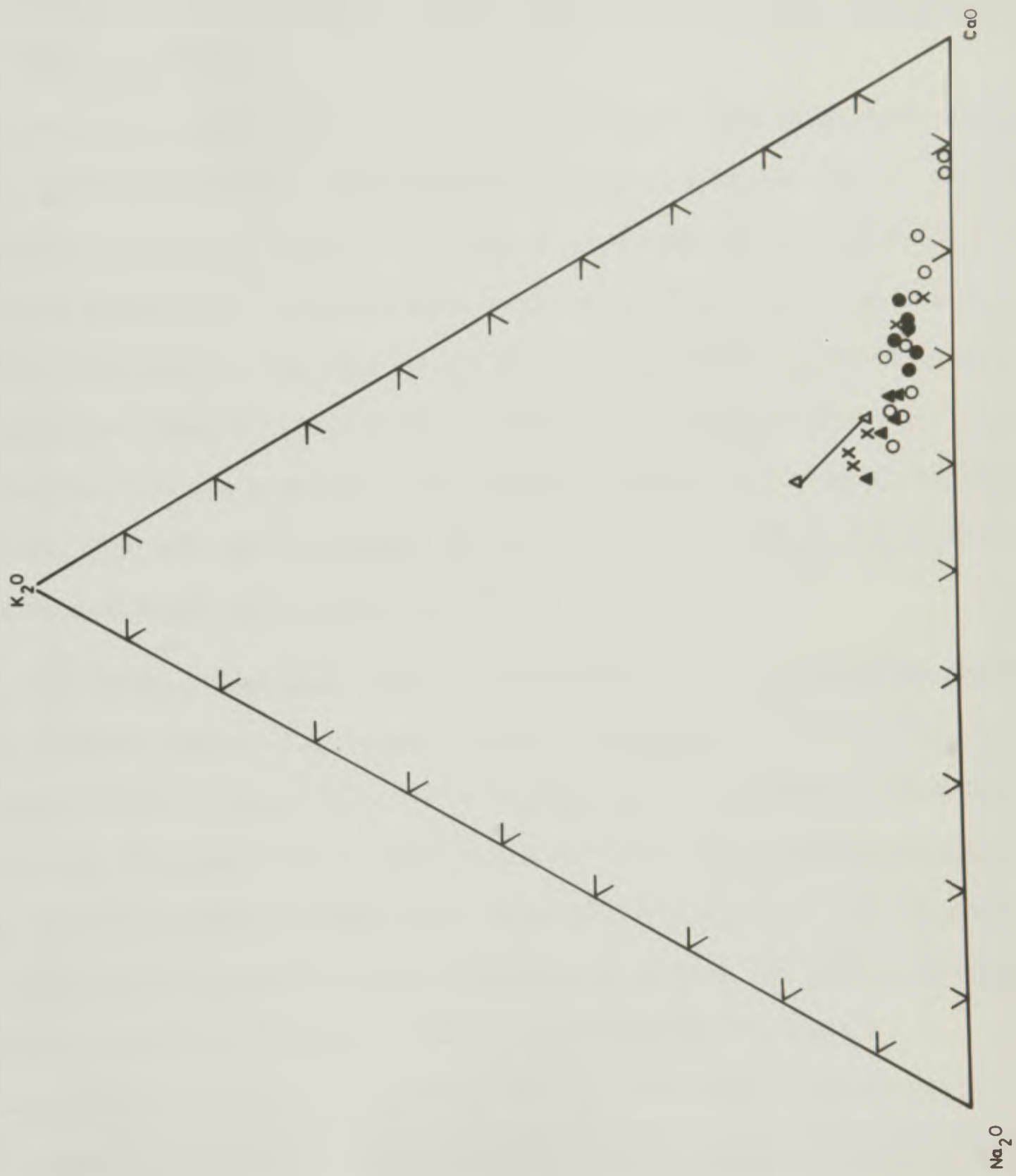


Fig 20 PLOT OF $K_2O : Na_2O : CaO$ RATIOS FOR ANALYSED ROCKS FROM MONTSERRAT.



shown by the lavas of Mount Misery, St. Kitts (Baker, 1968, Fig. 6). Most calc-alkaline volcanic series e.g. St. Lucia (Tomblin, 1964) and Crater Lake (Williams, 1942) show a slightly lower proportion of iron compared with the Montserrat rocks but a few series e.g. South Sandwich Islands (J. F. Tomblin and P. E. Baker, unpublished data) are relatively rich in iron.

16:1:6 $K_2O : Na_2O : CaO$ Ratios.

The relative proportions of K_2O , Na_2O and CaO in rocks from Montserrat are shown in Fig. 20. The main difference in the Montserrat lavas compared with those from other calc-alkaline suites lies in the comparative lack of enrichment of K_2O relative to Na_2O and CaO in the more acid rocks. Compared with lavas from other islands in the Lesser Antilles the Montserrat basalts are high in K_2O but the Montserrat andesites contain less K_2O than andesites from all the islands in the Lesser Antilles except St. Kitts. Andesites and dacites from St. Lucia are exceptionally rich in K_2O relative to Na_2O and CaO (Tomblin, 1964, Fig. 29) but in general the Lesser Antillean lavas are impoverished in K_2O relative to world-wide calc-alkaline suites.

16:1:7 Total Iron Oxide - Magnesia Ratios and Iron Enrichment - Total Mafic Ratios.

Plots of magnesia against total iron and of iron enrichment ($FeO + Fe_2O_3/MgO + FeO + Fe_2O_3$) against total mafics ($MgO + FeO + Fe_2O_3$) for the Montserrat lavas are shown in Figs. 21 and 22 respectively. The trends of the Hawaiian tholeiite and alkali series (Tilley, Yoder and Schairer, 1964⁵) are shown for comparison in both figures and the island arc calc-alkaline trend as exemplified by lavas from the Lesser Antilles and the Solomon Islands (Brown and Schairer, 1960) is also plotted in Fig. 21.

On the magnesia/total iron diagram (Fig. 21) the Montserrat lavas plot roughly parallel to the lower part of the Hawaiian alkali curve but the Montserranian lavas are richer in MgO . The trend in the Montserrat lavas is similar to that shown by other lavas from the Lesser Antilles and the Solomon Islands except that the Montserrat lavas are slightly enriched in total iron. Ultrabasic cumulates from Montserrat have lower

Fig 21 PLOT OF $\text{MgO} : (\text{FeO} + \text{Fe}_2\text{O}_3)$ RATIOS FOR MONTSERRAT LAVAS. THE TRENDS OF HAWAIIAN ALKALI AND THOLEIITE SERIES (TILLEY, YODER AND SCHAIRER 1965) AND OF THE ISLAND-ARC CALC-ALKALINE SERIES (BROWN AND SCHAIRER 1968) ARE SHOWN FOR COMPARISON.

KEY:
As in Fig. 18 except S.V.B. $\square$ - Average St. Vincent cumulate
(Average of 4 analyses, Lacroix, 1949)

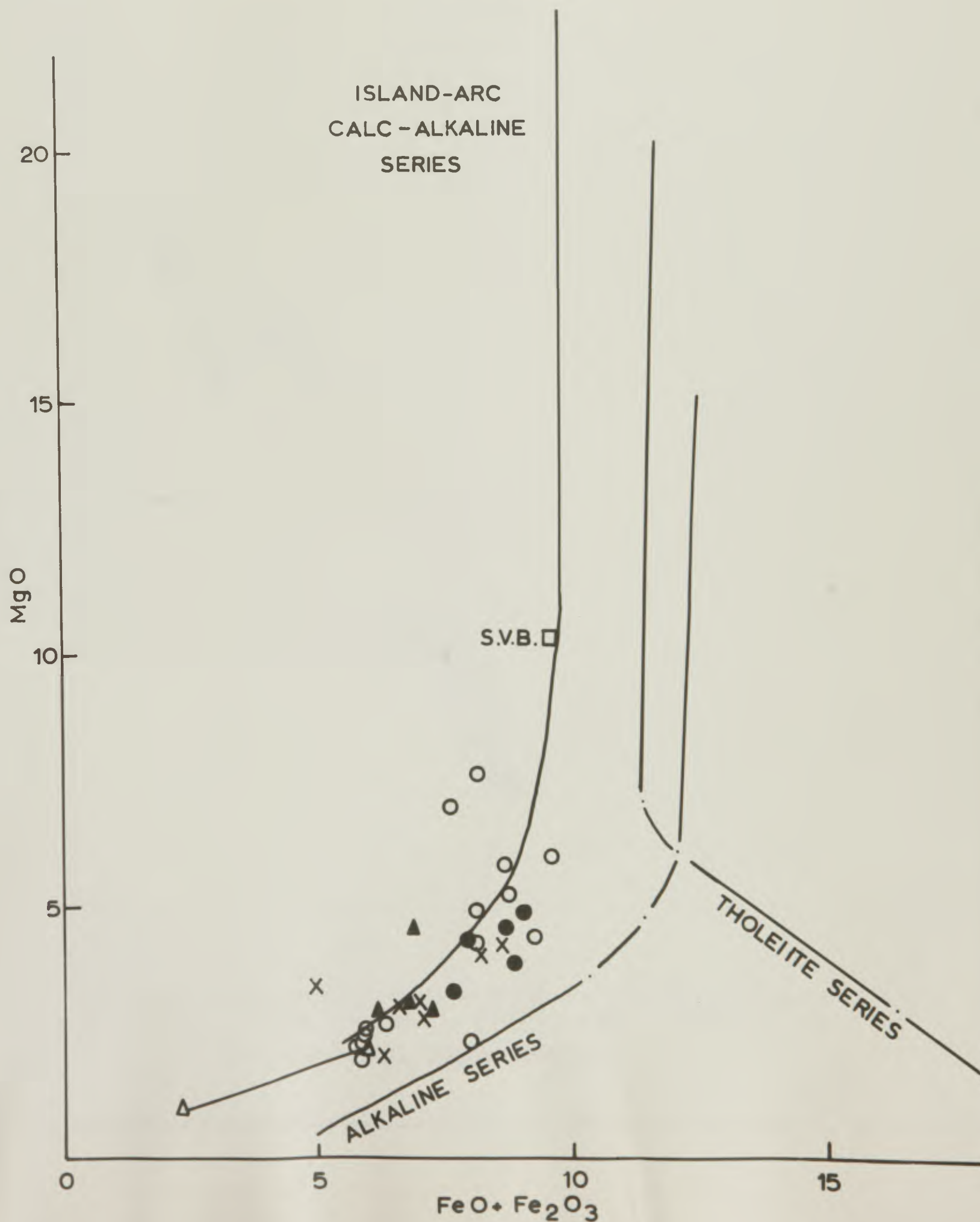
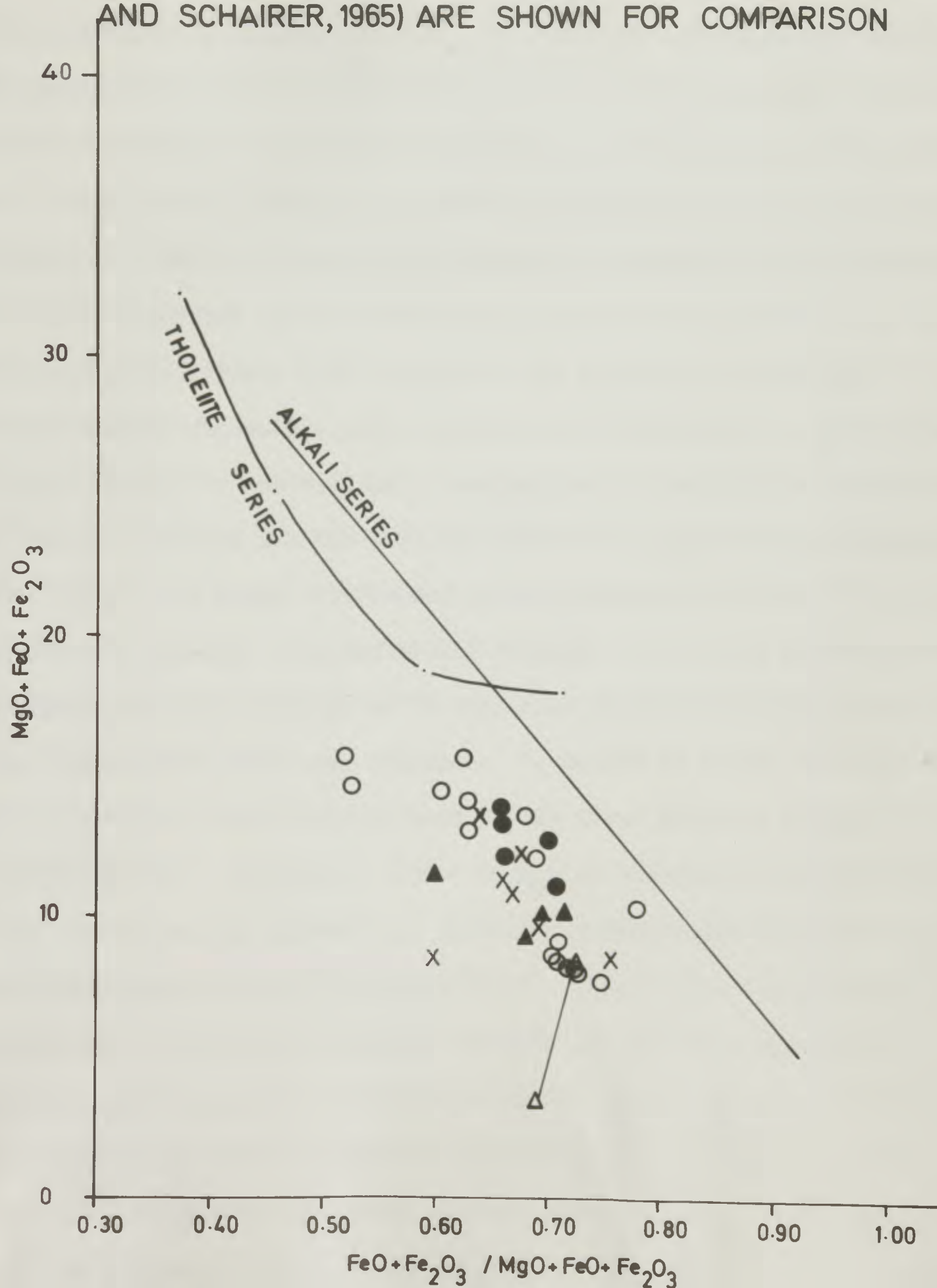


Fig.22. PLOT OF $(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3) : (\text{FeO} + \text{Fe}_2\text{O}_3 / \text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$ RATIOS FOR MONTSERRAT ROCKS. THE TRENDS OF THE HAWAIIAN ALKALI AND THOLEIITE SERIES (TILLEY, YODER AND SCHAIRER, 1965) ARE SHOWN FOR COMPARISON



contents of MgO and $(\text{FeO} + \text{Fe}_2\text{O}_3)$ and higher $\text{MgO}/(\text{FeO} + \text{Fe}_2\text{O}_3)$ ratios than cumulate blocks from St. Vincent and picrite basalts from the Solomon Islands so that the Montserrat rocks lie on a shorter trend than the "island-arc calc-alkaline" trend and deviate from the main trend at higher values of $(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$.

Brown and Schairer suggest (op. cit., p. 463) that the calc-alkaline suites in the Lesser Antilles and Solomon Islands are related to the tholeiite series during early stages of crystallisation in which the separation of olivine has a controlling effect on the $\text{MgO}/(\text{FeO} + \text{Fe}_2\text{O}_3)$ ratio. The plots, however, diverge markedly at basalt compositions which according to Brown and Schairer may reflect a difference in the oxygen fugacity of the suites, as suggested by the experimental work of Osborn (1959). In the calc-alkaline suite crystallisation under conditions of constant or increasing $f\text{O}_2$ leads to early precipitation of magnetite, which prevents iron enrichment in the residual liquid, whereas crystallisation at constant total composition (closed system) produces an iron enrichment trend. Evidence for the striking effect of magnetite crystallisation on the compositional trend of a magma is afforded by the Thingmuli suite which shows an initial tholeiitic affinity but also a calc-alkaline affinity in the more siliceous rocks, which can be correlated with the stage at which magnetite microphenocrysts appear abundantly in the lavas (Carmichael, 1964, pp. 440-444). It should be noted, however, that the separation of magnetite alone will not produce the trend observed in Fig. 22. The rise in iron enrichment $(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$ in the more siliceous rocks requires the separation of Mg-bearing phases e.g. pyroxene or hornblende along with magnetite.

The iron-magnesia and the iron enrichment - total mafic trends of the calc-alkaline suite can therefore be explained in terms of the early separation of olivine followed by the later separation of magnetite together with pyroxene or hornblende and this is close to the observed sequence of crystallisation of mafic minerals in both lavas (p. 116) and ultrabasic cumulates (p. 108) from Montserrat. It must be admitted however that the Montserrat series provides only limited evidence for the olivine accumulate stage of the "island-arc calc-alkaline" trend (see also p. 149).

16:1:8 Variation of Major Elements in the Banded Hornblende-Hypersthene Andesite Blocks (18612).

Numerous banded blocks of hornblende-hypersthene andesite lava occur in Pea Ghaut. These blocks consist of irregular black, white or grey bands usually with the grey bands predominant and the white bands less abundant than the black. The boundaries of the bands are sharp and the bands swell and pinch out irregularly (Plate 20B) but are seldom highly contorted.

On the basis of their phenocryst assemblages the different bands are all classified as hornblende-hypersthene andesites but nevertheless the modal proportions of phenocrysts in the different bands vary quite considerably (Table 8). In addition the colour and probably also the composition of the finely microcrystalline groundmasses of the different bands also vary.

Chemical analyses of separated black, grey and white bands from one of the lava blocks (18612) are given in Table 12 (numbers 46-50). These analyses show that the white band is considerably enriched in SiO_2 , Na_2O and K_2O and depleted in TiO_2 , Al_2O_3 , Fe_2O_3 , MgO and CaO with respect to the black and grey bands which have almost identical compositions. The latter fact is rather surprising in view of the difference in the modal analyses of the two bands.

Blocks of pumice showing similar banding and compositional variation to those described above have been reported at many calc-alkali volcanoes e.g. Lassen Peak (MacDonald and Katsura, 1965) and Katmai (Williams et al., 1956) but this is the first recorded occurrence from the Lesser Antilles. Most of the examples of banded blocks in the literature are of pumice rather than lava and the more basic material is usually, though not always, subordinate to the more acid. It is possible that examples of this more usual type of banded pumice are also present on Montserrat since light-coloured pumice blocks from the pyroclast flow at the base of the pyroclastic succession in Pea Ghaut contain irregular bands of much darker material (p. 61). These blocks may possibly be genetically related to the banded lava blocks but more detailed chemical

and mineralogical work is needed to prove this.

Banded pumice fragments from elsewhere have usually been interpreted as indicating the incomplete mixing of two different magmas and MacDonald and Katsura (1965, p. 480) suggested that mixing within a composite magma body rather than the chance encounter of two genetically distinct magmas, was the most likely way in which the banded pumice blocks of Lassen Peak were formed. As the different bands in the Montserrat blocks have an essentially similar mineralogy the writer considers that the incomplete mixing of magmas within a composite andesitic magma body may also be an appropriate explanation for these blocks. Nevertheless the degree of mixing in the present case does not appear to have been very great and it is interesting that the chemical data appear to preclude the possibility that the grey bands crystallised from magma formed by the mixing of magmas corresponding in composition to the white and black bands. This is the usual explanation of bands of intermediate colour in banded pumice (e.g. MacDonald and Katsura, 1965, p. 479) but a review of the literature on banded pumice failed to reveal any chemical analyses of intermediate bands so that this explanation may be based on inadequate evidence. Although the complex relationships of the different bands in the Montserrat blocks suggest that the different bands were liquid at the time of the formation of the blocks the high viscosity of the different material at the time of their incorporation may have prevented much mixing.

16:2 TRACE ELEMENTS.

Nockolds and Allen (1953, Table 6a) determined the abundances of eleven trace elements in seven lavas from Montserrat and these analyses are reproduced in Table 14 along with new determinations of thirteen trace elements in a further thirteen whole rocks and the glassy groundmass of a Soufriere Hills pumice (18615). Abundances (in p.p.m.) of all these elements, except F, are plotted against SiO_2 in Figs. 23 and 24.

16:2:1 Analytical Methods.

Fluorine was determined by colorimetric analysis on the Technicon AutoAnalyser, using the fading reaction of fluorine on the zirconium xylonyl orange complex (Fuge,

TABLE 14. TRACE ELEMENTS IN ROCKS from MONTserrat

	1	2	3	4	6	8	13	14	15	18	20	24	27	28	33	34	37	38	43	46	47
Rb	-	-	3	5	10	20	14	-	8	8	20	15	20	13	20	11	17	25	19	40	-
Ba	21	37	65	75	75	100	200	145	130	135	150	180	150	205	150	160	175	200	205	300	680
Sr	230	350	260	245	500	750	285	260	235	200	300	205	250	240	300	205	210	400	195	250	-
Zr	10	N.D.	55	75	80	85	105	60	100	95	100	100	100	110	100	105	125	125	120	100	130
Cu	60	115	86	84	-	-	50	82	74	56	-	27	-	36	-	37	23	-	24	-	25
Co	88	107	31	28	35	30	30	70	19	18	25	17	20	11	15	12	14	20	8	10	4
Ni	23	43	5	7	20	5	37	5	3	1	10	41	5	1	N.D.	1	2	N.D.	1	N.D.	N.D.
Sc	33	45	4	31	50	20	21	26	21	18	30	15	20	12	N.D.	11	14	N.D.	11	N.D.	N.D.
V	250	335	360	265	400	300	150	195	185	170	200	130	150	85	150	75	105	170	65	100	45
Cr	7	22	14	20	35	5	17	9	16	4	15	17	5	7	N.D.	4	7	5	N.D.	N.D.	N.D.
Ga	-	-	17.5	17.5	30	25	17	-	18	16.5	25	16	25	18	25	18	17.5	25	18.5	20	14
Li	-	-	7	9	5	20	13	-	11	13	15	15	15	17	30	14	16	30	17	45	-
F	178	186	275	155	-	-	268	203	-	-	-	63	-	312	-	115	-	-	105	-	-
SiO ₂	42.3	43.2	49.3	50.1	52.00	52.64	53.8	54.1	54.9	56.3	56.75	58.0	58.36	58.5	59.68	59.8	60.0	60.08	62.5	64.21	71.75
K/Rb	-	-	1433	1000	661	415	593	-	400	663	290	500	376	539	290	645	389	332	468	228	-
Rb/Sr	-	-	-	0.013	0.021	0.020	0.027	0.049	-	0.034	0.043	0.067	0.081	0.080	0.054	0.067	0.054	0.081	0.063	0.097	0.160
Ni/Co	0.261	0.400	0.161	0.250	0.571	0.167	1.233	0.071	0.158	0.056	0.400	2.411	0.250	0.091	0	0.083	0.143	0	0.125	0	0
V/Ni	10.9	7.8	72	37.9	20	10	4.1	29	61	170	20	3.2	30	85		70	52.5		65		

NOTES. 1. ANALYSTS:- FLUORINE ANALYSES - MR. R. FUGE
OTHER ELEMENTS - Nos. 1-4, 13-15, 18, 24, 28, 34, 37, 43 - MRS. N. GARTON
Nos. 6, 8, 20, 27, 33, 36, 38 - MR. R. ALLEN (NOCKOLD and ALLEN, 1953)
No. 47 - MR. R. GOODMAN

- METHODS - SEE P. /32-
- FOR SPECIMEN DESCRIPTIONS - SEE TABLE 13
- N.D. = NOT DETECTED; - = NOT DETERMINED

1969). Automated colorimetric analysis (Fuge, 1967a) was also used for the determination of Cr in minerals separated from the ultrabasic blocks and V in these minerals (see Table 11) was determined spectrophotometrically according to the method of Fuge (1967b). Apart from the fluorine analyses all the trace element analyses shown in Table 14 were obtained by optical spectrography using Hilger large quartz-glass spectrographs. Fourteen of these analyses were made by Mrs. N. Garton and Mr. R. Goodman at the Department of Geology and Mineralogy, Oxford University while the other seven were made by Mr. R. Allen at the Department of Mineralogy and Petrology, Cambridge University.

Details of the procedure used at Cambridge are given in Nockolds and Allen (1953, p. 105-106). The procedure used during the present investigations is basically similar to that used by Nockolds and Allen but Pd was used as an internal standard and results were standardised relative to accepted values of trace elements in the U.S.G.S. standards G1, W1 and AGV 1. Full details of the procedure which was established at Oxford by Ahrens and Taylor are given, for example, by Tomblin (1964, Appendix D). The lines used were as follows:-

Blue Run:- Pd 3958.64 Sc 4246 Cr 4254 La 4333 Sr 4607 Ba 4934.

UV Run:- Ga 2944 V 3185 Cu 3274 Ni 3414.76 Zr 3438 Co 3453 Pd 3258.8.

Alkali Run:- Na 5688 Li 6707 Rb 7800.

16:2:2 Reproducibility and Accuracy of Trace Element Analyses.

All the spectrographic analyses made during the present study were carried out in duplicate and the values given in Table 14 are average values. The duplicate analyses are always within 20% of one another and agreement is usually much better than this. Nockolds and Allen (1953, p. 105) estimated an accuracy of $\pm 30\%$ for their spectrographic results but the new analyses should be more accurate due to better standardisation. One source of error in the present work is that Co interferes with the Ni line (3414.76). At Co : Ni = 1 about 8% of the Ni line intensity is actually due to Co 3414.73 (Mrs. N. Garton, pers. comm.). The Ni values in Table 14 have not been corrected to allow for

this effect which may be considerable especially in rocks with low Ni contents and high Co/Ni ratios.

There is less comparative analytical data for trace elements in the Montserrat rocks than there was for major elements. However, values of Sr, V and Ga and probably also of Sc, Rb and Li determined by Allen are consistently a little higher than the values for these elements obtained at Oxford (Figs. 23 and 24) which suggests that there is some discrepancy due to inter-laboratory errors. Values of V and Cr for the two ultrabasic blocks determined by spectrophotometric and colorimetric methods are also higher than the values determined spectrographically.

Results for F, Cr and V in some U.S.G.S. standard rocks determined by colorimetric or spectrophotometric methods agree well with the average values (Appendix 1, Table 1).

16:2:3 Variation of Trace Elements in the Montserrat Rocks.

In this section the concentration and behaviour of each of the thirteen trace elements determined in the Montserrat rocks is discussed and comparisons are made with other lavas from the Lesser Antilles (Baker, 1963, 1968a; Tomblin, 1964; Rea 1966) and other calc-alkaline provinces (Nockolds and Allen, 1953; Taylor, 1968, 1969; Taylor, Kaye et al., 1969a; Taylor, Capp et al., 1969). Comparative chemical data are also given in Table 16.

Rubidium.

Rubidium increases fairly steadily with increasing acidity in the Montserrat lavas, and also shows a rough positive correlation with potassium. Rubidium contents in the Montserrat lavas are low compared with Martinique and very low compared with St. Lucia. They are also low compared with calc-alkaline suites in general.

The K/Rb ratio decreases and the Rb/Sr ratio increases quite steadily with increasing silica in the Montserrat lavas. The K/Rb ratio decreases with increasing acidity in all the Lesser Antillean suites so far investigated and the K/Rb ratios in the St. Lucian dacites are among the lowest ever recorded from calc-alkali rocks. In many calc-

Fig. 23. VARIATION OF Cu, Co, Ni, Sc, V and Cr in MONTSERRAT ROCKS.

KEY: ○ — White River Pyroclast Fall Series
 ● — Other South Soufriere Hill Lavas
 △ — Soufriere Hills Lavas
 x — Data from Nockolds and Allen (1953 Table 6a)

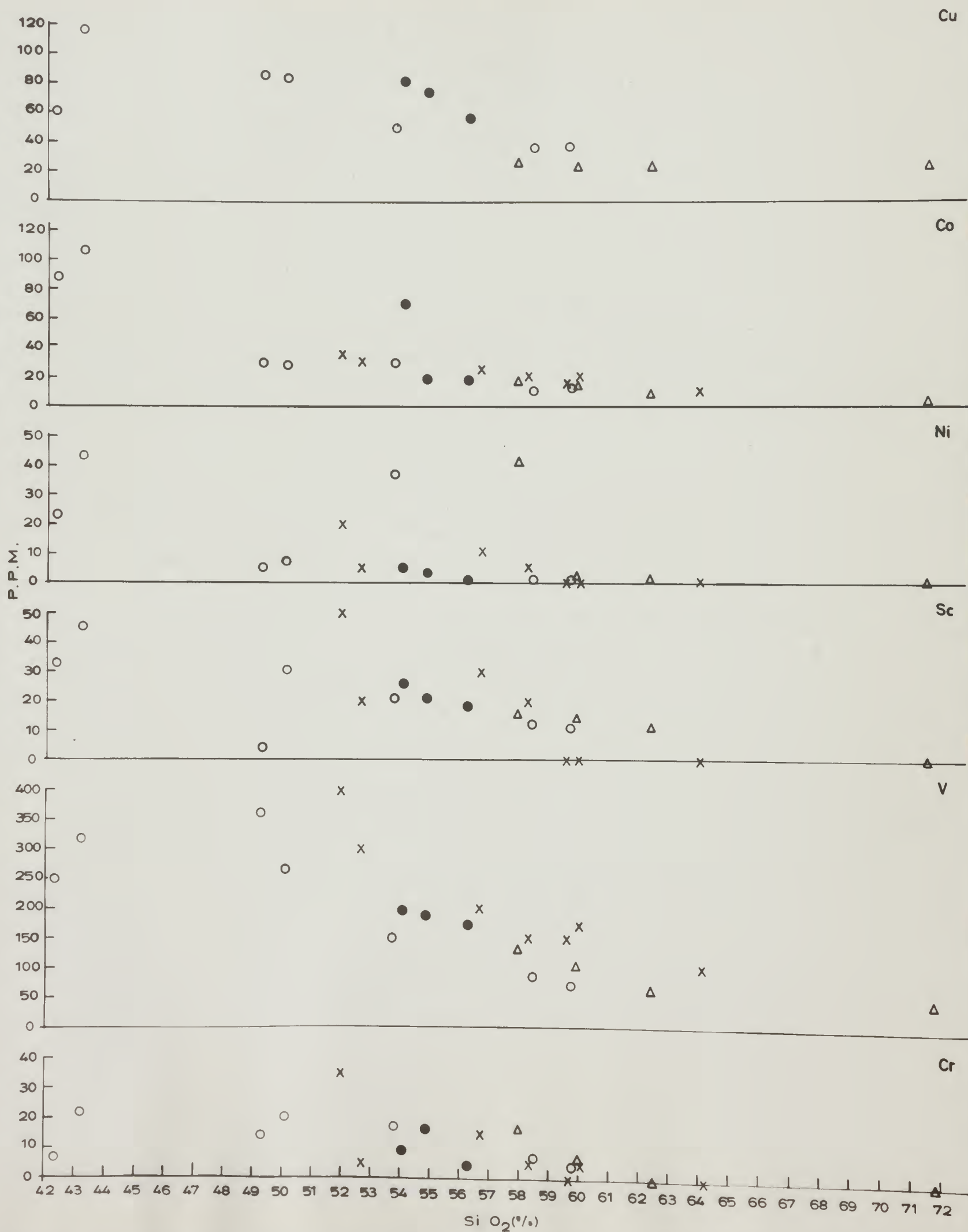
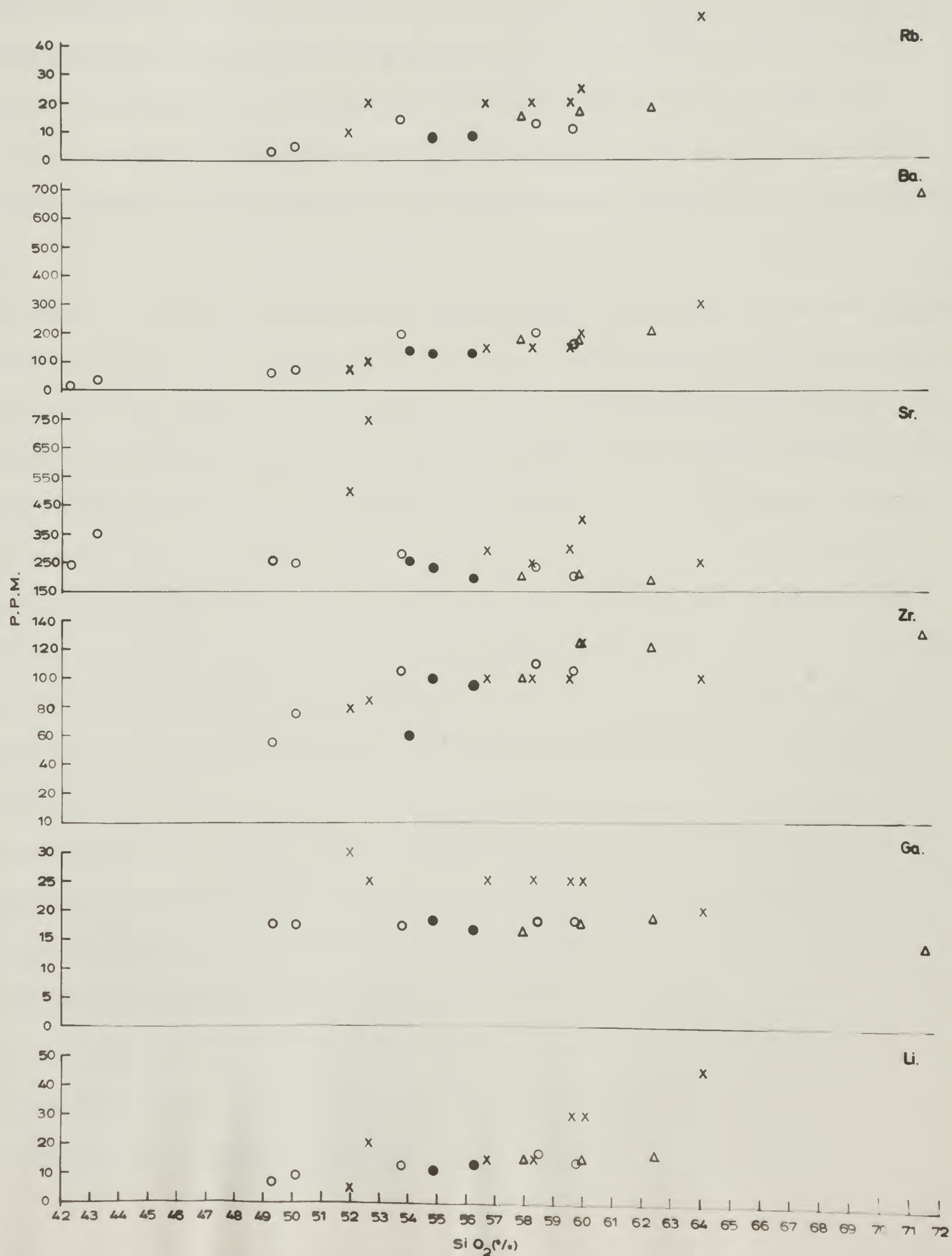


Fig. 24. VARIATION OF Rb, Ba, Sr, Zr, Ga and Li in MONTSERRAT ROCKS.

KEY—As in Fig. 23.



alkaline suites the K/Rb is fairly constant while in a few suites (e.g. Lassen Peak) the ratio actually increases with increasing acidity.

Barium.

Barium increases fairly steadily with increasing acidity in the Montserrat ultrabasic blocks and lavas but is considerably enriched in the groundmass of 18615. The amount of barium in the Montserrat lavas is low compared with other islands in the Lesser Antilles and very low compared with most calc-alkaline suites. Similar barium contents have, however, been recorded in low K andesites e.g. from Saipan (Taylor, 1969).

Strontium.

The values of strontium determined by Nockolds and Allen show considerable variation and are a good deal higher than values determined during the present study (Fig. 24). The latter data^t suggest that strontium remains relatively constant throughout the Montserrat series but shows a slight tendency to decrease with increasing acidity. On the other hand Nockolds and Allen's values show a marked decrease in strontium content throughout the series.

The Montserrat lavas contain similar amounts of strontium to lavas from other islands in the Lesser Antilles but strontium increases slightly in more acid lavas from St. Kitts and shows no systematic variation at all in the St. Lucian lavas. The Lesser Antillean lavas are probably slightly depleted in strontium compared with other calc-alkaline suites.

Nockolds and Allen (1953) attribute the variable behaviour of strontium in different calc-alkaline provinces to differences in the amount of plagioclase removed from the magma but recent work (Brooks, 1968; Berlin and Henderson, 1968) has shown that the crystallisation of pyroxene is also likely to be important.

Zirconium.

The Montserrat basalts are considerably enriched in zirconium relative to the ultrabasic blocks but zirconium increases fairly steadily with increasing acidity in

the Montserrat lavas. Abundances of zirconium in lavas from other islands in the Lesser Antilles and from many other calc-alkaline suites resemble those in the Montserrat lavas. High K andesites (Taylor, 1969) however, have higher abundances of zirconium.

Copper.

Copper decreases irregularly with increasing acidity throughout the Montserrat rocks. The concentration of copper in basalts and andesites from Montserrat and St. Kitts is quite similar but the St. Lucian basalts are enriched and the St. Lucian andesites are depleted in copper relative to the other islands. Values of copper in the Lesser Antillean lavas are similar or perhaps slightly lower than those in other calc-alkaline suites.

Cobalt.

Cobalt is greatly enriched in the ultrabasic blocks relative to the basalts but shows a fairly regular decrease with increasing silica content in the rest of the series. Values are closely comparable with other islands in the Lesser Antilles although they tend to be a little higher than in the St. Lucian lavas. Cobalt is slightly less abundant in the Lesser Antillean lavas than in other calc-alkaline suites.

Nickel.

In general nickel decreases with increasing acidity in the Montserrat rocks but the ultrabasic blocks and two other rocks have exceptionally high nickel contents. One of these rocks (18641) is quite rich in modal olivine but 18618 and 18620 which are richer in modal olivine have "normal" nickel contents. The other rock which is abnormally rich in nickel is the virtually aphyric welded scoriae (18642) of the White River Pyroclast Fall Series.

Nickel contents in the Montserrat lavas are generally higher than in lavas from St. Kitts but slightly lower than in lavas from St. Lucia and a little lower than in most calc-alkaline suites.

Ni/Co ratios.

Taylor, Kaye et al. (1969a) have shown that high alumina basalts and andesites in the circum-Pacific typically have Ni/Co ratios of less than one. This is also the case for basalts and andesites from Montserrat and the rest of the Lesser Antilles but lavas from Crater Lake and Lassen Peak have higher ratios. The Ni/Co ratio in the Montserrat lavas has a very erratic relationship with silica content but on average the ratios in the basalts are slightly higher than those in the andesites.

Scandium.

Scandium is very low in the basalt cinders (18620) of the White River Pyroclast Fall Series but otherwise decreases quite regularly with increasing SiO_2 in the Montserrat rocks. Values are generally similar to those for cobalt. Scandium contents in the Montserrat lavas are quite similar to those in other lavas from the Lesser Antilles, although scandium is rather high in the St. Lucian basalts. The Lesser Antillean lavas tend to have slightly lower contents of scandium compared with most calc-alkaline suites.

Vanadium.

Vanadium rises with increasing SiO_2 in the ultrabasic blocks and if one excludes the older analyses reaches a maximum value of 360 p.p.m. at 49.3% SiO_2 in the basalt cinders (18620) of the White River Pyroclast Fall Series. Thereafter vanadium decreases quite sharply with increasing silica in the Montserrat lavas. The vanadium curve closely resembles that for total iron and both elements reach maximum values at 49.3% SiO_2 and are depleted in andesites from the White River Pyroclast Fall Series relative to other andesites. However values of vanadium decrease more rapidly than total iron in the Montserrat basalts and andesites.

The Lesser Antillean basalts all contain roughly similar concentrations of vanadium although preliminary data (Lewis 1968, Table 5) suggest that the St. Vincent basalts may contain over 300 p.p.m. V. In addition, the St. Lucian andesites contain less vanadium than andesites from Montserrat and St. Kitts. The Antillean basalts are slightly richer in vanadium compared with most high-alumina basalts while the Antillean andesites contain

considerably less vanadium than andesites from other calc-alkaline suites.

V/Ni ratios.

The V/Ni ratios in the Montserrat lavas and the Lesser Antillean lavas in general are high. High V/Ni ratios are typical of calc-alkaline lavas which have V/Ni ratios greater than those in alkali and tholeiitic basalts by at least an order of magnitude (Taylor, Capp et al., 1969).

Chromium.

Chromium is rather erratically distributed in the Montserrat rocks but tends to be higher in the basalts than the andesites. It also shows a slight positive correlation with nickel. Chromium is typically concentrated in early-formed clinopyroxene (Wager and Mitchell, 1951) and most of the Montserranian lavas which are rich in chromium contain abundant modal clinopyroxene. The almost aphyric welded basaltic scoriae (18642) is however quite rich in chromium and in the ultrabasic blocks Cr is much higher in 18593 than in 18592 which may reflect the greater abundance of olivine in the former.

Contents of chromium in lavas from Montserrat, St. Kitts and Martinique are quite similar but the St. Lucian lavas contain about five times as much chromium as lavas from the other islands. The chromium contents in the St. Lucian lavas are however, closely comparable with values for other calc-alkaline suites.

Gallium.

Gallium contents of around 20 p.p.m. are recorded in basalts and andesites from Montserrat, the Lesser Antilles and calc-alkaline suites in general. Gallium shows a rough positive correlation with aluminium in the Lesser Antillean basalts and andesites but is slightly enriched relative to aluminium in the groundmass of 18615, in dacites from St. Lucia and in many acid calc-alkaline lavas.

Lithium.

Lithium increases with increasing acidity in the Montserrat lavas but the rate of increase, indicated by Nockolds and Allen's results is considerably greater than that

indicated by the present work. The Montserratian and St. Lucian lavas contain similar amounts of lithium.

Fluorine.

Fluorine is very erratically distributed in the Montserrat rocks but tends to be higher in pyroclastics than in lavas. This is in accord with the findings of Noble et al. (1967) who showed that halogens are lost from volcanic rocks during crystallisation.

16:3 STRONTIUM AND LEAD ISOTOPE RATIOS AND URANIUM AND THORIUM ABUNDANCES.

During the present study seven new Sr isotope analyses of Montserrat rocks were made by Dr. D. Green and Mrs. D. Connelly of the Department of Geology and Mineralogy, Oxford University and these analyses together with an outline of the method of analysis are given in Table 15. In addition, important data on the Lesser Antillean lavas have recently been published (e.g. Donnelly et al., 1969) including Sr isotope analyses (Pushkar, 1968), Pb isotope analyses (Armstrong and Cooper, 1969) and Th and U abundance data (Rogers in Donnelly et al., 1969). This work includes new data for Montserrat lavas and these are also given in Table 15.

In the following section the Sr isotope ratios, the Pb isotope ratios and the Th and U abundances in the Montserrat rocks are discussed in turn. Comparisons are made with other calc-alkaline lavas from the Lesser Antilles and elsewhere.

16:3:1 $Sr^{87/86}$ Ratios.

Corrected $Sr^{87/86}$ ratios in five basalts, two andesites and one metamorphic block from Montserrat are given in Table 15. As the Rb/Sr ratios in these rocks are very low (<0.1 - Table 14) and all the lavas are believed to be less than four million years old the corrected $Sr^{87/86}$ ratios must be very close to the initial ratios. The average $Sr^{87/86}$ ratio for the Montserrat lavas is 0.7034 ± 0.0009 and somewhat surprisingly the andesites have slightly lower values than the basalts. The $Sr^{87/86}$ ratios in the Montserratian lavas are a little low compared with most circumoceanic volcanics (Hedge, 1966; Pushkar, 1968) and are only slightly high compared with abyssal oceanic volcanics

TABLE 15. STRONTIUM and LEAD ISOTOPE RATIOS and THORIUM and URANIUM CONTENTS
in MONTSERRAT LAVAS

SPECIMEN NO.	BASALTS						ANDESITES							METAMORPHIC BLOCK
	18657 404	18637 296	18642 333C	18575 26	TD 1717	TD 1822	18641 324	18610 133	TD 1820	TD 1826	TD 1829	TD 1832	64 -30	
Sr ^{87/86}	0.7026 +0.0010	0.7045 +0.0008	0.7026 +0.0011	0.7049 +0.0008	0.7035 +0.0002	-	0.7024 +0.0010	0.7035 +0.0009	-	-	-	-	-	0.7057 +0.0012
Pb ^{206/204}	-	-	-	-	-	18.918	-	-	-	-	-	-	18.939	18.772
Pb ^{207/204}	-	-	-	-	-	15.694	-	-	-	-	-	-	15.621	15.606
Pb ^{208/204}	-	-	-	-	-	38.785	-	-	-	-	-	-	38.628	38.653
Th (p.p.m.)	-	-	-	-	1.82	1.22	-	-	2.55	2.74	3.01	3.34	-	-
U (p.p.m.)	-	-	-	-	0.74	0.97	-	-	0.80	0.95	0.94	0.78	-	-

NOTES

1. ANALYSTS
 - a. Strontium isotope analyses by Dr. D. Green (cols. 1, 2, 4, 7, 8); Mrs. D. Connelly (cols. 3 and 15); and Dr. P. Pushkar (col. 5)
 - b. Lead isotope analyses by Dr. R. L. Armstrong.
 - c. Thorium, Uranium analyses by Dr. J.J.W. Rogers.
2. METHODS
 - a. Strontium isotope analyses (cols. 1-4, 7, 8 and 15). Isotope ratios measured on A.E.I. M.S.2 mass spectrometer at Oxford University, Department of Geology. All measured ratios normalised to $Sr^{86}/^{88} = 0.1194$ and corrected to a value of 0.7080 for Eimer Amend $SrCO_3$.
 - b. For details of all other methods see Donnelly et al., 1969.

3. DETAILS OF SPECIMENS

- a. For cols. 1-4, 7, 8 and 15 see Table 13.
- b. TD1717 Basalt, near Shoe Rock
- TD1822 Basalt, O'Garra (referred to as a hypersthene - andesite in Donnelly et al., 1969 Table 1, but as it contains 54.8% SiO_2 it is referred to here as a basalt. The lead isotope measurements are of a different sample (64-26) from the same locality).
- TD1820 Hypersthene-andesite, Galway's.
- TD1826 Andesite, Galways.
- TD1829 Hypersthene-andesite, Little Bay.
- TD1832 Hypersthene-andesite, St. George's Hill.
- 64-30 Andesite - Labradorite - Dacite, Tuitts.
- 64-37 Andesite, near Fogarty Valley.

(Tatsumoto et al., 1965).

Previous to the present work eleven $\text{Sr}^{87/86}$ ratios for Lesser Antillean lavas have been published (Pushkar, 1968; Donnelly et al., 1969) and these ratios together with those from Table 15 are plotted in Fig. 25. These results show that 13 Lesser Antillean lavas have $\text{Sr}^{87/86}$ ratios of between 0.702 and 0.705 but two lavas each from Dominica and St. Lucia have higher ratios. The high ratios in the Dominican and St. Lucian lavas are unlikely to be due to mantle inhomogeneity since other lavas from these islands have normal ratios. They probably indicate the local incorporation into magmas of material containing radiogenic strontium as discussed in section 17:3.

16:3:2 Lead Isotope Ratios.

Corrected lead isotope ratios determined by Dr. R. L. Armstrong (in Donnelly et al., 1969) for three Montserratian lavas are given in Table 15. Armstrong has also measured lead isotope ratios in a basalt and an andesite from St. Kitts and two andesites from Dominica. The ratios in the Montserrat lavas and in the St. Kitts lavas are very similar whereas the Dominican lavas have significantly higher ratios, which suggests that the overall pattern of variation throughout the Lesser Antilles may be similar to that shown by the strontium isotope ratios. However, the lead isotope ratios even in the Montserratian lavas, are considerably higher than in abyssal oceanic igneous rocks (Tatsumoto, 1966). In addition the Lesser Antillean andesites contain much higher quantities of radiogenic lead than andesites from Japan (Tatsumoto, 1969). The Lesser Antillean lavas are also enriched in radiogenic lead compared with older rocks in the Eastern Caribbean, including the Cretaceous to Eocene spilites and keratophyres from Puerto Rico and the Virgin Islands. The latter are characterised by low contents of radiogenic lead similar to those found in oceanic tholeiites.

The high values of radiogenic lead in lavas from the Lesser Antilles could indicate derivation from a source with a high U/Pb ratio but are probably due to the mixing of two leads as discussed more fully in section 17:3.

16:3:3 Thorium and Uranium.

Thorium and uranium contents determined by Dr. J. J. W. Rogers in six lavas from Montserrat are given in Table 15. Dr. Rogers (in Donnelly et al., 1969) has also determined Th and U in several lavas from the Lesser Antilles, and these results confirm the trends shown by the strontium and lead isotopes in that contents of Th and probably also the Th/U ratio are highest in lavas from St. Lucia and Dominica. Contents of Th and U are however, a good deal higher in andesites than in basalts throughout the Lesser Antilles. The Lesser Antillean lavas are enriched in Th and U relative to the spilites and keratophyres of the Virgin Islands and Puerto Rico but the difference is less striking than in the case of the lead isotopes.

The Lesser Antillean lavas have similar abundances of Th and U to andesites from Saipan and Fiji (Taylor, Capp et al., 1969) and to "non-tholeiitic" volcanics from Japan (Tatsumoto, 1969, Table 1). They contain considerably more Th and U than abyssal tholeiites (Tatsumoto, 1966) but much less Th and U than continental rocks (Taylor and White, 1966).

It is interesting also that the observed Th/U ratios in the lavas (1.3 to 4.1) are in general lower than the apparent Th/U ratio (~ 3.8) for the environment in which the lead isotopes evolved. Armstrong (in Donnelly et al., 1969) suggests that this discrepancy might lie in the hydrous environment of melting in which U, which can be oxidised, might be preferentially extracted giving a melt with a lower Th/U ratio.

16:4 SUMMARY OF THE PETROCHEMISTRY.

The chemical data presented in this chapter strongly suggest that the Montserrat lavas form a closely related series of rocks. Plots of the major and minor elements against SiO_2 approximate to regular curves. As expected the ultrabasic cumulates often plot on a different trend to the lavas but for some elements e.g. Mg, Ba, Sc the blocks and the lavas actually plot on the same trend. The rocks of South Soufriere Hill differ from those of the other Montserranian volcanoes in that their SiO_2 range is larger and

the South Soufriere Hill andesites are slightly depleted in total iron, MgO , TiO_2 and V and slightly enriched in Na_2O and Al_2O_3 relative to andesites from the other volcanoes. Apart from this there is very little difference in the chemistry of andesites from South Soufriere Hill and the other volcanoes except that silica reaches higher values in the latter.

Petrochemically, the Montserrat lavas resemble those from most of the other islands in the Lesser Antilles, especially St. Kitts. However they have less K_2O , Rb, Ba and Cr and more Na_2O , V, Co and Cu than lavas from St. Lucia, and lower $\text{Sr}^{87/86}$ ratios and smaller amounts of radiogenic lead than lavas from St. Lucia and Dominica (Table 16). It appears that the St. Lucian and Dominican lavas make up a petrochemically distinct group among the lavas of the Lesser Antilles but there is, at present, insufficient data available to enable one to say whether the lavas of Martinique, which lies between Dominica and St. Lucia in the central part of the Lesser Antilles, also belong to this group. More data are also needed for Grenada where lavas are exceptionally rich in K_2O .

As well as inter-island differences in chemistry, differences in the chemistry of lavas from different volcanoes in the Lesser Antilles and especially between the "basaltic" and "andesitic" volcanoes (see Chapter 14) were expected. However, the present study suggests that the main chemical difference between the "basaltic" volcanoes (e.g. South Soufriere Hill) and the "andesitic" volcanoes (e.g. Soufriere Hills) lies in the different ranges of silica contents of their lavas. Apart from a few minor differences, the andesites at both types of volcano appear to be quite similar chemically.

Although the Montserrat lavas bear an overall chemical resemblance to lavas from other calc-alkaline suites they are somewhat depleted in TiO_2 , Rb, Sr, Ba, Ni and Cr and enriched in Al_2O_3 and CaO compared with most calc-alkaline lavas especially those from continental areas (e.g. the Cascades - Table 16, Nos. 10, 26, 32). Basalts from Montserrat contain slightly more K_2O than most high alumina basalts (Table 16, Nos. 10-13) but the Montserrat andesites are considerably depleted in K_2O relative to most andesites. The Montserrat andesites and most other andesites from the Lesser Antilles

TABLE 16. CHEMICAL ANALYSES OF BASALTS, ANDESITES AND DACITES FROM MONTSERRAT, THE LESSER ANTILLES AND ELSEWHERE WITH ESTIMATED COMPOSITIONS OF THE UPPER MANTLE AND DEEP SEA CLAY FOR COMPARISON

	BASALTS												ANDESITES																DACITES			OTHERS		
	MONTSERRAT				ST. K.	ST. LUCIA		ST. VINCENT		CASC.	S.S.I.	TAUPO	H.A.B.	THOL.	ALK.	MONTSERRAT					ST. K.	DOM.	MTQ.	ST. L.	ST. V.	CASC.	SAIP	AND.	BOUG.	MONT.	ST. L.	CASC.	MANT.	CLAY
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
SiO ₂	52.5	51.8	53.3	53.9	50.9	51.9	54.1	52.6	47.6	51.2	51.2	51.7	50.7	49.3	47.7	59.4	58.2	60.5	58.9	60.4	59.5	60.5	60.2	61.5	55.9	59.8	57.3	59.5	60.8	63.6	64.6	65.7	45.2	52.0
TiO ₂	0.8	0.8	1.1	0.7	1.0	0.9	1.0	0.9	1.1	1.4	0.8	-	1.1	1.5	2.9	0.5	0.5	0.5	0.4	0.5	0.6	0.6	0.7	0.5	0.9	0.7	0.6	0.7	0.8	0.4	0.5	0.6	0.7	0.8
Al ₂ O ₃	19.1	19.6	16.1	18.8	19.4	17.8	16.0	18.5	15.8	17.7	18.1	16.9	17.8	17.1	18.1	18.3	18.5	17.7	19.3	17.5	18.2	18.7	16.9	17.9	18.0	17.4	17.4	17.2	16.8	16.8	16.8	16.9	3.5	15.9
Fe ₂ O ₃	3.7	3.3	4.2	3.6	3.7	2.3	3.9	4.1	1.9	2.1	2.7	10.4	3.6	2.0	4.2	3.3	3.8	2.7	2.9	3.3	3.7	3.0	2.7	1.4	3.3	1.5	7.3	6.1	5.1	3.3	0.8	1.3	0.5	
FeO	5.1	5.4	6.7	4.9	5.4	6.3	7.8	4.9	7.1	7.2	7.4		6.6	6.8	5.9	3.2	3.1	3.3	2.9	3.2	3.5	2.5	3.8	3.4	5.2	4.2				2.4	3.0	2.5	8.0	8.4
MnO	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.1	-	-	0.1	0.1	0.1	0.1		
MgO	4.7	4.7	5.3	4.4	4.7	4.6	3.5	4.8	11.9	6.6	6.2	6.5	5.5	7.3	4.8	2.5	3.1	2.8	2.2	3.0	2.3	2.1	2.6	2.3	3.2	3.4	3.5	3.4	2.2	2.3	1.7	2.0	37.5	3.5
CaO	9.3	10.0	8.5	8.9	10.5	10.8	7.8	9.9	11.3	9.5	11.0	11.0	10.5	11.8	8.8	7.3	7.8	7.0	7.4	7.0	6.7	6.8	7.6	7.2	8.3	6.3	8.7	7.0	5.6	6.1	6.4	4.2	3.1	4.1
Na ₂ O	3.1	3.1	2.7	3.4	3.2	2.9	3.5	2.8	2.2	3.1	2.0	3.1	2.6	2.7	4.0	3.5	3.4	3.6	3.9	3.5	3.8	3.5	3.5	2.6	3.5	4.0	2.6	3.7	4.1	3.6	3.1	4.2	0.6	5.4
K ₂ O	0.7	0.8	1.3	0.6	0.5	0.7	0.6	0.5	0.6	0.6	0.3	0.4	0.5	0.2	1.7	0.8	0.7	0.9	0.8	0.8	0.6	1.5	1.0	1.4	0.6	1.4	0.7	1.6	3.3	1.1	1.5	2.1	0.1	3.0
H ₂ O+	0.7	0.3	0.5	0.5	0.4	1.4	1.4	0.8	0.2	0.2	-	-	0.6	0.7	0.8	0.9	0.7	0.7	0.9	0.5	0.8	0.6	0.7	1.5	0.8	0.7				0.3	1.3	0.3	-	-
P ₂ O ₅	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	-	0.2	0.2	0.9	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.3				0.1	0.1	0.1	0.1	
Fe ₂ O ₃ /FeO	0.73	0.61	0.63	0.73	0.69	0.37	0.50	0.84	0.27	0.29	0.36	-	0.54	0.29	0.71	1.0	1.23	0.88	1.00	1.03	1.06	1.20	0.71	0.41	0.63	0.36				1.38	0.27	0.52	0.06	
Fe ₂ O ₃ +FeO/MgO	1.9	1.9	2.1	1.9	1.9	1.9	3.3	1.9	0.8	1.4	1.6	-	1.8	1.2	2.1	2.6	2.2	2.1	2.6	2.2	3.1	2.6	2.5	2.1	2.7	1.7				2.5	2.2	1.9	0.23	
Rb	10	12		8	-	29	16	-		40	11	10		410	33	17	16	20	13	19	-	66	40	51		55	10	31	88	40	112	115	< 3	110
Ba	108	100		136	130	169	190	-		250	62	115		14	498	171	164	182	205	182	266	-	238	383		625	110	270	400	300	243	900	4	2300
Sr	380	490		250	264	310	273	190		975	135	328		130	815	250	230	275	240	262	286	360	333	270		970	215	385	620	250	277	780	50	180
Zr	83	80		80	83	69	90	-		80	80	100		95	333	108	101	118	110	114	93	-	91	97		120	90	110	170	100	88	170	45	150
Th	1.5	1.8		1.2	1.5	-	1.9	1.7		-	-	1.1		0.15	3.9	2.9	-	2.9	-	-	-	6.1	-	1.4		-	1.3	2.2	5.5	-	7.7	-	0.08	7
U	0.85	0.74		0.97	0.36	-	0.46	0.90		-	-	0.2		0.08	0.99	0.87	-	0.87	-	-	-	1.69	-	0.87		-	0.4	0.7	2.2	-	2.3	-	0.03	1.3
Cu	73	84		78	60	99	88	-		-	139	35		77	36	33	40	24	36	25	28	-	-	8		-	55	54	40	-	5	-	40	250
Co	28	31		44	27	18	17	10		35	39	40		32	25	16	18	14	11	15	16	-	16	9		15	20	24	13	10	5	1	100-260	74
Ni	13	11		4	17	42	10	3		100	14	25		97	51	6	12	1	1	9	2	-	1	6		35	15	18	3	N.D.	5	1	1000	225
Sc	24	33		23	32	58	47	-		20	34	40		61	26	13	19	6	12	8	15	-	8	15		15	31	30	20	N.D.	7	N.D.	25	19
V	280	320		190	275	245	290	330		160	317	255		292	252	130	147	122	85	121	98	-	112	52		115	195	175	160	100	35	40	100	120
Cr	18	20		12	49	176	10	-		200	34	40		77	36	6	10	3	7	6	7	-	1	32		55	44	56	3	N.D.	27	3	1000-5000	90
Ga	21	18		18	18	10	11	-		20	17	13		17	22	20	20	21	18	20	17	-	24	16		22	-	16	-	20	16	19		20
Li	11	11		11	-	12	18	-		25	6	10		9	11	18	15	24	17	22	-	-	38	21		33	-	10	-	45	34	47		57
K/Rb	591	556		623	-	166	381	-		122	227	344		1300	418	391	363	374	508	347	-	189	208	227		217	590	430	297	228	123	151		
Rb/Sr	0.03	0.02		0.02	-	0.09	0.06	-		0.04	0.08	0.03		0.01	0.04	0.07	0.07	0.07	0.05	0.07	-	0.18	0.12	0.19		0.06	0.05	0.08	0.14	0.16	0.40	0.1		
Ni/Co	0.46	0.36		0.09	0.63	2.33	0.59	0.33		2.86	0.36	0.86		3.03	2.04	0.38	0.67	0.07	0.09	0.60	0.12	-	0.06	0.67		2.33	0.75	0.75	0.23	0	1.00	1.00	10	
V/Ni	21.5	29.1		47.5	16.2	5.8	29.0	110.0		1.6	22.6	10.2		3.0	4.9	21.6	12.3	122	85	13.4	49.0	-	112.0	8.7		3.3	13.0	9.7	53.3		7.0	40.0		
Th/U	1.8	2.4		1.2	4.2	-	4.1	1.9		-	-	5.9		1.8	3.9	3.3	-	3.3	-	-	-	3.6	-	1.6		-	3.3	3.1	2.5	-	3.3	-		
Sr ⁸⁷ /86	0.7036 ±0.0008	0.7035 ±0.0006		0.7049 ±0.0008	0.7029 ±0.0003	-	-	-		-	-	-		0.7021	0.7025 -0.7045	0.7030 ±0.0009	0.7024 ±0.0010	0.7035 0.0009	-	-	0.7046 ±0.0007	0.7055 ±0.0005	-	0.7060 ±0.0007		-	-	-	-	-	-	-		

Table 16A.Key to Table 16.

1. Average basalt, Montserrat. (Average of Table 12, Nos. 3-10, 12-15; Table 14, Nos. 3, 4, 6, 8, 13, 14, 15; Table 15, Nos. 1-6).
2. Average olivine-basalt, Montserrat. (Average of Table 12, Nos. 4, 6, 7, 8, 10; Table 14, Nos. 4, 6, 8; Table 15, Nos. 1, 2, 5).
3. Analysis 2 minus phenocrysts. (35% An_{60} , 5% Wo_{44} , En_{35} , Fs_{21} , 3% Fe_{80} , 1.5% magnetite. Representative mineral compositions from Deer, Howie and Zussman, 1963, Vols. 1, 2, 4, 5).
4. Average two-pyroxene basalt, Montserrat. (Average of Table 12, Nos. 9, 14, 15; Table 14, Nos. 14, 15; Table 15, Nos. 4, 6).
5. Average basalt, St. Kitts. (Data from Baker, 1968a, Table 6, Nos. 2, 3, 5, 6, 7, 8, 9; Table 7, Nos. 2, 3, 5, 7, 8; Donnelly et al., 1969, Table 1, TD 1692; Table 3, No. 4).
6. Average porphyritic basalt, St. Lucia. (Data from Tomblin, 1964, Table 12, Nos. 1, 3; Table 14, No. 83).
7. Average aphyric basalt, St. Lucia. (Data from Tomblin, 1964, Table 12, Nos. 2, 4; Table 14, No. 34; Donnelly et al., 1969, Table 1, TD 1694).
8. Average basalt, St. Vincent. (Data from Robson and Tomblin, 1966, Table 11, Nos. 1, 4, 5, 7; Lewis, 1968b, Table 1, Nos. 5, 6; Table 5, Nos. 5, 6; Donnelly et al., 1969, Table 1, TD 1703).
9. Olivine-phyric basalt, St. Vincent. (Lewis, 1968b, Table 1, No. 4).
10. Average basalt, Cascades. (Data from Coombs and Howard, 1960, p. 15, No. 1; p. 46, No. 14; Williams, 1935, p. 295, Nos. 3, 4, 5; Turner and Verhoogen, 1960, Table 28, Nos. 1, 3; Nockolds and Allen, 1953, Table 2, Nos. 1, 3; Table 3, Nos. A, 1; Table 7, Nos. 1, 2).
11. Average basalt, South Sandwich Islands. (Data from Baker, 1968b, Table 2, No. 1; Table 3, No. 2).
12. High alumina-basalt, Taupo New Zealand. (Data from Taylor, 1969, Tables 1-6, No. 1).

Table 16A Continued....

13. Average circum-oceanic basalt (Lewis, 1968b, Table 3, No. 1).
14. Average oceanic tholeiite. (Data from Engel et al., 1965; except Th, U - from Tatsumoto, 1969, Table 2; and $\text{Sr}^{87/86}$ data from Gast 1966, Table 2).
15. Average oceanic alkali basalt. (Data from Engel et al., 1965; except Th, U data for Hawaiian alkali basalts from Heier et al., 1964; and $\text{Sr}^{87/86}$ data from Gast, 1966 Table 2).
16. Average andesite, Montserrat. (Average of Table 12, Nos. 17-44; Table 14, Nos. 18, 20, 24, 27, 28, 33, 34, 37, 38, 43; Table 15, Nos. 7-12).
17. Average two-pyroxene andesite, Montserrat. (Average of Table 12, Nos. 17, 18, 20, 21, 23-28, 30, 35, 36, 39; Table 14, Nos. 18, 20, 24, 27, 28; Table 15, No. 7).
18. Average hornblende-hypersthene andesite, Montserrat. (Average of Table 12, Nos. 32, 33, 34, 37, 38, 39, 40, 42, 43, 44; Table 14, Nos. 33, 34, 37, 38, 43; Table 15, Nos. 8-12).
19. Average andesite, base of Andesite Coarse Fall Zone, White River Pyroclast Fall Series. (Average of Table 12, Nos. 25, 26, 28, 29, 30; Table 14, No. 28).
20. Average andesite, Soufriere Hills, Montserrat. (Average of Table 12, Nos. 24, 33, 35, 37, 38, 40, 42, 43; Table 14, Nos. 24, 33, 37, 38, 43).
21. Average andesite, St. Kitts. (Data from Baker, 1968a, Table 6, Nos. 10-23; Table 7, Nos. 10-14, 16-22; Donnelly et al., 1969, Table 3, No. 10).
22. Average andesite, Dominica. (Data from Robson and Tomblin, 1966, Table 7, Nos. 1-4; Table 8, No. 1; Donnelly et al., 1969, Table 1, TD 1701, TD 1824, Table 3, No. 12, 13).
23. Average andesite, Martinique. (Data from Robson and Tomblin, 1966, Table 9, Nos. 1-5, 8; Nockolds and Allen, 1953, Table 6, Nos. 3, 8, 9).
24. Average andesite, St. Lucia. (Data from Tomblin, 1964, Table 12, Nos. 6-12, Table 14, Nos. 203, 38, 290; Donnelly et al., 1969, Table 1, TD 1685, Table 3, Nos. 14, 15).
25. Average andesite, St. Vincent. (Data from Robson and Tomblin, 1966, Table 11,

Table 16A Continued....

- Nos. 2, 3, 6, 8).
26. Average andesite, Cascades. (Data from Coombs and Howard, 1960, p. 5, Nos. 1, 2; p. 10, Nos. 1, 3; p. 15, No. 2; p. 26, No. 2; p. 32, D. E. G. H; p. 37, Nos. 1, 2; p. 46, No. 13; Williams, 1935, p. 295, Nos. 6, 7; Turner and Verhoogen, 1960, Table 28, Nos. 4, 5; Nockolds and Allen, 1953, Table 2, Nos. 4, 5, 6, 7; Table 3, No. 8; Table 7, Nos. 4, 5, 6, 7, 8).
27. Average low-K andesite, Saipan. (Data from Taylor, 1969, Tables 1-6, No. 3).
28. Average andesite. (Analyses from Western United States, New Guinea, New Zealand, Bougainville, Japan. Taylor, 1969, Tables 1-6, No. 4).
29. High-K andesite, Bougainville. (Data from Taylor, 1969, Tables 1-6, No. 5).
30. Average dacite, Montserrat. (Average of Table 12, Nos. 45, 46; Table 14, No. 46).
31. Average dacite, St. Lucia. (Data from Tomblin, 1964, Table 12, Nos. 13, 14, 16, 17, 18, 20, 21, 22; Table 14, Nos. 13, 87; Donnelly et al., 1969, Table 1, ID 1827).
32. Average dacite, Cascades. (Data from Coombs and Howard, 1960, p. 10, Nos. 2, 4; p. 15, Nos. 3, 4; p. 23, No. 2; p. 32, A, B, C; p. 46, Nos. 1-7; Williams, 1935, p. 295, No. 8; Turner and Verhoogen, 1960, Table 28, Nos. 6, 7, 8; Nockolds and Allen, 1953, Table 2, Nos. 8, 9; Table 3, No. 3; Table 7, Nos. 10, 11, 12, 13).
33. Pyrolite upper mantle. (Major elements from D. H. Green and Ringwood, 1967, Table 20; Minor elements from Taylor, Kaye et al., 1969a, p. 283, and computed from data in Engel et al., 1965 and Goles, 1967, Table 11.1 using the pyrolite model of Ringwood, 1962).
34. Deep sea clay. (Data from Turekian and Wedepohl, 1961).

- Notes. 1. All major element analyses in Table 16 corrected to 100%.
2. Comparative chemistry of ultrabasic cumulate blocks from Montserrat and elsewhere in the Lesser Antilles is given in Table 17.

CHAPTER 17.

PETROGENESIS.

The following processes, either singly or in combination have sometimes been considered important in the petrogenesis of calc-alkaline lavas:-

1. Fractional crystallisation of basaltic magma under strongly oxidising (Osborn, 1959) or hydrous (Green and Ringwood, 1968) conditions.
2. Partial melting of a wide variety of source materials including lower crustal material (Hess, 1960), wet peridotite (O'Hara, 1965; Yoder, 1969a), quartz eclogite (Green and Ringwood, 1968), and basalt (Green and Ringwood, 1968, Taylor, Capp et al., 1969).
3. Contamination of basaltic magma by sialic material (e.g. Daly, 1933; Kuno, 1959), or mixing of basaltic and siliceous magmas (e.g. Larsen et al., 1936).
4. Gas transfer (Stanton, 1968).

The aim of this chapter is an assessment, in the light of the evidence presented in this thesis, of the relative importance of these processes in the petrogenesis of the Montserrat lavas. The implications of the present work for theories of petrogenesis of other calc-alkaline lavas from the Lesser Antilles and elsewhere will also be considered.

17:1 THE ROLE OF FRACTIONAL CRYSTALLISATION.

17:1:1 Current Theories.

Investigation of the behaviour of the experimental systems, $\text{MgO} - \text{FeO} - \text{Fe}_2\text{O}_3 - \text{SiO}_2$ and $\text{MgO} - \text{FeO} - \text{Fe}_2\text{O}_3 - \text{CaAl}_2\text{Si}_2\text{O}_8 - \text{SiO}_2$ at different oxygen fugacities (Osborn, 1959, Hoeder and Osborn, 1966) has shown that the course of fractional crystallisation at constant total bulk composition (constant oxygen content, as in a closed system) is towards low oxygen fugacities and ferrogabbroic liquids (tholeiitic trend). With fractional crystallisation at constant oxygen fugacity (variable oxygen content) the change in liquid composition is towards increasing silica and decreasing iron oxide as soon as

magnetite begins to crystallise (calc-alkaline trend). Applying these results to natural systems Osborn (1969a) has suggested that orogenic andesites are derived by the fractional crystallisation of basalt in the lower crust under conditions of high oxygen fugacity and that Alpine peridotites represent the complementary crystal cumulates.

Approaching the problem from a different angle namely a high pressure investigation of the partial melting fields of synthetic rocks Green and Ringwood (1968) concluded that fractional crystallisation of hydrous basalt at 30 to 40 km. depth under conditions of $P_{H_2O} < P_{LOAD}$ was a possible method for the production of the calc-alkaline suite. Their investigations indicated the removal of a rather different extract (mostly clinopyroxene and amphibole with small amounts of orthopyroxene, ilmenite and plagioclase) than that which Osborn has shown to crystallise from the synthetic systems (plagioclase, pyroxene, olivine and magnetite).

17.1.2 Fractional Crystallisation On Montserrat.

The evidence outlined in Chapter 15 indicates that at least two periods of fractional crystallisation - one occurring at shallow depths and the other at intermediate depths in the crust - have affected the magmas which gave rise to the Montserrat rocks.

Fractional Crystallisation at Shallow Depths.

This stage of crystallisation probably takes place at pressures approaching one atmosphere (< 3 km. depth) and involves the separation of the common microphenocrysts and also some of the phenocrysts in the lavas though many of the latter may actually originate at deeper levels in the crust (p. 115). That some crystal fractionation takes place at this stage is indicated by the presence of cognate basaltic inclusions in some andesitic lavas and the composition of these (Table 12, No. 11) is such that their removal from an andesitic magma will result in an increase of SiO_2 , K_2O and Na_2O and a decrease in total iron and MgO in the residual liquid. In addition the similarity between the average Montserrat olivine-basalt, calculated phenocryst-free (Table 16, No. 3) and the aphyric basaltic scoriae (Table 12, No. 13) indicates that the latter might well

have been produced by the removal of crystals similar to those found as phenocrysts in the basalts, from a magma of the composition of the average olivine-basalt (Table 16, No. 2).

A comparison of analyses 2 and 3 in Table 16 also emphasizes the considerable effect of phenocrysts on the composition of the lavas. It is clearly important therefore to know if all the constituents in the lavas are co-magmatic since whole rock analyses will not bear any direct relationship to the composition of original magmas unless this is the case. Petrographic evidence suggests that the Montserrat lavas contain constituents with varied histories ranging from "old" phenocrysts with complex crystallisation histories to interstitial material deposited from late-stage fluids (p. 115-118). It is probable however that most of these different constituents crystallised from the same magma under different physical conditions rather than from different magmas so that in general the composition of the porphyritic lavas may approximate to that of the original magmas. Incorporation of xenocrystic material, accumulation or separation of certain minerals preferentially to others and late-stage alteration may change this original composition slightly but it seems unlikely that any very fundamental chemical changes are brought about by the operation of these processes at shallow depths.

Fractional Crystallisation at Intermediate Depths.

The ultrabasic cumulate blocks found at South Soufriere Hill and at other volcanoes in the Lesser Antilles (p. 103-108) are direct evidence for the fractional crystallisation of basaltic magma in the Lesser Antilles. On the basis of the mineralogy and chemistry of ultrabasic cumulates from St. Vincent Lewis (1964, p. 198-201) was able to make estimates of many of the physical parameters under which they formed. Similar reasoning can be applied to the Montserrat blocks as follows. The calcic plagioclase, magnesian olivine and aluminous amphibole (p. 106) in the Montserrat blocks indicate crystallisation at high temperatures. The abundance of amphibole reflects the high content of water in the original magma and the very high An content of the plagioclases is almost certainly another indication of crystallisation under high water vapour pressures

as suggested by experimental work on the Ab - An - H₂O system (Yoder et al., 1957; Yoder 1969b; see also Lewis, 1968⁹). The high Fe₂O₃/FeO ratios in the Montserrat blocks show that crystallisation took place at high oxygen fugacities, which factor is probably related to the high water content of the magma since oxygen is probably produced mainly by the dissociation of water according to the reaction $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$.

The coexistence of magnesian olivine and calcic plagioclase in the Montserrat cumulates restricts their origin to depths equivalent to pressures less than 7kb., at which pressure plagioclase and olivine react to produce two pyroxenes and spinel (Kushiro and Yoder, 1966; Yoder, 1966). In addition, Yoder and Tilley (1962) have shown that in general the effect of increasing water vapour pressure on the crystallisation of basalts is to lower the liquidus of plagioclase and the amount of plagioclase crystallising relative to other phases. At 9-10 kb. under hydrous conditions ($P_{\text{H}_2\text{O}} < P_{\text{LOAD}}$) calcic plagioclase is a minor phase occurring near the solidus (Green and Ringwood, 1968). Hence the presence of abundant calcic plagioclase along with amphibole in the Montserrat blocks indicates crystallisation at relatively low pressures and relatively shallow depths. A comparison of the sequence of crystallisation in the Montserrat blocks with that in the Warner high alumina basalt (Yoder and Tilley, 1962, Fig. 28) suggests that they are unlikely to have crystallised at water vapour pressures greater than 2,500 bars since under these conditions amphibole precedes plagioclase in the experimental system and there is no evidence of this relationship in the cumulates. On the basis of similar arguments and because plagioclase invariably precedes clinopyroxene as well as amphibole in the St. Vincent blocks, Lewis (1964, p. 202-204) suggested that these blocks might have crystallised at water vapour pressures of between 1,500 and 2,000 bars, corresponding to depths of between 6 and 8 km. The Montserrat blocks may have crystallised at similar depths.

The Montserrat ultrabasic cumulates occur within a block fall composed mainly of fragments of scoriaceous andesite of very uniform composition (p. 122). The block fall passes upwards without any apparent break in composition into a series of fine basaltic

pyroclast falls (p. 34) and this suggests that the upper two zones of the White River Pyroclast Fall Series may be the products of the emptying of a gravity differentiated magma chamber in which andesitic magma overlay magma of basaltic composition. The restriction of the ultrabasic blocks, which would presumably represent material from the bottom of the chamber, to andesitic horizons rather than basaltic ones might be due to the greater force of the andesitic eruptions.

In any case the close association of andesite, basalt and ultrabasic cumulate blocks at South Soufriere Hill is strongly suggestive of a genetic relationship whereby the andesites have been derived from basaltic magma by the removal of material of the composition of the blocks. To test this possibility the composition and the amount of material which must be removed from the average Montserrat olivine-basalt (Table 16, No. 2) to give the average White River Pyroclast Fall Series andesite (Table 16, No. 19) has been calculated according to the method outlined in Appendix 2 (p. 179). In Table 17 the composition of this material is compared with that of ultrabasic cumulates from Montserrat and elsewhere in the Lesser Antilles. The calculated extract (Table 17, No. 1) and the average Montserrat cumulate (Table 17, No. 3) contain similar amounts of SiO_2 , Fe_2O_3 , MnO , MgO , CaO , Na_2O , P_2O_5 , Ni and Sc . The calculated abundances of the other elements are however somewhat different from their abundances in the cumulates and agreement is particularly bad for total iron, TiO_2 , V , K_2O , Zr and Sr .

Clearly there are many uncertainties in these calculations. For a start more analytical data are required as, for example, the trace element abundances in the andesites are based on a single analysis but there are more fundamental difficulties than this. Thus one does not know whether the analysed blocks are representative of the material removed from the basalt or whether the olivine-basalt lavas approach the composition of the original basaltic magma or how much if any, allowance should be made in the calculations for the effect of the phenocrysts on the composition of the lavas.

As regards the first point the differences between the Montserrat ultrabasic blocks and ultrabasic blocks from elsewhere in the Lesser Antilles and in other calc-alkaline

TABLE 17. CALCULATED COMPOSITIONS OF EXTRACTS REQUIRED TO PRODUCE MONTSERRAT ANDESITES FROM THE AVERAGE MONTSERRAT OLIVINE-BASALT, COMPARED WITH THE COMPOSITION OF EJECTED CUMULATE BLOCKS FROM THE LESSER ANTILLES.

	1	2	3	4	5	6	7
SiO ₂	43.3	43.3	43.3	42.2	42.5	42.4	42.4
TiO ₂	1.3	1.1	0.8	1.0	1.4	0.9	1.0
Al ₂ O ₃	19.8	21.5	24.2	21.5	16.4	25.6	21.3
Fe ₂ O ₃	3.8	3.3	3.9	3.6	11.4	4.3	4.4
FeO	8.1	7.5	4.2	5.8		5.6	5.5
MnO	0.2	0.2	0.1	0.1	0.1	0.1	0.1
MgO	7.5	6.3	7.3	10.6	11.7	5.3	9.4
CaO	13.1	13.2	14.2	14.5	14.3	14.4	14.4
Na ₂ O	2.1	2.7	1.9	0.6	1.9	1.3	1.3
K ₂ O	0.8	0.8	0.1	0.1	0.3	0.1	0.1
P ₂ O ₅	0.0	0.1	0.0	0.1	0.0	0.1	0.1
Ba	-20	21	29				
Sr	475	295	290				
Zr	45	47	5				
Cu	140	141	88				
Co	54	37	98				
Ni	23	7	33				
Sc	57	56	39				
V	590	531	292				
Cr	35	34	15				
% of Parent Magma Removed	46.6	50.1					

1. Calculated composition of material, 46.6% of which removed from the average Montserrat olivine-basalt (Table 16, no. 2) would give a residue with the composition of the average White River Pyroclast Fall Series andesite (Table 16, no. 19).
2. Calculated composition of material, 50.1% of which removed from the average Montserrat olivine-basalt (Table 16, no. 2) would give a residue with the composition of the average Soufriere Hills andesite (Table 16, no. 20).
3. Average Montserrat ultrabasic cumulate block (Average of nos. 1 and 2, Table 12).
4. Average of 4 analyses of ejected ultrabasic blocks from St. Vincent (Lacroix 1949, nos. 8, 9, 10, 11, p. 587).
5. Average of 2 analyses of ejected ultrabasic blocks from Carriacou, Grenadines (T. A. Jackson, pers. comm.).
6. Analysis of hornblende-eucrite block from Mt. Misery, St. Kitts (Baker, 1968, Table 6, no. 1).
7. Average of 9 analyses of ultrabasic cumulates from Montserrat, St. Vincent, Carriacou and St. Kitts.

suites (p. 106) may be significant. Blocks containing only anorthite and olivine, which are quite common in other suites have not been found on Montserrat and the Montserrat blocks contain higher proportions of amphibole but less olivine and clinopyroxene than blocks from elsewhere. Lewis (1964, Chapter 11) has shown that of the blocks from the Soufriere volcano, St. Vincent the anorthite-olivine blocks were the first to form, so that if the course of crystallisation below South Soufriere Hill was the same as that at St. Vincent the analysed amphibole-bearing blocks will represent only a part of the total crystal extract. The absence of anorthite-olivine blocks in the White River Pyroclast Fall Series might be due to a less violent eruption than that which occurred at St. Vincent disrupting material only from the top of the crystal pile. It is possible therefore that the composition of the average St. Vincent block (Table 17, No. 4) or of the average Lesser Antillean cumulate (Table 17, No. 7) might give a better indication of the composition of material removed from the Montserrat basalt but even these must be regarded as an inadequate guide since they are the average of very few analyses and it is impossible to estimate the relative importance of the different types of block in the total extract. If however the average St. Vincent or Lesser Antillean block rather than the average Montserrat blocks is representative of the material removed from the Montserrat basalt the amounts of Al_2O_3 and total iron in the residual liquid would be much closer to the values actually found in the White River Pyroclast Fall Series andesites.

It seems possible therefore to account for most of the observed differences in the composition of the Montserrat olivine-basalts and the White River Pyroclast Fall Series andesites in terms of an extract of similar composition to the Montserrat, St. Vincent or Lesser Antillean ultrabasic blocks. It is difficult however to account for the differences in K_2O and probably also in total iron, TiO_2 , V and Cr in the basalts and andesites in this way so that fractional crystallisation may not be the only process controlling the behaviour of these elements. Thus gas transfer may play an important role in producing the observed differences in K_2O contents (p. 173). As regards the

other elements that show major discrepancies it may be significant that they are all typically concentrated in ore minerals so that processes like the accumulation of magnetite in the basalts might account for the observed discrepancies. There is however, little evidence for this except that the Montserrat basalts contain slightly greater amounts of modal magnetite than the andesites. Another possibility is that the analysed ultrabasic blocks are poorer in magnetite than the crystal extract as a whole. This is apparently the case with the analysed ultrabasic blocks from Montserrat which contain an average of only 1.15% modal magnetite compared with an average of 6.0% for the Montserrat blocks as a whole. It is not possible to say whether or not this is also the case with the St. Vincent blocks since Lacroix (1949) did not present modal analyses of the analysed blocks.

It is clearly impossible at the present time to say definitely whether or not the andesites of the White River Pyroclast Fall Series have formed by the fractional crystallisation of basaltic magma but as the lavas of South Soufriere Hill show a complete compositional gradation from basalt to andesite and andesitic pyroclastics at this volcano contain ultrabasic cumulates with approximately the same composition as the extract required in such a process there is a strong possibility that this is the case.

It is also possible to account for many of the chemical characteristics of andesites from the other Montserrat volcanoes by a similar process. For example to produce the average Soufriere Hills andesite (Table 16, No. 20) from the average South Soufriere Hill olivine-basalt requires the removal of 50.1% of material, the composition of which (Table 17, No. 2) approximates to that of the average Montserrat ultrabasic block. However, because of the greater volume of andesite at the Soufriere Hills and because the andesites are richer in SiO_2 than those at South Soufriere Hill a greater volume of basaltic magma would be required to produce these andesites than is required to produce the andesites at South Soufriere Hill. Basalts do not however occur among the products of this volcano.

It is likely of course that the relative volumes of andesite and basalt at the surface do not reflect their relative volumes at depth due perhaps to the preferential eruption of andesite (Kuno, 1968). It is important also to remember that the islands of the Lesser Antilles represent only the uppermost parts of what may be thick volcanic piles (p. 169) and there is no reason to suppose that the lavas on the islands are representative of the composition of the whole pile. Various lines of evidence suggest that the proportion of basalt to andesite increases with depth. For example, gravity and seismic refraction data for the Lesser Antilles can be interpreted as indicating the presence of a considerable thickness of basaltic material beneath the arc (p. 4). The recent demonstration by Baragar and Goodwin (1969, p. 141) that salic components increase with increasing stratigraphic level in Archaen calc-alkaline volcanic belts of the Canadian Shield and that the overall average composition of these belts is somewhere between that of tholeiitic basalt and andesite is also of interest.

In view of these considerations it is obvious that the preponderance of andesite among the products of a volcano does not rule out the possibility that these andesites were produced by the fractional crystallisation of basaltic magma and the data given in Table 17 indicate the chemical feasibility of such a process in the production of the Soufriere Hills andesites. However all the volcanoes on Montserrat, apart from South Soufriere Hill are characterised not by a preponderance of andesite over basalt but by a complete lack of basalts, basaltic andesites and ultrabasic cumulate blocks so that the fractional crystallisation of basaltic magma is a rather unlikely mechanism for the production of andesites at these volcanoes.

It appears therefore that the volcanoes on Montserrat reflect the pattern in the Lesser Antilles as a whole, where two different types of volcano have been recognised (p. 75). It is probable that andesites at volcanoes like South Soufriere Hill, where there is a compositional gradation from basalt to basaltic andesite to two-pyroxene andesite and where ultrabasic cumulates occur, have been produced by the fractional crystallisation of basaltic magma. On the other hand it is less likely that andesites

at volcanoes like the Soufriere Hills, which have erupted nothing but andesite, have formed by this mechanism (Tomblin, 1968; Rea, 1969). Most volcanoes in the Lesser Antilles belong to the second category but examples of the first type include Soufriere, St. Vincent, Mt. St. Catherine, Grenada and Mt. Misery, St. Kitts as well as South Soufriere Hill. The Soufriere volcano, St. Lucia (Tomblin, 1964) is somewhat different from other volcanoes in that it has erupted some basalt together with a large amount of andesite and dacite. However, no ultrabasic cumulates have been found and there is a large compositional break between the basalts and the andesites so that the fractional crystallisation of basaltic magma may not be the mechanism by which the andesites are produced at this volcano.

17:1:3 Comparison of Fractional Crystallisation in the Lesser Antilles with Fractional Crystallisation in Experimental Systems.

Before leaving the subject of fractional crystallisation it is necessary to compare the process of fractional crystallisation outlined in the previous section with the processes put forward by Osborn (1959) and T. H. Green and Ringwood (1968) to account for the petrogenesis of the calc-alkaline suite.

The process suggested by T. H. Green and Ringwood (1968, pp. 112-113) involves the fractional crystallisation of wet basalt at 9-10 kb. ($P_{\text{LOAD}} > P_{\text{H}_2\text{O}}$) corresponding to depths of 30-40 km. The process involves the removal of amphibole and to a lesser extent clinopyroxene and possibly also orthopyroxene, calcic plagioclase and garnet from a high-alumina basalt parent. Osborn (1959), on the other hand suggests a process involving the separation of plagioclase, pyroxene, olivine and magnetite from a high alumina basalt under conditions of high oxygen fugacity somewhere in the lower crust. In a later paper the same author (Osborn, 1969^a) has suggested that Alpine peridotites represent the "complementary" crystal cumulates from this process. Osborn (1969^a, p. 317-318) considers that the absence of plagioclase from the peridotites is a result of the suppression of plagioclase crystallisation at high water vapour pressures and the tendency of plagioclase to float rather than sink in basaltic liquids.

Clearly the processes envisaged by Osborn and by T. H. Green and Ringwood are taking place at greater depths than the crystallisation of which the Antillean ultrabasic cumulates are evidence. They are also taking place on a larger scale since it is proposed, on Osborn's theory at any rate, that all andesites have formed in this way whereas only a few of the Lesser Antillean andesites are thought to have been derived by the fractional crystallisation of basaltic magma. The mineralogy of the extracts also differs from that of the Lesser Antillean cumulates. Thus, T. H. Green and Ringwood's extract contains very little plagioclase and no olivine and although the analysed amphiboles are quite similar in composition to analysed amphiboles from the St. Vincent blocks (compare T. H. Green and Ringwood, 1968; Table 24 and Lewis, 1964; Table 28) the analysed clinopyroxenes contain more Al_2O_3 than the St. Vincent clinopyroxenes (T. H. Green and Ringwood, 1968. Table 23 and Lewis, 1964. Table 20) and the plagioclases (An_{66} - T. H. Green and Ringwood, 1968. Table 25) are much less calcic (An_{96-90} - Lewis, 1969. Table 9). The extract obtained by Osborn is quite similar to that in the Antillean blocks except that it does not contain amphibole, which is hardly surprising since Osborn has not yet added water to his experimental systems.

It is apparent therefore that the processes of fractional crystallisation proposed by Osborn (1959) and T. H. Green and Ringwood (1968) to account for the petrogenesis of andesites differ in many ways from the fractional crystallisation which produced the Lesser Antillean ultrabasic cumulates. Nevertheless it is still possible that most of the andesites in the Lesser Antilles have been derived by processes like those suggested by Osborn or T. H. Green and Ringwood and that the fractional crystallisation of basalt indicated by the Lesser Antillean cumulates is a minor high level process superimposed on a much more extensive fractional crystallisation at depth. There is however no direct evidence to support such an assumption and there is some evidence against it.

For a start, the volume problem is obviously more acute in the case of theories which advocate the formation of all andesites and dacites by the fractional crystallisa-

tion of basaltic magma than for theories which advocate the production of only small amounts of rather basic andesite. Again, it is difficult to see why small amounts of basaltic magma should rise to relatively high levels in the crust before fractionation begins while the main mass of basaltic magma fractionates at greater depths.

More particularly Taylor, Kaye et al., (1969a) have criticized Osborn's mechanism for the production of andesites on the grounds that the similar concentrations of V and Ni in high alumina basalts and andesites mean that the andesites cannot be derived from the basalts by processes which involve the removal of large quantities of magnetite (which is rich in V) or olivine (which is rich in Ni). Although Taylor's interpretation of the data has been challenged (Osborn, 1969b) and trace element variation may be affected by many factors including concentration of volatiles (Ringwood, 1955, p. 249), wall rock reaction (D. H. Green and Ringwood, 1967), contamination or gas transfer (see p. 173) this is probably a valid criticism (Taylor, Kaye et al., 1969b). Removal of much clinopyroxene as in the fractionation scheme proposed by T. H. Green and Ringwood (1968) might also deplete the residual liquid in Ni beyond the values typical of andesites. Another crucial objection to Osborn's theory concerns the crystallisation of plagioclase. Under the conditions of fractionation suggested by T. H. Green and Ringwood (1968) plagioclase is a minor phase occurring near the solidus and Osborn (1969^a) has suggested that plagioclase is rare in Alpine peridotites either because high water vapour pressures suppress its crystallisation or because it tends to float rather than sink in basaltic magmas. There is, however, definite evidence that plagioclase, far from being suppressed is an early phase to crystallise in dacites, andesites, basalts and ultrabasic cumulates from the Lesser Antilles and the abundance of plagioclase in the latter is evidence that plagioclase sinks rather than floats in basaltic magmas in the Lesser Antilles. In any case it seems unlikely that plagioclase would be rare in cumulates formed by the fractional crystallisation of basalt at the depths and water vapour pressures ($\sim$ 600 bars) envisaged by Osborn. The crystallisation of plagioclase from basaltic magmas is not significantly suppressed at water vapour pressures of 600

bars (Yoder and Tilley, 1962) and at much higher water vapour pressures amphibole, which like plagioclase is not a prominent constituent of Alpine peridotites will be an important phase. Therefore, even allowing for the fact that high oxygen fugacities may suppress plagioclase crystallisation (Hamilton et al., 1964) it seems unlikely that the crystal cumulates formed from basalt magma crystallising under the conditions envisaged by Osborn will have the composition of Alpine peridotite. In addition, there is no evidence whatsoever for the existence of crystal cumulates of the sort expected from T. H. Green and Ringwood's process.

17:1:4 Summary.

There is evidence for two major periods of crystallisation in the Montserrat rocks. One of these, which occurs near the surface at low pressures probably has little fundamental petrogenetic significance. The other, which occurs deeper in the crust (6-8 km.), involves the separation of sub-silicic crystal aggregates from basaltic magma and is probably instrumental in producing andesites at the South Soufriere Hill centre. It is unlikely that andesites at the other volcanoes on Montserrat have been produced either by this mechanism or by the large scale fractionation processes of basaltic magma proposed by Osborn (1959) or T. H. Green and Ringwood (1968). It is therefore necessary to consider other possible methods of petrogenesis for these andesites and the ultimate source of the Montserrat basalts must also be considered. Chemical evidence suggests that these problems are closely connected. The Montserrat basalts and andesites show similar chemical characteristics (p. 41) and there appears to be very little chemical difference between those two-pyroxene andesites, which are presumed to have been derived by the fractional crystallisation of basalt, and those for which this mechanism appears to be inappropriate (p. 42). A possible explanation of this is that both basaltic and andesitic magmas are derived by different degrees of partial melting of the same source rock. This possibility is investigated in the next section.

17:2 THE ROLE OF PARTIAL MELTING.

In general the role played by partial melting in the petrogenesis of the calc-alkaline suite is very difficult to assess as direct evidence - in the form, say, of residual refractory material is either absent or very difficult to recognise. In this section, therefore, possible source rocks are examined mainly with regard to their chemical suitability and their likely availability in orogenic areas.

17:2:1 The Partial Melting of Lower Crustal Material.

Hess (1960 p. 179-184) suggested that the partial melting of crustal rocks could produce an andesitic liquid. More recently this mode of origin has been proposed for andesites and dacites in areas like St. Lucia (Tomblin, 1964, p. 179-184) or Alaska (Forbes et al., 1969) where there is little or no basalt.

It is difficult however, to produce basaltic liquids by this process so that the partial melting of crustal material is an unlikely mechanism for the petrogenesis of the Montserrat basalts and it is also an unlikely mechanism for the production of the Montserrat andesites which appear to be chemically related to the basalts (p. 44). In any case temperatures at the base of the crust are almost certainly insufficient for the generation of andesites (Osborn 1969a, p. 306-309).

The low $\text{Sr}^{87/86}$ ratios and the low contents of K, Rb, Ba, U and Th (Tables 14 and 15) severely limit the possible role of old continental crust in the petrogenesis of the Montserrat lavas or calc-alkaline lavas in general (Taylor and White, 1965). These chemical constraints do not however apply to relatively young volcanic material which may be an important constituent of the crust immediately beneath island arcs and material of this type may have played an important "secondary" role in the petrogenesis of the Montserrat lavas as discussed in section 17:3:5.

17:2:2 The Partial Melting of Peridotite.

O'Hara (1965) suggested that the partial fusion of peridotite at depth under water saturated conditions, in a low pressure regime, to give andesitic liquids is an

important process contributing to the formation of calc-alkaline rocks. Yoder (1969) came to an essentially similar conclusion based largely on an experimental investigation of the system:- $\text{Di} - \text{Fo} - \text{SiO}_2$ with and without water, at high pressures (Kushiro, 1969). According to Yoder (1969, p. 85-86) calc-alkaline andesites are likely to be the partial melting product of peridotite under hydrous conditions whereas under anhydrous conditions tholeiitic basalt is the product of partial melting. The high-alumina basalts are also derived from peridotite by partial melting under hydrous conditions but at higher temperatures than the andesites. T. H. Green and Ringwood (1968, p. 113) also suggest that the high alumina basalts associated with the calc-alkaline suite are derived by partial melting in the upper mantle though in this case the suggested source rock is pyrolite rather than peridotite. However, T. H. Green and Ringwood imply that the high alumina basalts are only indirectly related to the andesites in the sense that the generation of andesitic magma by partial melting of quartz eclogite or amphibolite may cause instability and melting of pyrolite elsewhere in mantle, giving rise to basaltic magmas.

The writer has already stressed (p. 155) that the chemical data presented in Chapter 16 point to a genetic link between basalts and andesites on Montserrat and this suggests that T. H. Green and Ringwood's (1968) model for the independent production of high alumina basalts and andesites is not applicable to the Montserrat rocks. There are also geochemical and other objections to peridotite as a source rock for andesites. The principal difficulty is that the contents of certain ferromagnesian trace elements notably Ni in high alumina basalts and andesites are too low for these rocks to have been derived in a single stage from a peridotite mantle (see e.g. Taylor, Kaye et al., 1969a). As discussed in section 17:2:4 the chemical characteristics of high alumina basalts from Montserrat and elsewhere favour derivation from the mantle by a two stage process. Another objection to peridotite as a source rock is that the descent of cold lithosphere along Benioff Zones beneath island arcs may mean that temperatures high enough for the melting of peridotite are not reached in the areas of the mantle where andesites originate (p. 162).

17:2:3 The Partial Melting of Quartz Eclogite.

T. H. Green and Ringwood (1968) have shown that the partial melting of quartz eclogite at pressures of 30-40 kb., corresponding to depths of between 100 and 150 km., is a possible method for the petrogenesis of the calc-alkaline suite. Under these conditions andesites are produced in the dry and dacites are produced by wet melting. Previously, D. H. Green and Ringwood (1966) had proposed a mechanism for obtaining oversaturated quartz eclogite compositions in the upper mantle. According to this model large piles of basalt, derived by partial melting of pyrolite in the mantle, accumulate in orogenic areas. With the cessation of this basaltic volcanic activity the geotherms in the orogenic area fall and the deeper regions of the basaltic pile transform to eclogite. The eclogite, being denser than the ultramafic upper mantle begins to sink and eventually reaches a level in the mantle (probably at depths of 100-150 km.) where the temperature is high enough to cause partial melting of the eclogite.

The overall mechanism envisaged by T. H. Green and Ringwood is therefore a two-stage partial melting process and as such is not open to many of the geochemical criticisms which can be made of processes which seek to derive andesites in a single stage from the mantle (see section 17:2:4). Nevertheless, Taylor, Kaye et al., (1969a) have criticized T. H. Green and Ringwood's theory on geochemical grounds. They have shown (op. cit., p. 279-283) that dry partial melting of eclogite whether by equilibrium or non-equilibrium melting will not produce the high V/Ni ratios typical of calc-alkaline rocks (see e.g. Table 14). Melting of the garnet phase alone could produce the right ratios but high Ni concentrations will be contributed by the melting of clinopyroxene.

In addition all theories involving the generation of andesites and dacites at depth in the mantle must somehow account for the fact that the andesites and dacites, which may contain up to 70% SiO_2 reach the surface without undergoing extensive reaction and desilification with the olivine-bearing peridotites through which they must pass on the way up (Osborn, 1969a, p. 309).

17:2:4 Partial Melting of Basalt.

T. H. Green and Ringwood (1968) have suggested a method for the petrogenesis of the calc-alkaline suite by the partial melting of basalt at 9-10 kb. (30-40 km.) under wet conditions ($P_{H_2O} < P_{LOAD}$). It is proposed that this melting takes place at the base of the basalt pile developed in orogenic areas as described in the previous section so that this is essentially a complementary process to the petrogenesis of the calc-alkaline suite by the partial melting of quartz-eclogite. The partial melting of wet basalt is also comparable to the fractional crystallisation of wet basalts, under the same conditions, as described in section 17:1:1. Both T. H. Green and Ringwood's models can be linked to the hypothesis of sea-floor spreading but the hypothesis of the wet melting of basalt is not subject to the geochemical criticisms which can be made of the eclogite model (p. 158).

Recently, there have been other successful attempts (e.g. Taylor, Capp et al., 1969) to fit a two-stage process for the generation of andesitic magma from the mantle to models based on sea-floor spreading described for example by Isacks et al. (1968) and Raleigh and Lee (1969). This section will attempt to show how such a model might apply to the petrogenesis of calc-alkaline volcanics in Montserrat and in the Lesser Antilles as a whole. It is first necessary to examine the available chemical data to see why a two-stage derivation from the mantle seems to be required.

It is generally agreed that the chemical characteristics of the upper mantle include high contents of MgO, Ni, Co, Cr; low contents of K_2O , Rb, Ba, Sr, Th, U; high $MgO/Fe_2O_3 + FeO$ and Ni/Co ratios and low V/Ni, Th/U and $Sr^{87/86}$ ratios (Table 16, No. 34). It is therefore reasonable to suppose that primary liquids formed by melting in the upper mantle will have somewhat similar characteristics. Oceanic tholeiites (Table 16, No. 14) may be close to the composition of such primary liquids (T. H. Green and Ringwood, 1967) and their compositional similarity to Ca achondrites is further evidence for their primitive nature. Compared with oceanic tholeiites, basalts and andesites from Montserrat (Table 16, Nos. 1 and 16) and elsewhere in the Lesser Antilles are enriched in Al_2O_3 , K_2O , P_2O_5 , Rb, Sr, Ba, Th, U; depleted in MgO, TiO_2 , Ni and Cr and have high $FeO +$

$\text{Fe}_2\text{O}_3/\text{MgO}$, Co/Ni , Rb/Sr and Rb/K ratios. Although the abundance data for some of these elements e.g. K, P, Ba, Sr, Rb is of doubtful significance because concentrations of these elements are not always determined by simple processes of crystal fractionation or melting in closed systems (Ringwood, 1966; Harris, 1967; this thesis - sections 17:3 and 17:4) the low values of MgO , Ni , Cr and Mg/Fe and Ni/Co ratios in the Lesser Antillean lavas strongly suggest that these lavas are derivative types.

Taylor, Kaye et al. (1969a, p. 283) suggest values of 1,000 p.p.m. Ni; 100-200 p.p.m. Co and 1,000 - 5,000 p.p.m. Cr in the mantle and the content of MgO is probably about 35% (Table 16, No. 34). Oceanic tholeiites (Table 16, No. 14) which presumably represent primary liquids derived from this material (O. H. Green and Ringwood, 1967) average about 100 p.p.m. Ni; 30 p.p.m. Co; 80 p.p.m. Cr and 8% MgO . If these figures give a realistic indication of partition values of Ni, Co and Cr between melt and residue in the mantle it seems unlikely that melts containing about 6-12 p.p.m. Ni, 6-18 p.p.m. Cr and Ni/Co ratios of about 0.4 which are the values, found in andesites and basalts from Montserrat, (Table 16, Nos. 1, 16) could be produced by a single stage of partial melting in the upper mantle. Of course the partition values are likely to be different for wet melting (e.g. Ringwood, 1955) but a difference of at least an order of magnitude would be necessary to account for the Ni values in the Montserrat basalts and andesites. Similar considerations apply to other lavas from the Lesser Antilles (Lewis, 1968b) and from calc-alkaline suites in general (Taylor, Kaye et al., 1969a). It may be that certain MgO - rich basalts from the Lesser Antilles (e.g. Table 16, No. 9), the Solomon Islands (Stanton and Bell, 1969) and other calc-alkaline suites might have been derived in a single stage from the mantle but these basalts might equally well be accumulative types formed by the crystal settling of olivine and clinopyroxene. Basalts of this type were not found on Montserrat.

Although the derivation of calc-alkaline basalts and andesites from the mantle by two stages of partial melting is favoured it must be admitted that the chemical data presented above could be interpreted in other ways. For example the high-alumina basalts

and andesites could be derived from a mantle which has been depleted in MgO , Ni , Co and Cr and enriched in K_2O , Rb , Ba , Sr , Th , U etc. or alternately oceanic tholeiites might be derived from a residual or depleted layer in the upper mantle from which many elements such as the radioactive elements have been transported to the crust (Tatsumoto et al., 1965). Again primary basalt generated by partial melting of typical upper mantle material might undergo fractionation at depths of about 30 km. where forsterite and possibly enstatite separate, increasing the Al_2O_3 content and the Fe/Mg and Co/Ni ratios in the residual liquid (D. H. Green and Ringwood, 1967; Lewis, 1968b). There is, however, no direct evidence for the operation of either of these processes and a layer of atypical composition in the mantle would have to be quite thick to give rise to sufficient andesite and high alumina basalt to build an island arc.

A more reasonable model for the derivation of the calc-alkaline suite stems from the concept that the ocean floor descends beneath island arcs, a concept supported by much geophysical evidence (e.g. Raleigh and Lee, 1969, p. 99-107). The descent of the ocean floor is marked by a narrow, planar zone of seismic activity known as the Benioff Zone which dips at about 45° towards the continental side of the island arc (Benioff, 1954), by a zone of negative gravity anomalies (Vening Meinesz, 1934), by a deep ocean trench and by low heat flow (Lee, et al., 1966). According to the two-stage model for the mantle derivation of the calc-alkaline suite (e.g. Taylor, Capp et al., 1969) basalt generated by partial melting in the mantle beneath mid-ocean ridges is transported as ocean crust and re-enters the mantle along the Benioff Zone where it undergoes varying degrees of partial melting to produce the different magmas of the calc-alkaline suite. This hypothesis is now examined critically in the light of evidence from Montserrat and the Lesser Antilles.

The Lesser Antilles has all the tectonic features normally associated with island arcs but there is some variation between the northern and southern parts of the arc. North of Dominica the Lesser Antilles is a double arc with a trench on the ocean side of the older arc, a Benioff Zone and relatively intense seismic activity. The southern

part of the Lesser Antilles, on the other hand is a single arc and the trench gives way southwards to the Barbados Ridge although the negative gravity anomaly continues through this feature. Earthquakes beneath this part of the arc also lie in a Benioff Zone but there is less seismic activity than in the northern part of the arc (p. 5). This suggests that although underthrusting of the sea floor occurs along the entire length of the Lesser Antilles the rate of underthrusting may be greater in the northern part of the arc than in the south. It is interesting to note that an inverse correlation between the rate of underthrusting, as indicated by the frequency of earthquakes along the Benioff Zone, and the thickness of sediment in the trench has been reported for other trenches including the Tonga-Kermadec trench (Raleigh and Lee, 1969, p. 105) and the Peru-Chile trench (Gutenberg and Richter, 1954).

The oceanic crust consists of three seismic layers overlying the Moho. There is no universal agreement about the composition of the three layers but layer one consists of about 0.2 km. of unconsolidated sediment. Layer two which is about 1.7 km. thick is composed of basalt, mostly tholeiitic in character. The composition of layer three which is about 4 km. thick is in dispute but probably consists of oceanic tholeiite (low K-tholeiite) although serpentinite is a possible alternative. There is also doubt about how much of this material is actually carried into the mantle. According to Talwani and Hayes (1967) much of the sediment may be scraped off and thrust under the continental side of the trenches. Heat flow measurements in island arcs suggest that of the material that does descend into the mantle along the Benioff Zone only the sedimentary and basaltic material are likely to melt (Oxburgh, 1969). The heat available is unlikely to be sufficient for melting of the peridotite which presumably underlies layer three especially if this peridotite has given up its low-melting basaltic fraction at the mid-ocean ridge.

Chemically oceanic tholeiite is a likely parent for the calc-alkaline suite (Taylor, Capp et al, 1969; p. 16-17) and basalts with very strong compositional affinities to oceanic tholeiites are common in certain island arcs e.g. the South Sandwich

Islands (Table 16, No. 11) and may be represented in the Lesser Antilles by the rare aphyric basalts from St. Lucia (Table 16, No. 7). In any case oceanic tholeiites have almost identical contents of total iron, Na_2O , Zr, V, Cu and Li and similar contents of Al_2O_3 , CaO and Sc to basalts and andesites from Montserrat. MgO, Ni and Cr contents and Ni/Co ratios are lower in the Montserrat lavas than in oceanic tholeiites but the values of these elements in the former is consistent with a two-stage derivation from the mantle (p. 159). Certain elements including K, Rb, Ba, Th and U are low in both the oceanic tholeiites and the Lesser Antillean lavas but these elements are enriched in the Lesser Antillean lavas by 1-3 orders of magnitude compared with oceanic tholeiites. Some additional source for these elements and also for radiogenic Sr (p. 139) and radiogenic Pb (p. 140) in the Lesser Antillean lavas, especially those from St. Lucia and Dominica appears to be required. Possible sources are discussed in section 17:3.

Oceanic tholeiite appears to be a possible parent for the Lesser Antillean lavas not only in terms of its chemical composition but also in terms of the volume available for melting. Dr. J. F. Tomblin (pers. comm.) has estimated on the basis of reasonable values for spreading rates for the North Atlantic, the thickness of oceanic tholeiite in oceanic crust and the length of the Lesser Antillean arc that at least 12 cu. km. of oceanic tholeiite impinges on the Lesser Antilles every 100 years. The total volume of material erupted along the arc in the last 100 years is estimated at about 4 cu. km.

Clearly, different degrees of partial melting of oceanic tholeiite are required to produce the Lesser Antillean basalts and andesites. High temperatures will lead to more complete melting and will favour the production of basaltic liquids and experimental evidence suggests that dry melting conditions will have the same effect. Thus, Yoder and Tilley (1962, Fig. 27) have shown that under dry conditions olivine tholeiite melts completely over a small temperature range, whereas under conditions of high water vapour pressure melting takes place over an extended range with the groundmass, plagioclase and amphibole melting before the other phases. Melting relations of Lesser Antillean lavas (Brown and Schairer, 1968) appear to support the assumption that dry conditions favour

the production of basalts, since under dry conditions hypersthene andesite from St. Lucia melted at a higher temperature than a St. Lucian basalt.

Of course under the physical conditions prevailing along the Benioff Zone the oceanic tholeiite may be transformed into amphibolite (high water vapour pressure, 230-40 km. depth) or quartz-eclogite (? 100 km. depth) and this will effect the products of partial melting. The effect of water on the partial melting of quartz-eclogite is apparently similar to its effect on the partial melting of basalt in that higher water vapour pressures favour the production of more acid liquids. Thus, T. H. Green and Ringwood (1968, p. 130) have shown qualitatively that the low melting fraction of a quartz-eclogite at 27-36 kb. under dry conditions is of andesitic composition whereas under wet conditions it is a rhyodacite. In the case of amphibolite temperature may be the most important factor in determining the composition of the partial melt. Partial melting at low temperatures will give rise to andesitic liquids whereas melting at higher temperatures resulting in more complete melting will give basaltic andesites and basalts (T. H. Green and Ringwood, 1968, p. 149).

It appears therefore, that the presence and amount of water may have a considerable effect on the composition of liquid obtained by the partial melting of oceanic tholeiite or its equivalent. Probably the most important source of water will be sediment carried into the upper mantle along the Benioff Zone. Indeed, it may be that differences in the relative amounts of basalt and andesite erupted in various parts of the Lesser Antilles and in other island arcs reflect the amount of water at the place of melting which in turn reflects the amount of sediment going down the Benioff Zone (p. 17/).

The model for the petrogenesis of andesites and basalts from the Lesser Antilles presented above is subject to certain criticisms. There is for example, some doubt about whether andesites and high alumina basalts are in fact generated from the Benioff Zone. Thus Gorshkov (1969, p. 97) suggests that although the focal zone of earthquakes in the volcanic zone of Kamchatka is located at depths of 150 to 180 km., volcanic foci and zones of magma generation occur at depths of between 60 and 90 km. In addition it

is very unlikely that andesites erupted from volcanoes far removed from the continental margins could be generated by melting at the Benioff Zone because the Benioff Zone under these volcanoes is too deep or does not exist at all. For example if one extrapolates the Benioff Zone inland from the west coast of the United States it is about 1,150 km. deep beneath the San Juan volcanic field. If however, the well-established relationship of K_2O contents in andesites to the depth of the Benioff Zone beneath volcanoes (Dickinson and Hatherton, 1967, Hatherton and Dickinson, 1969) is not entirely fortuitous it seems likely that most calc-alkaline magmas in island arcs and at continental margins are in fact derived from the Benioff Zone. It may be that Gorshkov has actually located intermediate magma chambers rather than the point of origin of the magmas.

If magmas in the Lesser Antilles do originate at the Benioff Zone they originate at depths of about 120 km. (northern islands) to 130 km. (southern islands), (Hatherton and Dickinson, 1969, Table 1) so that they must rise through a considerable thickness of ultrabasic upper mantle material before being erupted. That they do so without apparent desilification is another possible criticism of this model of petrogenesis (p. 158).

There is the further criticism that it is impossible to account for the abundances of certain elements e.g. K, Nb, Ba and radiogenic Sr and Pb, in the Lesser Antillean lavas in terms of the partial melting of oceanic tholeiite (p. 163). This however, does not necessarily invalidate the whole process but it may mean that subsidiary processes are going on to account for the abundances of these elements. The following sections (17:3 and 17:4) deal with possible subsidiary processes with a view to seeing whether they can explain the abundances of these elements and also the inter-island chemical variation within the Lesser Antilles.

17:3 THE ROLE OF CONTAMINATION.

Until comparatively recently the idea that andesites were derived by the incorporation of sialic material into basaltic magma was widely held (e.g. Daly, 1933; Tilley, 1950). There is now fairly conclusive evidence against this being the case including:-

1. Trace element data which show that the contents of certain elements notably K, Rb, U, Th, rare earths, Sn and Li are too low in rocks of the calc-alkaline suite for these rocks to have formed by the mixing of basaltic and sialic material in any reasonable proportions; (Taylor and White, 1966).
2. The low initial strontium isotope ratios in most calc-alkaline rocks (e.g. Pushkar, 1968) which severely limits the possible role played by continental material in the petrogenesis of the calc-alkaline suite, and
3. The development of high alumina basalts and andesites in island arcs e.g. Tonga which have formed across oceanic crust where no sial occurs.

Although this evidence precludes any large scale involvement by sialic material in the petrogenesis of calc-alkaline lavas it does not rule out limited contamination by sialic material or contamination from other sources.

There is not much petrographic evidence for contamination in the Montserrat lavas. The rounded quartz crystals in the hornblende-hypersthene andesites have been interpreted as phenocrysts that crystallised from an andesitic magma at depth and were later resorbed nearer the surface in an environment with which they were no longer in equilibrium (p. 98). Siliceous xenoliths were found in some basaltic lavas but show no sign of any reaction with the enclosing lava (p. 114) and although the banded hornblende-hypersthene andesite lava blocks provide evidence of the mixing of acid and basic andesitic magmas this mixing has had a very limited compositional effect (p. 132).

Petrochemical evidence for contamination in the Montserrat lavas is a little stronger. If these lavas are derived mainly by the partial melting of oceanic tholeiite as suggested in the preceeding section then contamination may well be important as a

means of enriching the Montserrat lavas in certain elements notably K, Rb, Ba, Th, U and radiogenic lead, which are higher in the Montserrat lavas than one would expect if oceanic tholeiite was the only material involved in their genesis. In addition, varying amounts of contamination might explain some of the petrochemical variations within the Lesser Antilles. The possible roles of different sources of contamination are discussed below.

17:3:1 The Role of Oceanic Sediment.

The amount of oceanic sediment going down the Benioff Zone is in doubt (p. 162) and will in any case probably be small compared with the amount of oceanic tholeiite but as the sediment will melt before the tholeiite its effect on the ultimate composition of the partial melt might be considerable. It is also to be expected that the less complete the melting of the oceanic tholeiite the greater will be the effect of the sedimentary component on the composition of the melt.

The clay portion of oceanic sediment is rich in radiogenic strontium (Dasch et al., 1966) and is a possible source of Sr^{87} in some of the Lesser Antillean lavas (Donnelly et al., 1969). In addition sediments from the western North Atlantic (Chow and Patterson, 1962) are slightly enriched in Pb^{206} compared with most of the basalts and andesites in the Lesser Antilles and would be an ideal source for most of the andesite-basalt lead, the remainder coming from oceanic tholeiite. Sediments which contain enough radiogenic lead to account for the Pb^{206} contents in the Dominican andesites have not so far been found near the Lesser Antilles so that some extra source of Pb^{206} in these lavas may be indicated. Contamination by deep sea clays (Table 16, No. 35) also provides a possible means of increasing the content of K_2O in a melt without substantially increasing the SiO_2 content as well and this is a possible explanation of high K_2O contents in basalts from Grenada.

However the rather limited data available appear to indicate that the contents of Ni, Ba, Mn and possibly Sr^{87} are too high in oceanic sediment (Table 16, No. 35) for it to have played a major role in the petrogenesis of calc-alkaline rocks (e.g. Taylor, Capp

et al., 1969, p. 17) although it should be noted that there is no necessity that contamination lead to homogenisation of all elements and isotopes. It may also be difficult to account for the inter-island chemical differences in the Lesser Antilles by the melting of oceanic tholeiite and oceanic sediment alone since the availability and composition of these materials should be approximately constant along the entire length of the arc. The crucial factor however is not how much material is available along the arc but how much material descends along the Benioff Zone and this may not be the same all along the arc (p. 162 and 171).

17:3:2 The Role of Continent-Derived Sediment.

Material derived from South America probably includes detritus from the pre-Cambrian shield of Guyana and is thus a possible source of radiogenic Sr and Pb in lavas from the Lesser Antilles. Such material is almost certainly more abundant at the southern end of the Lesser Antilles and this might partly explain the apparent restriction of lavas with high contents of radiogenic nuclides to the central and southern parts of the arc (Dominica, St. Lucia and ? the Grenadines). Sediments derived from South America cannot however be the source of the high K_2O contents in the Grenada basalts unless they are very low in SiO_2 which is unlikely.

17:3:3 The Role of Alkali Basalt.

Variable amounts of alkali basalt may be present within oceanic crust and this material (Table 16, No. 15) may contribute certain elements including K, Rb, Ba, Sr and Zr to calc-alkaline magmas (Taylor, Capp et al., 1969, p. 17).

17:3:4 Wall Rock Reaction.

D. H. Green and Ringwood (1967) suggested that wall rock reaction may be an important factor in enriching certain magmas notably alkali basalt magmas in elements like K, Rb, Ba, Th, U, Zr - the so called incompatible elements which are not constituents of any of the minerals thought to be present in the mantle. Not much is known about the importance of this process in the petrogenesis of the calc-alkaline suite. However if

andesitic magmas are derived from the Benioff Zone there has apparently been little or no reaction with sub-silicic mantle rocks during the passage of the magmas to the surface (p. 158). On the other hand wall rock reaction with crustal rocks is considered to be a possible source of radiogenic nuclides and large cation elements in the Lesser Antillean lavas (p. 170).

O'Hara (1965) stressed the importance of time in determining the amount of fractional crystallisation in a magma and clearly the time a body of magma remains in the mantle or crust prior to eruption will also be a crucial factor in determining how much wall rock reaction occurs. In this respect it is interesting that the recent volcano-seismic crises in Montserrat suggest that andesitic magma in the Lesser Antilles may remain within the crust for a long period before being erupted (p. 66). Other factors of possible importance in determining the amount of wall rock reaction include the water content and viscosity of the magma and also the size of the magma body since the ratio of surface area to volume of the magma decreases with increasing size.

17:3:5 The Role of Contamination by Material from within the Lesser Antilles.

This category is considered to include not only material derived from the islands but also the material which underlies the arc. The exact nature of the latter is not known but it is reasonable to suppose that the piles which rise from the surface of the submarine ridge (p. 3) and culminate in the islands are composed almost entirely of volcanic material. The ridge itself might represent folded continental material (p. 5) but as most island arcs originate across oceanic crust it is probably composed mostly of older calc-alkaline volcanic material (p. 4), which geophysical evidence suggests might be largely of basaltic composition (p. 4). The metasedimentary blocks found in lavas and pyroclastics from Montserrat (p. 112) indicate the presence of some sedimentary material beneath the arc but the sediments may be volcanoclastic (p. 115).

Irrespective of the thickness of the volcanic pile it seems likely that the material at the bottom will differ in age and composition from that making up the islands. Although rocks older than Miocene are rare on the islands material at the bottom of the

pile may be upper Jurassic (equivalent to the oldest known rocks in the Lesser Antilles - p. 6) or older. On account of its age this material may be somewhat enriched in radiogenic nuclides, although material which had similar initial $\text{Sr}^{87/86}$ (0.704) and Rb/Sr ($<1/2$) ratios to those in present day lavas would have to be at the very least 200 m.y. old before the $\text{Sr}^{87/86}$ ratios approached the maximum values found in lavas from the Lesser Antilles. Some extra source of Sr^{87} in certain lavas and of Pb^{206} in all the lavas in the Lesser Antilles appears to be necessary (p. 167) but the assimilation of material from beneath the arc may be capable of giving the limited enrichment of Sr^{87} relative to oceanic tholeiite that is found in most lavas from the Lesser Antilles.

Material from beneath the arc may also be a source of the large cation elements in modern magmas either by a process involving its remelting along the Benioff Zone or by wall rock reaction in which the large cations would be preferentially extracted by a process akin to zone refining (Harris, 1957). Continual recycling of small amounts of arc material in this way would be expected to give melts progressively enriched in the large cation elements with time and this process, which involves the assimilation of essentially co-magmatic calc-alkaline material is not subject to the geochemical criticisms that can be made to large-scale assimilation of oceanic sediment (p. 167). "Evolved" chemical characteristics in island arcs, including enrichment in the large cation elements and possibly in radiogenic nuclides might thus be directly related to the age of the arc as suggested by Baker (1968b).

It is interesting then that the chemically "evolved" islands in the central part of the Lesser Antilles may be older than the other islands. These islands occupy larger areas and rise to greater heights above sea level than the other islands and, if as seems likely, island arcs develop outwards from the centre (see e.g. de Sitter, 1956, Fig. 28) they are certainly the oldest islands in the arc. Their "evolved" chemical characteristics may to some extent reflect this.

Alternatively, it could be the position of these islands at the centre of the arc that is the crucial factor in determining their size and "evolved" chemical characteris-

tics. Thus the radiogenic nuclide and large cation element anomalies are greater in the case of islands like St. Lucia and Dominica where plate motion is perpendicular to the arc than in islands like Montserrat, St. Kitts or St. Vincent where plate motion is at an acute angle to the arc front and the sea floor materials must travel a greater distance and for a greater time to reach the depths at which melting occurs. If more material descends beneath the central portion of the arc larger volcanic piles will be produced here and if the proportion of oceanic sediment going down the Benioff Zone is also greater the resultant melts will probably be more acid (p. 164) and enriched in large cations and radiogenic nuclides. Although the frequency distribution of earthquakes beneath the Lesser Antilles suggests that at the present time the rate of oceanic underthrusting is greatest beneath the northern, rather than the central part of the arc, (p. 162) this may not have been the case throughout the development of the arc.

17:4 THE ROLE OF GAS TRANSFER.

Stanton (1968) has shown that the compositional trend of lavas - picritic basalt, "normal tholeiite", andesite, dacite - which occur in certain calc-alkaline suites e.g. the Solomon Islands (Stanton and Bell, 1969) is not linear. Processes of fractional crystallisation, partial melting and assimilation acting on a tholeiitic parent will all produce a linearly related set of products but a process involving gas transfer in an open system is capable of producing a compositional trend similar to that seen in lavas from the Solomon Islands. Stanton goes on to suggest that gas transfer may be of fundamental importance in the petrogenesis of andesites.

Stanton admits (op. cit., p. 212) that his data only indicate that if andesites and picrite basalts are both derived from tholeiitic basalt the process involves a differential loss of material from the system and that a combination of processes e.g. fractional crystallisation followed by gas loss would also produce the required trends. In any case the compositional trend in the lavas from the Solomon Islands may not be representative of that in calc-alkaline suites in general. Thus, ultrabasic blocks,

basalts and andesites from the Lesser Antilles fall on a linear trend (see e.g. Ree, 1966, Figs. 32 and 33) similar to that expected if the andesites were produced from the basalts by fractional crystallisation involving the removal of material of the composition of the blocks. In addition Stanton's data do not preclude the derivation of andesite by the partial melting of tholeiitic basalt although they do suggest that residual material from such a process is extremely uncommon among surficial igneous rocks. This is hardly surprising if the partial melting occurs at depth in the mantle.

The writer, therefore, regards Stanton's claims of fundamental importance of gas transfer in the petrogenesis of andesites as extravagant. Nevertheless, gas transfer may be an important secondary process as suggested for example by Best (1969, p. 72-73) and discussed below.

Kennedy (1955) has pointed out that water in a melt will diffuse and distribute itself so that its chemical potential is the same throughout the magma chamber. By this mechanism water tends to be concentrated towards the top of magma chambers where the lowest pressures and temperatures prevail. Alkalis and some other metals will co-ordinate and migrate with water so that compositional zoning in the magma chamber may result. Although this concept lacks definitive experimental confirmation studies of compositionally zoned ash-flow sheets (e.g. Smith and Bailey, 1966; Lipman, 1967) confirm its possibility.

There can be little doubt that volatiles, and especially water are important constituents of magmas in the Lesser Antilles and fluctuations in water vapour pressure may account for many of the unique petrographic characteristics of these lavas (p. 118). It is expected, therefore, that gas transfer will take place in these magmas. Depending on such factors as the geometry of the magma chamber, the proximity of the magma to the surface, the water content of the magma and soon variable degrees of transfer may result. In addition the experimental work of Orville (1963) on the system KAlSi_3O_8 - $\text{NaAlSi}_3\text{O}_8$ - NaCl - KCl - H_2O has shown that the $\text{K}_2\text{O} / (\text{K}_2\text{O} + \text{Na}_2\text{O})$ ratio in the vapour phase is dependent on both temperature and pressure, being greater at higher temperatures and

lower pressures which suggests that the composition of the transferred material may very considerably depending on the physical conditions. Gas transfer may thus be capable of producing the erratic behaviour of certain elements e.g. K_2O in the Montserrat lavas though it will not adequately explain the uniformly high values of K_2O in a range of lavas such as those from Grenada.

Under conditions of high temperature and low pressure such as those prevailing in a near-surface magma chamber K_2O and $7SiO_2$ may be preferentially concentrated in a water-rich vapour phase. It is possible that tridymite, cristobalite and the quartz-mica aggregates which occur interstitially in some of the Montserrat lavas, were precipitated from such a phase (p. III).

17:5 SUMMARY.

With so many variables and so many unknowns it is unreasonable to expect a unique solution to the problem of the petrogenesis of the Montserrat lavas or calc-alkaline lavas in general. The evidence presented in this thesis suggests that several processes may have played a part in the petrogenesis of the Montserrat lavas but that most of these were of secondary importance. The following scheme for the petrogenesis of the Montserrat lavas is proposed.

The fundamental process is believed to involve the partial melting of oceanic tholeiite, or its metamorphosed equivalent along the Benioff Zone beneath the Lesser Antilles. The oceanic tholeiite is itself generated by the partial melting of pyrolite in the mantle beneath the Mid-Atlantic Ridge, according to the model of D. H. Green and Ringwood (1967) and is transported by sea floor spreading to the Lesser Antilles.

Oceanic tholeiite is a suitable parent for the Montserrat and the Lesser Antillean lavas in terms of composition and availability. The only difficulty is that the Lesser Antillean lavas, particularly those from St. Lucia and Dominica are so enriched in the large and highly charged cation elements and radiogenic nuclides compared with oceanic tholeiite than an extra source for these appears to be required. Relatively small amounts of alkali basalt, oceanic sediment and detritus from South America or the

Lesser Antilles may be carried into the upper mantle and melted with the oceanic tholeiite and these are possible sources of the anomalous elements and also of water. Various considerations suggest that of this material, oceanic sediment and sediment derived from the Lesser Antilles may be the most important.

The composition of the magmas resulting from the melting of material along the Benioff Zone will vary depending on the physical conditions. Low temperatures and hydrous conditions will favour the production of andesitic liquids whereas dry melting and high temperatures will tend to produce basaltic liquids.

As the arc evolves the tendency is probably towards wetter melting conditions as more material from the arc or more oceanic sediment does down the Benioff Zone. This would give rise to more siliceous, more contaminated melts with time, which would account for Tomblin's (1968) observation that the proportion of andesite to basalt in the Lesser Antilles increases in the younger rocks. It also suggests that the compositional differences between island-arcs like the Lesser Antilles and the South Sandwich Islands (Baker, 1968b) may be due to their different ages.

As the magmas generated along the Benioff Zone ascend to the surface they may be modified by a number of secondary processes. These include fractional crystallisation, wall rock reaction, assimilation and gas transfer.

There is evidence in the Lesser Antillean rocks for at least two periods of fractional crystallisation. One of these occurs near the surface, at low pressures and probably has little fundamental petrogenetic effect. The other, which occurs deeper in the crust (? 6-8 km.) involves the separation of sub-silicic aggregates from basaltic magma and is probably instrumental in producing andesites at certain volcanoes in the Lesser Antilles, like Soufriere, St. Vincent and South Soufriere Hill, Montserrat.

The relative importance of the other "secondary" processes is rather difficult to assess. Wall rock reaction does not appear to be very important within the mantle but may occur within the crust. Gas transfer is likely to be quite important especially in water rich magmas and may be in some measure responsible for the erratic behaviour of

certain elements notably K_2O in the Lesser Antillean lavas.

The compositional variation within the Lesser Antilles may to some extent reflect differences in the relative importance of different "secondary" petrogenetic processes at different places. The restriction of chemically "evolved" lavas to the islands of St. Lucia, Dominica, and Martinique in the central portion of the arc may, however, reflect the fact that these islands are the oldest in the Lesser Antilles although their position relative to the direction of underthrusting of oceanic crust might also be important.

Finally, it should be stressed that of all the processes discussed above there is direct evidence for the operation of only one - fractional crystallisation. The evidence for all the others is as yet circumstantial.

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APPENDIX 1. REPLICATE CHEMICAL ANALYSES of MONTSERRAT
LAVAS by VARIOUS METHODS

TABLE 1. Duplicate chemical analyses of Montserrat lavas and analyses of standard rocks by "Rapid" Methods.

TABLE 2. Chemical analyses of Montserrat lavas by combined Classical and "Rapid" Methods.

TABLE 3. Chemical analyses of Montserrat rocks by X-ray Fluorescence Spectroscopy.

TABLE 1. DUPLICATE ANALYSES of MONTSERRAT LAVAS and ANALYSES of STANDARD ROCKS by "RAPID" METHODS

	7	7	39	39	48	48	GD 1	GD 1 _{Av.}	BCR 1	BCR 1 _{Av.}	AGV 1	AGV 1 _{Av.}
SiO	52.5	51.9	61.2	60.7	57.6	57.4	63.5	64.4	55.0	54.48	59.0	58.99
TiO ₂	0.81	0.79	0.50	0.55	0.58	0.61	0.61	0.60	1.97	2.23	1.00	1.08
Al ₂ O ₃	20.0	19.7	18.3	18.3	17.8	18.2	16.8	16.3	13.7	13.65	17.1	17.01
Fe ₂ O ₃	4.60	4.77	4.20	4.23	2.88	2.88	3.59	3.60	3.98	3.68	4.97	4.51
FeO	4.47	4.47	2.17	2.17	4.14	4.14	1.41	1.37	8.66	8.91	2.08	2.04
MnO	0.19	0.18	0.17	0.16	0.19	0.17	0.06	0.06	0.21	0.17	0.12	0.09
MgO	4.74	4.85	2.27	2.04	3.31	3.35	2.34	2.55	3.38	3.28	1.45	1.49
CaO	10.03	10.06	6.75	6.90	8.10	8.23	3.44	3.55	7.05	6.95	4.85	4.98
Na ₂ O	2.94	3.14	3.74	3.69	3.46	3.53	4.11	4.16	3.30	3.31	4.25	4.33
K ₂ O	0.80	0.75	0.77	0.73	0.79	0.73	3.49	3.61	1.78	1.68	3.05	2.89
H ₂ O+	0.09	0.09	0.75	0.75	0.50	0.50	1.24	1.38	0.61	0.77		
P ₂ O ₅	0.10	0.12	0.07	0.11	0.10	0.13	0.22	0.23				
TOTAL	101.27	100.82	100.89	100.33	99.45	99.84						
F									455	485	428	435
Cr									15	16	12	13
V									390	384	123	121

NOTES. 1. ANALYST - R. FUGE

2. FOR DETAILS OF METHODS SEE P. 119, 132.

3. DETAILS OF SPECIMENS - 7, 39 and 48 - see TABLE 13; GD 1 - Department of Geology, U.C.W., Aberystwyth standard. Granodiorite, Dalbeattie.
 GD 1_{Av} - Average composition of GD 1 calculated from data in Geological X-ray Analytical Group Sub-Committee on Standard Materials 1968
 BCR 1 and AGV 1 - U.S.G.S. standards - details in Flanagan (1967, p. 290)
 BCR_{Av} and AGV 1_{Av} - average values of BCR 1 and AGV 1 from Flanagan (1969, Table 4).

TABLE 2. CHEMICAL ANALYSES of MONTSERRAT ROCKS by COMBINED CLASSICAL and "RAPID" METHODS

	3	4	7	10	12	13	15	16	17	18	21	22	23	24	25	28	29	34	35	36	37	39	40	41	42	43	44
SiO ₂	47.74	51.72	51.92	52.47	53.13	53.97	54.43	55.54	56.31	55.09	56.47	56.81	56.60	57.71	56.96	58.05	59.39	59.16	58.29	59.14	59.43	60.21	60.09	58.88	60.97	61.36	62.54
TiO ₂	0.75	0.76	0.76	0.81		1.35	0.59			0.60								0.44	0.46	0.50	0.50	0.45	0.47	0.41	0.42	0.42	0.38
Al ₂ O ₃	19.9	19.6	19.6	19.4	16.8	16.8	18.8		18.5	18.5			18.4	17.4		19.8	18.4	18.5	18.6	18.4	18.0	17.5	17.6	18.7	17.7	17.0	17.0
Fe ₂ O ₃	4.56	3.20	4.31	3.53	4.68	4.68	3.53			4.19			4.33	4.12		2.03	4.08	2.53	5.96	4.08	2.73	3.89	2.96	2.07	2.98	3.63	1.99
FeO	4.95	5.67	4.47	5.02	4.20	4.20	4.20		3.74				2.72	2.64		3.67	2.87	3.36	0.69	2.87	3.98	2.17	3.29	3.64	2.85	2.41	3.07
MnO	0.16	0.19	0.18	0.15	0.15	0.15	0.18		0.21				0.16	0.17		0.16	0.18	0.18	0.16	0.18	0.18	0.14	0.15	0.16	0.18	0.16	0.17
MgO	5.63	4.75	4.51	3.62	4.38	4.38	3.79		3.35				3.40	4.29		2.15	2.39	2.36	2.90	2.39	2.69	1.99	2.61	2.26	2.46	2.18	1.93
CaO	11.75	11.11	10.66	9.98	8.79	8.79	9.50		8.62				9.03	7.86		7.87	7.94	7.22	7.82	7.94	7.70	7.11	6.96	6.68	6.50	6.82	6.45
Na ₂ O	2.22	2.59	2.94	3.27	3.35	2.90	3.31	3.41	2.97	3.46	3.08	3.16	3.34	3.38	4.47	3.90	3.88	3.63	3.40	3.42	3.49	3.50	3.68	3.17	4.20	3.52	3.46
K ₂ O	0.52	0.60	0.80	0.87	0.70	1.00	0.77		0.87	0.64	0.88	0.55	0.80	0.90	0.94	0.83	0.90	0.83	0.80	0.80	0.80	0.75	0.93	0.98	1.04	1.07	1.17
H ₂ O+	0.88	0.32	0.09	0.15		0.77	0.15			0.48			0.67	0.55		0.90		1.35	0.27	0.56	0.19	0.97	0.52	2.54	0.95	1.12	1.81
H ₂ O-	0.41	0.18	0.17	0.16	1.02	1.02	0.28		0.22				0.32	0.15		0.22		0.17	0.25	0.11	0.05	0.82	0.30	0.44	0.29	0.31	0.35
P ₂ O ₅	0.06	0.12	0.13	0.17		0.21	0.15		0.15				0.13	0.14		0.20		0.18	0.13	0.13	0.13	0.10	0.13	0.06	0.15	0.13	0.10
TOTAL	99.53	100.81	100.54	99.60	100.22	100.22	99.68		99.25				100.48	99.80		100.21		99.91	99.73	100.52	99.87	99.60	99.69	99.99	100.69	100.13	100.42

- NOTES.
1. ANALYST - W. J. REA
 2. FOR METHODS of ANALYSES SEE P. 120
 3. FOR SPECIMEN DESCRIPTIONS SEE TABLE 13.

TABLE 3. REPLICATE ANALYSES of MONTSERRAT ROCKS by X-RAY FLUORESCENCE SPECTROSCOPY

	1	2	4	5	9	11	12	14	17	26	30	32	39	48	49	50	51	52
SiO ₂	43.75	43.88	52.77	56.33	54.92	55.41	54.97	56.80	59.78	61.29	59.39	63.27	65.54	60.27	61.15	64.84	49.85	77.39
TiO ₂	1.08	1.01	0.77	0.80	0.88	0.70	0.81	0.73	0.63	0.62	0.58	0.59	0.39	0.61	0.57	0.43	0.71	0.28
Al ₂ O ₃	22.04	21.14	19.61	18.11	17.86	18.02	17.35	18.62	16.87	17.34	18.30	16.66	15.78	17.95	17.46	16.70	12.66	9.80
Fe ₂ O ₃	4.53	3.64	8.51	8.25	3.06	5.77	8.32	2.51	6.95	2.71	2.16	2.30	5.07	2.13	6.21	1.39	1.04	0.60
FeO	3.61	4.40			4.96	2.27		5.00		3.03	3.49	3.37		4.14		2.95	1.89	2.11
MnO	0.09	0.11	0.17	0.18	0.17	0.18	0.19	0.18	0.15	0.17	0.17	0.17	0.24	0.17	0.16	0.15	0.32	0.09
MgO	7.37	8.77	3.42	3.43	4.22	4.17	3.16	2.72	2.47	2.02	2.23	2.05	1.34	2.19	1.95	1.77	9.65	0.53
CaO	15.71	15.17	10.51	8.88	9.08	9.54	9.21	8.99	8.20	7.28	7.92	7.16	6.38	8.26	7.95	6.84	23.03	7.01
Na ₂ O	1.62	1.58	3.34	3.16	3.96	3.19	3.90	3.48	3.66	4.35	4.54	3.29	4.06	3.31	3.57	3.68	0.48	1.89
K ₂ O	0.11	0.11	0.68	0.60	0.68	0.60	0.87	0.82	1.02	0.90	0.81	0.92	0.86	0.81	0.84	1.09	0.03	0.20
P ₂ O ₅	0.08	0.07	0.22	0.15	0.19	0.13	0.24	0.15	0.16	0.18	0.20	0.22	0.14	0.15	0.15	0.16	0.22	0.09
S	0.03	0.01	N.D.	0.09	0.05	0.03	0.97	0.01	0.10	0.20	0.17	0.01	0.21	0.01	N.D.	0.01	0.24	0.04

NOTES.

1. ANALYST DR. G. HOLLAND with FeO ANALYSES by MR. W. J. REA
2. ALL ANALYSES CALCULATED to 100% WATER FREE
3. FOR SPECIMEN DESCRIPTIONS SEE TABLE 13.

APPENDIX 2.NOTE ON METHODS.

Details of the methods used for major and trace element analysis and for optical determinations have been outlined in the main part of the thesis (sections 16:1:1, 16:2:1, 15:2). Granulometric analyses of pyroclastics were carried out according to the method described by Baker (1963, p. 208). The methods used in the calculation of the norm and of the composition of extracts required to give various andesites by the fractional crystallisation of basaltic magmas (see Table 17) are described below.

A. The Calculation of the Norm.

The norm was calculated using an Algol computer programme written by Dr. P. Catermole. This calculates the norm according to a slightly simplified version of Niggli's (1936) method (see e.g. Barth, 1962, p. 65-70). The main simplification is that pyrite has not been calculated.

B. Method used to calculate the Composition of Extracts in Table 17.

The basalt and andesite analyses are first of all recalculated to 100%, water free.

Let p = amount of extract removed from basaltic magma expressed as a percentage of the amount of the basaltic magma. p is calculated so that the % SiO_2 in the calculated extract equals that in the average Montserrat ultrabasic cumulate block.

Let a = percentage of any oxide or element in the basaltic magma.

b = percentage of same oxide or element in the derived andesitic magma.

x = percentage of same oxide or element in the extract.

The absolute amount of basaltic magma does not matter. Starting with 100 gms:-

100 gms. basaltic magma, which contains a gms. oxide or element minus p gms.

extract which contains $\frac{p \cdot x}{100}$ gms. oxide or element will give:-

(100 - p) gms. andesitic liquid which contains $(a - \frac{p \cdot x}{100})$ gms. oxide or element

$$\% \text{ of oxide or element in andesitic liquid} = \left(\frac{a - \frac{p \cdot x}{100}}{100 - p} \right) 100 = b$$

$$\text{and } x = \frac{100}{p} \left(a - \frac{b}{100} (100 - p) \right).$$

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