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THE ROYAL SOCIETY EXPEDITION TO MONTSERRAT, B.W.I.
THE VOLCANIC HISTORY AND PETROLOGY OF
MONTSERRAT, WITH OBSERVATIONS ON
MT PELÉ, IN MARTINIQUE

By

A. G. MACGREGOR, F.R.S.E., F.G.S.

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[PLATES 1—9]

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I. INTRODUCTION

Early in 1936 the Royal Society, in collaboration with the Colonial Office, organized an expedition to Montserrat, with the object of studying the geology of the island, and of investigating earthquakes and soufrière activity that had caused considerable damage and alarm in the years 1934 and 1935. The personnel of the expedition consisted of Dr C. F. Powell as physicist, and the writer as geologist.

Dr Powell carried out seismological observations with Jaggard shock-recorders and a Wiechert seismograph; his results are published separately (Powell 1937, 1938). A study of the soufrières and their gases was made jointly by Dr Powell and myself, with local assistance. As regards both earthquakes and soufrières, this report deals almost entirely with geological and topographical data for which I am personally responsible.

The present account of the geology and petrology of Montserrat* is based on 11 weeks' field work carried out in March, April and May 1936. A short visit to Martinique, early in May, during which several days were devoted to the study of Mt Pelé (Montagne Pelée) and its surroundings, proved of great value as a basis of comparison.

In the middle of May, Dr T. A. Jaggard, of the Hawaii Volcano Observatory, came to Montserrat at the invitation of the Royal Society. Mr F. A. Perret, of the Mt Pelé Volcano Museum, who had made a series of valuable seismo-volcanic observations in Montserrat in 1934 and 1935, arrived by the same steamer. By this time the volcanic history of Montserrat was almost completely elucidated. The visit of these distinguished volcanologists afforded, however, a unique opportunity for joint discussions on general volcanological problems, and of this Dr Powell and I took full advantage. After my departure from Montserrat Sir Gerald Lennox-Conyngham visited the island on behalf of the Royal Society.

In addition to 14 specimens of corals and fossiliferous limestone, about 365 rock and mineral specimens were collected in Montserrat; from these about 160 slides were prepared for microscopic examination. The localities of the specimens are indicated accurately on the manuscript geological field map deposited for reference in the Geological Survey and Museum, London. The sliced rocks have been incorporated in the "Foreign" reference collection of the Geological Survey of Great Britain. The fossils have been handed over to the British Museum (Natural History), London.

II. THE ISLAND ARCS OF THE ANTILLES

Montserrat (lat. $16^{\circ} 45' N.$, long. $62^{\circ} 10' W.$) in the Leeward Islands, a mountainous volcanic mass about 32 sq. miles in area, is a small member of the series of islands that form the volcanic arc of the Lesser Antilles or Caribbees (fig. 1).

* A preliminary geological report has already been published (MacGregor 1936).

The geological history of the Greater and Lesser Antilles has been the subject of controversy for many years. A discussion of the problems involved is quite beyond the scope of the present paper. It is, however, necessary to deal briefly with some of the current hypotheses, in order to bring the geological history of Montserrat into relationship with that of the other islands of the Caribbean area.

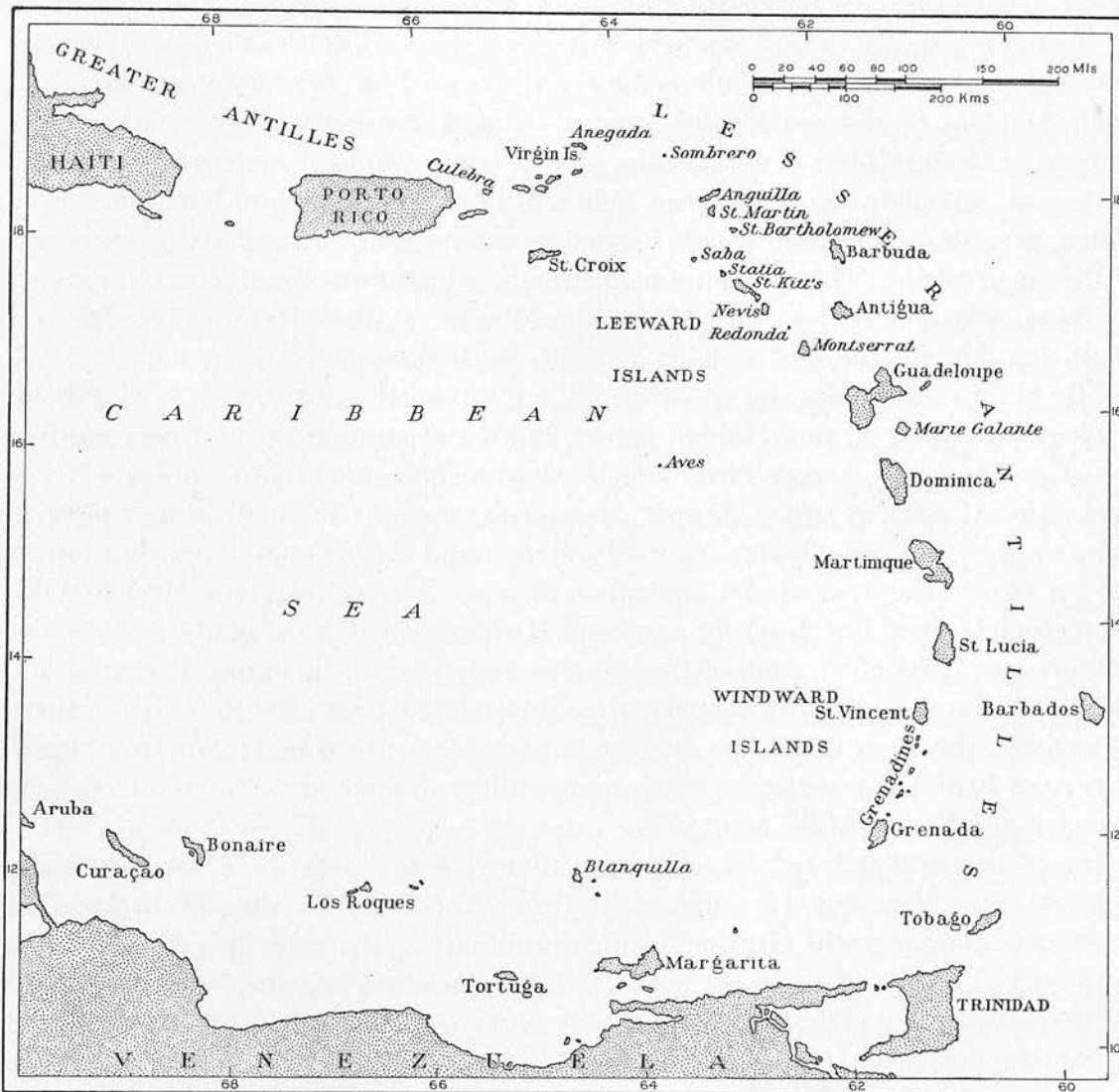


FIG. 1. Map of the Lesser Antilles.

According to one of the most recent and comprehensive geological syntheses, the islands of the Caribbean, including the Greater and Lesser Antilles, belong to a salient of arcuate folds that extend into the Atlantic between north Central America and northern South America (Woodring 1928). The most important periods of folding were at the close of the Cretaceous and at the close of the Eocene. Woodring infers the presence below the Lesser Antilles of a submarine ridge formed by Cretaceous orogeny.

There were also great earth movements that involved folding, warping, and faulting, in post-Miocene times (Vaughan 1919*a*; von Wolff 1929); and in many of the islands the effects on sea-level of distant Pleistocene glaciation, and Recent deglaciation, caused emergence followed by partial submergence (Vaughan 1919*a*).

The Antillean Islands are universally regarded as forming a series of arcs. In the Lesser Antilles the more important are: (1) an old outer arc, or series of arclets, formed by northern volcanic islands, in which the volcanoes, extinct and eroded by late Eocene time, were later variously submerged, covered by Tertiary limestones, and uplifted again; these low-lying limestone Caribbees extend from Sombrero through Antigua to Grande Terre of Guadeloupe; (2) an inner, younger, western arc or festoon of volcanic islands which have been built up during Miocene and later times, and which, according to Woodring, are located near the crest of an underlying fold-ridge of the earth's crust. These mountainous islands, which form the main volcanic arc, are Saba, Statia, St Kitt's, Nevis, Redonda, Montserrat, Basse Terre of Guadeloupe, Dominica, Martinique, St Lucia, St Vincent, the Grenadines and Grenada.

The main volcanic arc was recognized as such as early as 1810, by von Humboldt (Sapper 1905, p. 154) and Nugent (1811), but the separation of the Lesser Antilles into a series of arcs is more often associated with the name of Édouard Suess (Suess 1904, p. 544; 1909, p. 461). Sapper appears to be alone in subdividing the main volcanic arc into two sub-arcs, Saba-Montserrat and Guadeloupe-Grenada (Sapper 1905, p. 191). In a personal communication Professor Sapper has informed me that this subdivision is based purely on the geometrical arrangement of the islands. Successive authors have combined some of the more easterly islands, including Barbados and Tobago, in various ways, to form parts of external tectonic arcs connected with northern Venezuela, the Greater Antilles and the Bahamas (e.g. Reed 1921; Woodring 1928). The Aves Bank has been regarded as representing a fourth and innermost arc (e.g. Woodring 1928; von Wolff 1929).

In addition to Woodring's hypothesis mentioned above, there are two fundamentally opposed views regarding the origin of the Lesser Antilles. According to the first they represent, along with the Greater Antilles, unsubmerged parts of a great pre-existing land area. This view is especially associated with Spencer (1895, 1903) who interpreted the deep-sea troughs of the Caribbean area as submerged land valleys, not fold-troughs.* According to the other view, the Lesser Antilles are simply volcanic piles built up from the ocean floor (Hill 1905). Schuchert, in his recently published monumental synthesis of the geology of the Caribbean and adjacent lands, states that he supports this hypothesis of Hill (Schuchert 1935, p. 750). Schuchert's views are, however, rather obscure, for he says elsewhere that the volcanoes of the Lesser Antilles grew from the broad top of a tectonic arc, and yet contends that their origin is unconnected

* The deeps have also been interpreted as fault-troughs (Taber 1922). Recent work in the Bahamas has provided evidence lending some local support to Spencer's ideas, which had been widely discredited (Hess 1933).

with either orogeny or block-faulting (Schuchert 1935, p. 748). He appears to mean that the tectonic arc is very much older than the volcanic activity (Schuchert 1935, p. 393).

The writer believes that few geologists to-day will fail to admit a direct connexion between volcanic arcs and tectonic movements, although the exact mechanism of the formation of island festoons is still the subject of active controversy. A valuable synopsis of views on this subject, with special reference to the East Indies, has recently appeared (Kuenen 1935).

In the West Indian region the views of Hill and Schuchert seem to be at variance with our knowledge of Antillean and American petrology and geology. For instance, both the type of magma and the type of eruption characteristic of the Lesser Antilles are quite unlike those associated with oceanic volcanic islands. They are, however, very similar to those of volcanoes of the continental margin in the Lassen Peak district of California (p. 73), between the Sierra Nevada and the southern part of the Cascade Range. According to a recent account (Schuchert and Dunbar 1933) the North American cordillera were formed by Tertiary and Pleistocene upwarping and block-faulting (Cascadian revolution) that succeeded Jurassic-Cretaceous and late Cretaceous orogeny (Nevadian disturbance and Laramide revolution). The earth movements were at various stages accompanied by volcanism. Great eruptions in the Cascade Range occurred, for instance, in the Pliocene and Pleistocene, and have continued to the present day (Lassen Peak).

The tectonic and volcanic histories of California, Central America and the Antillean region, present very striking analogies, of which one example has been given.* The writer agrees with Woodring and others in regarding the main volcanic arc of the Lesser Antilles as built up by eruptions originating near the crest of a submerged tectonic arc of which the history goes back to the time of Laramide orogeny. It is further suggested that the origin of the volcanoes that now form the island festoon is connected with great crustal-warping and block-faulting movements in Miocene and (especially) Pliocene times, and that these earth movements and eruptions correspond to those of the "Cascadian revolution" of western North America.

The history of the Antillean arcs is thus regarded as exemplifying a series of events widely recognized in America and Asia, namely: Cretaceous and Tertiary orogeny near a continental margin, followed by comparatively recent uplift and block-faulting and the development, on the second major ridge landwards from the oceanic margin, of linear calc-alkaline volcanicity that tends in its later stages to be of the peléan explosive type.

† Cf. Stille's synthesis of the American cordillera (Stille 1936), which has come to hand since these lines were written. There are other comprehensive syntheses, dealing with the Caribbean area, which cannot be considered here owing to lack of space (Staub 1928; Rutten 1935; Sonder 1936; du Toit 1937). See also a very important report by Hess that has just appeared (1937).

III. THE CARIBBEAN VOLCANIC ARC IN HISTORIC TIMES

It may be taken as well established that intermittent local volcanic activity has been going on along the main volcanic arc for a period that is very long from a human standpoint, and to be measured almost certainly in millions of years. Estimates of the time of major activity range from the Miocene to late Pliocene or early Pleistocene (Schuchert 1935; Spencer 1903). The Caribbean volcanoes are therefore young from a geological point of view (not more than 20–25 million years old). Many of the islands still have active *soufrières*,* and hot or mineralized springs, while a number have long been known to contain well-preserved volcanic cones and craters.

The first recorded eruption was in St Kitt's in 1692. The dates of all known volcanic episodes of any importance are incorporated in fig. 2. This graphical summary is based on data given by Anderson and Flett (1903), Lacroix (1904), Sapper (1927), von Wolff (1929), Perret (1935), Romer (1936). The table shows at a glance: (1) the date of each volcanic episode; (2) the number of years of tranquillity that separated successive episodes in the Lesser Antilles as a whole, and at each centre; (3) the years that have elapsed since the last activity at each centre. As the islands are arranged geographically from left to right (north to south), the heavy arrows show clearly how the centre of activity has oscillated between northern and southern parts of the arc.

Most of the volcanic episodes have been eruptions of a minor character. Notable exceptions were the terrible and almost simultaneous outbursts of the *Soufrière* of St Vincent (Anderson and Flett 1903, 1908) and of Mt Pelé in Martinique (Lacroix 1904, 1908; Philémon 1930). These eruptions, which occurred in 1902, were characterized by intensely hot avalanches composed of gases, rock fragments and dust (*nuées ardentes* or *Glutwolken*).

Martinique, with the dormant Mt Pelé volcano, is situated about the middle of the eastward convexity of the volcanic arc. From Mt Pelé, Montserrat lies about 155 miles north-westwards, and St Vincent 125 miles southwards (fig. 1).

In Montserrat there have been no eruptions in historic times, but from 1897 to 1899, not long before the St Vincent and Mt Pelé eruptions, the activity of the *soufrières* showed a marked increase, and numerous local earthquakes occurred (Sapper 1903).† At the end of 1933 began another period of local earthquakes and abnormal *soufrière* activity, which is not yet completely over.

The Nevis episode of 1930, sympathetic with the serious eruption of Mt Pelé in 1929/32 (Perret 1935; Romer 1936) consisted of a series of local earthquake shocks (Powell 1937). I do not know whether they were accompanied by any recrudescence of activity at the *soufrières* of the island, which were described as extinct in 1922

* Active *soufrières* were known in Nevis, St Kitt's, Guadeloupe, Dominica, Martinique, St Lucia and St Vincent, in 1810 (Nugent 1811).

† According to Mr Gomez (p. 12) tremors increased in intensity until 1902, but were not renewed after the St Vincent and Martinique eruptions of that year.

(Earle 1922). Earthquakes experienced in Guadeloupe in 1850–1 were sympathetic with the Mt Pelé eruption of 1851 (Jaggard 1903).

According to the earthquake-gravity map compiled by the Navy-Princeton Expedition of 1932, earthquake epicentres have in the past been located in St Kitt's, Montserrat, Guadeloupe, Dominica, Martinique, St Vincent, and Grenada, as well as in Antigua, Barbados, and Tobago (Hess and others 1933).

IV. MONTSERRAT: TOPOGRAPHY; WATER SUPPLY; VEGETATION; ROADS; MAPS

The island of Montserrat, $10\frac{1}{2}$ miles long and 6 miles broad, is made up of six adjacent mountain masses and hills, each of which represents an old volcano modified by long-continued erosion* (fig. 3). From north to south they are Silver Hill, Centre Hills, Garibaldi Hill, St George's Hill, Soufrière Hills (including Chance's Mountain, 3002 ft., † the highest peak) and South Soufrière Hill (or Roche's Mountain). Each of these old cones has given rise to its own system of consequent radial drainage. The volcanoes are almost all separated from each other by well-marked hollows, or by zones of relatively low ground. These are original volcanic features, and are not due to faulting or erosion, although they have locally influenced the formation of stream courses. South Soufrière Hill and the Soufrière Hills are much less distinct units than the other volcanoes and are joined by a high col.

The average rainfall in the less elevated regions varies in different parts of the island from 41 to 78 in., the leeward (western) side of the island being wetter than the windward. The wettest months are generally September, October and November (Hardy 1922). The time incidence of rainfall may, however, vary very considerably.

The water supply is derived from mountain springs. These are tapped in the hills, and the water is conveyed to lower levels by means of small-diameter pipe-lines laid on the surface of the ground. Mr La Barrie, Inspector of Works and Roads, supplied me with a list of the more important springs, nineteen in number; ten of these supply the main pipe lines. The recent earthquakes dislocated the water supply considerably. Hot and mineralized springs are referred to in later sections.

The radial drainage channels of the hills are steep-sided gorges, locally known as "ghauts" or "guts". They are cut, to a large extent, in very porous volcanic tuff and agglomerate, and are mostly dry except in wet weather. Among the more important permanent streams are Balham River, Norris River, Tar River, Cold River and White River. Water also flows continually in Runaway Ghaut, Soldier Ghaut and Bugby Hole.

The higher slopes of the Centre (2450 ft.), Soufrière (3002 ft.) and South Soufrière

* At Roche Bluff, in the extreme south-east of the island, is a seventh volcanic centre, now largely covered up by the eruptive products of South Soufrière Hill, and there are some indications of an eighth (pp. 21, 22).

† All heights are taken from the Admiralty chart of 1869.

(2505 ft.) Hills, above the level of about 1000–1500 ft., are covered by dense tropical forest, containing many cabbage palms, tree ferns, etc. Many of the trees are of no great size, owing to the destruction wrought by the hurricane of 1928. On parts of

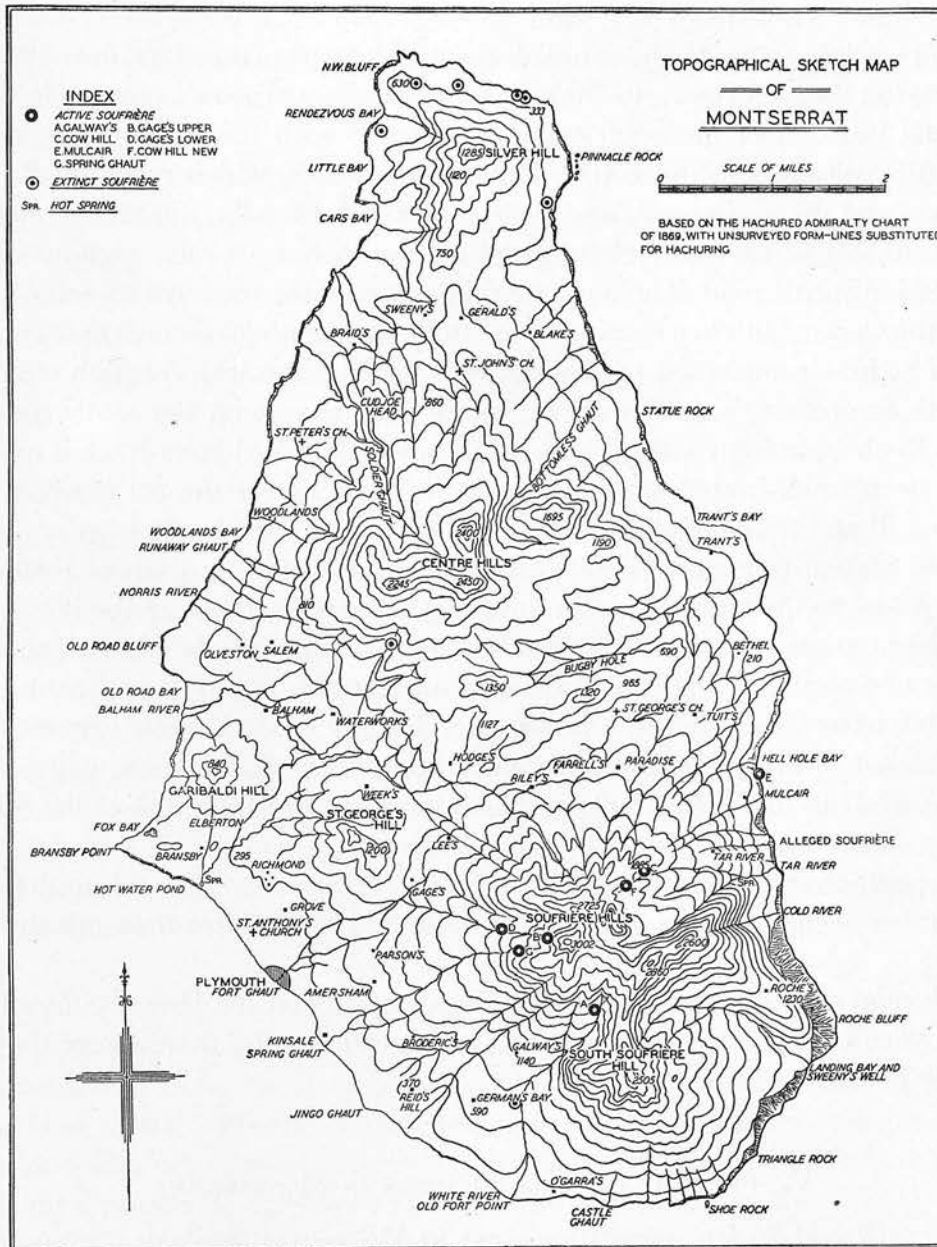


FIG. 3. (Heights are shown in feet, e.g. 3002.)

the lower slopes of the mountains, and on some of the smaller hills (Garibaldi Hill and Silver Hill), there is a considerable growth of scrub. Cacti of various kinds are quite common, especially in the drier parts near the coast, as for instance in the south-

east and north-east. There is a small mangrove swamp at Fox Bay. Mosquitos infected with malaria are said, however, to be unknown in the island.

The lower hill slopes, including even the steep sides of many of the ghauts, are intensively cultivated. The chief crops are at present sea-island cotton, limes and tomatoes.

A motor road that runs north-eastwards across the centre of the island from Plymouth, the capital (on the west coast), to Trant's (on the windward coast), more or less follows the mutual junction of the Soufrière Hills volcano with the St George's Hill and Centre Hills volcanoes to the north. Other motor roads, which run from Plymouth to O'Garra's on the south coast, and to St John's (via Cars Bay) in the northern part of the island, cut across many ghauts, and are therefore even more sinuous than the central "windward" road. The most northerly part of the road system follows radial ridges of the Centre Hills to a considerable extent. Communication north of St John's, and from St John's south-east to Trant's, is by rough hill track. A rough motor road runs south from Trant's to Tar River, but from there round the south end of the island to Roche's, Sweeny's Well, and O'Garra's, only a bad pony track is available. Another steep track leads from Roche's, in the east, across the col between South Soufrière Hill and the Soufrière Hills, to Galway's soufrière and Galway's.

The best map at present available is the hachured Admiralty chart of 1869, on the scale of 1.72 in. to the land mile. On this the general topography of the island is well brought out, but main roads, tracks, and buildings, are in many instances inaccurately located or unrecorded. The detail of the hachuring is also very often quite misleading. Considering its age, the chart is, however, wonderfully good; it shows very clearly the radial drainage of the main hill units, and brings out the fact that the valley systems of the Centre Hills and Silver Hill are much more mature than that of the Soufrière Hills.

The topography shown on fig. 3 and Plate 9 is based on the Admiralty Chart, but a number of place names have been added, and rough form-lines substituted for hachuring.

A small map of Montserrat, with form-lines, appears on the United States Hydrographic Office Chart, No. 1011; its scale is very much smaller than that of the British Admiralty Chart.

V. PREVIOUS GEOLOGICAL WORK IN MONTSERRAT

Before the Royal Society expedition went to Montserrat, geological mapping and systematic field work had never been attempted. The active soufrières had never been shown on a map, and their number was known only in the island. Some useful geological observations had, however, been published by visiting scientists, and others were made known to us by the inhabitants of Montserrat.

The first geological record is Nugent's account of part of the Soufrière Hills and of

Galloway's (Galway's) soufrière (Nugent 1811). He recognized the presence of porphyritic crystals of feldspar and hornblende in the local rocks, and described Galway's soufrière in some detail. His description might be applied, with little change, to the soufrière in its present condition. Nugent refers to the existence of another active soufrière, on the side of a mountain not more than a mile distant from Galway's in a straight line. This almost certainly implies that Gage's Upper soufrière was active in 1810. Nugent's observations were remarkable for their time, and provide a most valuable record.

In 1863 Duncan described a fossil (in the Geological Society collection) which was alleged to come from Montserrat, as a new species of coral (*Astraea antillarum*). The specimen is described as a rolled flint, found with silicified wood (Duncan 1863). As rolled flints and silicified wood are unknown in Montserrat, it is practically certain the specimen was wrongly localized.

In 1883 Waller published a detailed description of a "lava" specimen collected in Montserrat by Mr Joseph Sturge. He noted the presence of brown hornblende, of hypersthene, and of basic plagioclase feldspar (Waller 1883). This, according to Dr K. W. Earle, is the first record of hypersthene in the West Indies.

Twenty years later Karl Sapper, the eminent German volcanologist, spent a week in Montserrat and examined the central and southern parts of the island (Sapper 1903). He regarded the main mountain masses as much denuded volcanoes built up of tuffs and conglomerates, described St George's Hill, denied that Chance's Pond is a crater lake, recognized lava flows interbedded with tuffs between Sweeny's Well and O'Garra's, and collected fossils from Sweeny's Well. He described Galway's, Gage's Lower, and Gage's Upper soufrières and took measurements of temperatures and elevations. He called attention to the marked increase in the activity of the soufrières during the earthquake series of 1897-9. In a personal communication Professor Sapper has informed me that his fossils were never described. In 1904 Lacroix published a description of Sapper's Montserrat rock specimens (Lacroix 1904).

Shortly afterwards there appeared an account of the soils of Montserrat (Watts and Tempany 1905). I have not seen this paper, but a more recent one on the soils of the island, with notes on the geology and climatic conditions, was brought to my notice (Hardy 1922). Hardy classed the soils in two main groups: (1) talus or transported soils; (2) shoal or sedentary soils. The term "talus soils" is, I think, to some extent a misnomer, for reasons that will be given later (p. 34).

Dr K. W. Earle, while Government Geologist to the Windward and Leeward Islands, paid a short visit to Montserrat in 1923, and wrote a brief account of the physiography and geology. He very kindly gave me a typescript copy of his unpublished report. Earle observed that the tuffs on the whole dip away from the main and subsidiary mountain masses. He briefly described two rock specimens, reported the presence of the minerals gypsum, alum and alunogen at Galway's soufrière, and

halotrichite at Gage's, and collected fossils at Sweeny's Well. After examining the fossils he assigned them to the Pleistocene (p. 80).

Some years after Earle's visit, Davis, the American physiographer, fitted Montserrat into his physiographic evolution scheme for the Lesser Antilles (Davis 1926). This he did while passing in a steamer, and it is therefore not surprising to find that his interpretation of the topography was very largely wrong. Thus he regarded the Soufrière Hills and South Soufrière Hill as made up of several little-trenched volcanic cones of similar nature; they consist of two very considerably trenched volcanoes of different ages and of different structure. This difference of structure accounts for the steep south-easterly slopes of South Soufrière Hill (p. 15); Davis regarded the steep slope as due to a great landslip. He correctly deduced the relative ages of Silver Hill, the Centre Hills and the Soufrière Hills, from differences in the maturity of their erosion. With regard to the Soufrière Hills he appears to have been lucky, for it is clear from his account, and from the titles of his illustrations, that he took Chance's Mountain, and the spur to the north of it, to be distinct and little-trenched volcanic cones; they are parts of the same volcano separated by a deep gorge (p. 28). It is beyond the scope of the present paper to discuss Davis's ingenious explanation of the truncated spurs of the islands of the Lesser Antilles in terms of coral reefs and glacial control. As regards Montserrat, the facts can be explained more simply (p. 19).

Mr F. A. Perret, the well-known American volcanologist, visited the island several times during the earthquake period of 1934-5, and submitted to the Governor of the Leeward Islands a number of valuable reports on the earthquake and soufrière activity; these were published by the Colonial Office. Mr Perret is at present engaged in preparing for publication a scientific account of his work in Montserrat.

Mr C. A. Gomez, until lately Curator of the Botanical Station in Montserrat, placed at my disposal a detailed and up-to-date history of the local earthquake and soufrière activity, which he had prepared officially for the Government. This account was of the greatest value to the expedition.

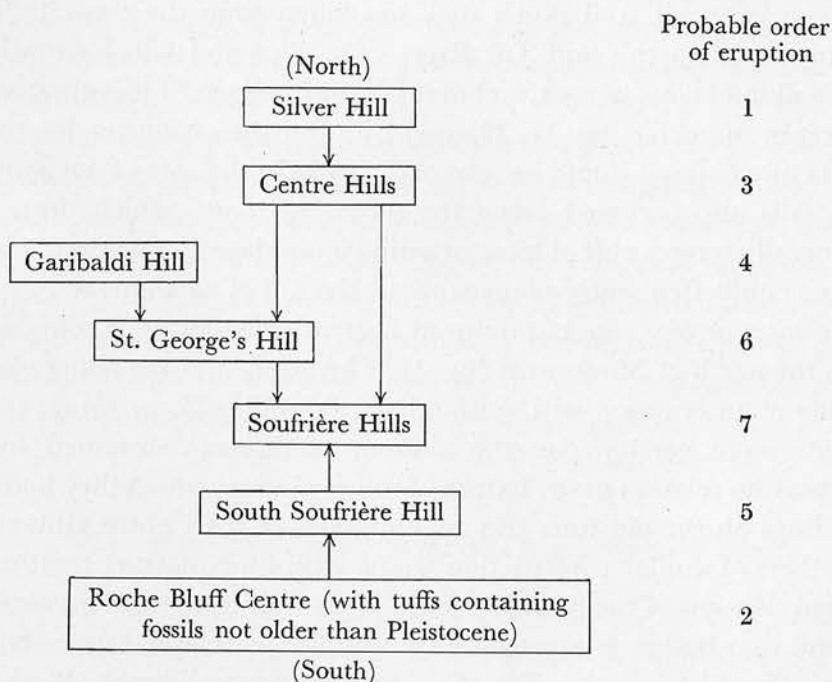
Mr T. Savage English, an enthusiastic local naturalist and amateur geologist, kindly lent me the manuscript of his "Records of Montserrat", in which he had incorporated the results of his geological observations on the main soufrières, hot springs, local black beach sands, etc. He was the first to recognize an old crater, with a central mass of igneous rock, near Tar River. Mr English personally pointed out to me, from near Tar River, various features of this area. After I had satisfied myself that his interpretation was correct, it was decided to christen the amphitheatre "English's Crater" (p. 28).

VI. SUMMARY OF VOLCANIC HISTORY

(a) *The eruptive sequence*

It is necessary, at this point, to give an outline of the volcanic history of Montserrat, in order that the discussion of the physiography (Section VII) may be intelligible.

The ascertained facts* regarding the relative ages of the different volcanoes are indicated by the arrows in the following diagram. The arrows lead from any one volcanic centre to a geographical neighbour of later date.



The evidence that fixes the relative age of adjacent volcanoes will be given in detail in later sections. Here it may be mentioned that the eruptions of the Soufrière Hills possibly overlapped, to some extent, those of South Soufrière Hill. All the volcanoes except Silver Hill, Garibaldi Hill, and the Centre Hills, have been proved to be of Pleistocene or more recent date. The probable order of eruption in the island as a whole is indicated by the numbers on the right. These are based on arguments that involve a certain amount of speculation (p. 17). The available evidence suggests that all the volcanoes, with the exception of Silver Hill, are of Pleistocene or Recent age. Silver Hill is believed to be late Miocene or early Pliocene (p. 19).

It is interesting to note how the centre of activity has oscillated from north to south, probably with gradually decreasing amplitude. This is reminiscent of the oscillation of activity in the Lesser Antilles as a whole (fig. 2).

* The problematical eighth volcano is here neglected (see pp. 20, 21).

(b) The recent volcanic earthquakes

The most recent event in the volcanic history of the island is the production of landslips and rock-falls by the more severe of the present series of earthquakes. They are very numerous on the precipitous wooded slopes of the central part of the Soufrière Hills, where they are conspicuous because the pale colours of the rocks laid bare show up against the surrounding dark green vegetation (fig. 9, Plate 1). The landslips and rock-falls are more numerous here than in any other part of the island, but there are some on St George's Hill (fig. 12, Plate 1) and on the steep slopes of the Centre Hills and South Soufrière Hill, and much rock has fallen from the coastal cliffs, as, for instance, between O'Garra's and Tar River. The slips and falls have affected both agglomerate and solid igneous rock, and many of the bandaite* blocks in steep "screes" are several feet in diameter (fig. 11, Plate 1). But for the exposures due to the earthquakes, practically nothing would be seen of the rocks of the core of the Soufrière Hills.

Numerous falls also occurred along the motoring roads, which, from their construction, generally have a cliff of loose or semi-consolidated agglomerate on one side. Slips from these cliffs frequently occur without the aid of earthquakes.

One of the more severe shocks produced a great rock-fall on Redonda, the small rocky islet to the north of Montserrat (fig. 1). The noise, and the rising cloud of dust, led to rumours of an eruption on the island (cf. Powell 1938, p. 26).

During the recent earthquakes the amount of damage sustained by buildings appeared to bear no relation to the nature of the ground on which they had been built. Certain buildings on the old tuffs and agglomerates of the Centre Hills suffered just as much as others of similar construction (stone with lime-mortar) built on the more unconsolidated deposits of the Soufrière Hills. This was at first rather surprising, as it has been found that buildings erected on unconsolidated alluvial deposits are usually more severely affected by earthquakes than those built on solid rock (West 1934, 1935). The explanation is probably to be found in assuming that in 1934-5, as in 1936, the earthquake foci were very near the surface, and altered their position from time to time over quite an extensive area of the central part of the island (Powell 1937, 1938).

In later parts of this report emphasis is laid on the observed time-association of the earthquakes and abnormal soufrière activity. This contemporaneity makes it clear that the phenomena are causally inter-related. Further evidence is provided by the distribution of some of the epicentres, as determined by Dr Powell. Those falling within his "Region II" (Powell 1938) lie in an elongated area almost coincident with a well marked line of soufrières trending E. 35° N. (p. 40). Another group of epicentres (falling within "Region I" of Powell) are clustered within the area occupied by St George's Hill volcano. Dr Powell informs me, however, that his results are not precise enough to preclude the possibility that the St George's Hill epicentres may actually be located above a plane of crustal weakness traversing the

* Bandaite = labradorite-dacite (p. 49).

hill in a direction about E. 30° S. Along this general line are situated Garibaldi Hill, St George's Hill, Gage's Lower soufrière, Spring Ghaut soufrière, Galway's soufrière, and part of the Roche Bluff volcanic centre (pp. 40, 82).

There is thus some basis for the suggestion that both earthquake and soufrière activity may be related to planes of crustal weakness. To establish such a relationship in Montserrat, or elsewhere in the volcanic arc, would be of great importance. It is therefore desirable that more accurate methods for the location of shallow earthquake foci should be devised. As a means of attaining greater accuracy Dr Powell suggests the use of seismological instruments with more extended time-scales than those employed in 1936. As regards depth, Dr Powell's results suggest that the majority of the foci were between 1 and 2 kilometres from the surface, and that some may have been rather less than a kilometre down.

Seismo-volcanic studies in the West Indies have not progressed sufficiently to justify conclusions regarding the events that lead up to local earthquakes, and the relation of the latter to local soufrière activity and to volcanic eruption in a distant part of the arc. Dr Powell and the writer would suggest, however, that relief of earth stresses and local recrudescence of activity in the highly gas-charged magma may act and react alternately. It appears to be significant that the major earthquake of November 1935, which was recorded over a large part of the world, marked the beginning of the decline of the Montserrat disturbances (cf. Powell 1938).

VII. RELATION OF PHYSICAL FEATURES TO GEOLOGY

(i) *Mountain and hill slopes.* It has already been pointed out that each of the old volcanoes of Montserrat gives rise to a hill, or group of hills, with consequent radial drainage channels. A striking feature of the island is the somewhat abrupt rise of the steep forested slopes of the central nuclei, or cores, of the Soufrière Hills and Centre Hills, the largest mountain groups, above the surrounding more gently sloping cultivated land (fig. 9, Plate 1). This is mainly due to the fact that the central cores are made up of solid intrusive bandaite and relatively hard and steeply dipping agglomerates, while the surrounding deposits, consisting of unconsolidated or semi-consolidated agglomerates, tuffs, volcanic sands, etc., radiate outwards with a dip that does not as a rule exceed 10° .

In the case of the Soufrière Hills, the youngest volcano, the inclination of the cultivated slopes between the ghauts is very largely original, as it conforms very closely to the dip of the tuffs (fig. 26, Plate 4).

The same principle applies to the slopes of St George's Hill. These are steep because the tuffs of this small volcano have a steep radial dip ($25-40^{\circ}$). Here there is no hard central core.

The south and south-eastern slopes of South Soufrière Hill are steeper than the

outer slopes of the Soufrière Hills because they are made up of the products of a different type of eruption. They are composed of an interbedded series of basaltic lavas and tuffs with an original dip of 20–30°. Erosion has locally made the inclination of the present hillsides only slightly steeper (fig. 14, Plate 2).

(ii) *Ghauts*. On the younger volcanic cones the main effect of erosion has thus been the formation of radial ghauts. In the Soufrière Hills, and in the older Centre Hills, the ghauts cut deeply into the central cores as well as into the more gently inclined outer slopes (fig. 21, Plate 3). The backward cutting of the ghauts into the central nucleus of the Soufrière Hills has produced marked serrations in the high ridges of this volcano (e.g. fig. 20, Plate 3). The name Montserrat, given to the island by Columbus, was apparently suggested by the resemblance of its serrated mountain profile to that of Montserrat in Spain.

The narrowness of the ghauts of the Soufrière Hills, as compared with broader and more U-shaped valleys of the Centre Hills, such as Soldier Ghaut and Bugby Hole, indicates that the drainage system of the Soufrière Hills is less mature, and that this volcano is, therefore, the younger. This feature is well seen on the hachured Admiralty chart. The ghauts of Silver Hill and Garibaldi Hill are also more mature.

In some cases drainage channels have been determined by the hollows separating different volcanoes. Thus the Balham River valley separates the Centre Hills from St George's Hill in its upper reaches, and from Garibaldi Hill nearer the sea. It is thus an exceptionally wide valley.

In other cases drainage channels have been determined by the line along which the deposits of a younger volcano abut on rising ground that forms part of an older volcano. For instance, a ghaut running northwards from the Soufrière Hills is deflected sharply eastwards at St George's Church, along the mutual junction of the Soufrière Hills and the Centre Hills (Plate 9). Similarly, White River Ghaut, in the south of the island, has been cut more or less along the line where the agglomerates of the Soufrière Hills abut on the slopes of the older South Soufrière Hill.

The marked deflection of Gage's Soufrière Ghaut at St George's Hill will be considered later (p. 27).

(iii) *Deltas and beaches*. A glance at the map will show that at the seaward end of many of the ghauts a small promontory has been formed (e.g. Spring Ghaut, White River Ghaut, Castle Ghaut, Bottomless Ghaut). This is the result of the accumulation of debris brought down in times of flood. At the seaward ends of the steep ghauts on the southern slopes of South Soufrière Hill, huge boulders form part of the cone of deposition.

The only alluvial delta of importance is at the mouth of the Balham River (Old Road Bay). Davis regarded the slightly embayed valleys of Silver Hill (presumably Cars Bay and Rendezvous Bay) as an indication of submergence. Old Road Bay seems to the writer to be even more suggestive. Most of the ghauts, on submergence, would

not give rise to embayed valleys, because of the facts mentioned in the last paragraph, and because they are excavated in loose deposits readily cut back by wave action.

In contrast to some of the other islands of the Lesser Antilles, there are no raised beaches in Montserrat. Low narrow platforms that border the sea in several places between Plymouth and O'Garra's appear to be due to the coalescence of detrital deposits from neighbouring ghauts, banked up by the agency of waves and currents.

Sandy beaches are found only at certain places on the west (leeward) coast, as at Cars Bay, Woodlands Bay, and Fox Bay, and on both sides of Plymouth. A striking feature of the sands is their dark colour. Concentration, by wave action, of the heavier constituents, leads to the production of very black layers. A sample of the "black sand" from Fox Bay proved, on microscopic examination, to be composed largely of magnetite, with much hypersthene, some ilmenite, augite, and plagioclase feldspar, and sparse fragments of dark brown hornblende and quartz. All these minerals are derived from local agglomerates and tuffs.

Only one "foreign" pebble was seen on the local cobble beaches, especially characteristic of the windward coasts. This was a pink foliated granite found by Mrs Jaggar near O'Garra's. It contains scraps of chloritized biotite and a little sphene.

(iv) *Coastal cliffs.* By far the greater part of the coast is fringed by cliffs of considerable height. They characteristically truncate the spurs between the radial ghauts. Hanging valleys have been locally produced between the truncated spurs (figs. 27, 28, Plate 5). Davis drew attention to the fact that truncated spurs are characteristic of most of the islands of the Lesser Antilles (Davis 1926). He thought they were formed because coral reefs that had once protected the islands from wave erosion, were destroyed during the Pleistocene Glacial Period. The writer regards the cliffs as due to marginal submergence and marine erosion (p. 19).

The highest cliffs are those just north of Roche Bluff, which rise fairly steeply to about 1000 ft. (fig. 24, Plate 4). There is another great cliff (possibly 450 ft.) at North-West Bluff in the north of the island.

It is worth noting, in connexion with the coasts of Montserrat, that there is practically no rise and fall of the tide. This makes many of the cliff sections inaccessible. It is, however, possible to scramble along the shore line all the way from O'Garra's past Roche Bluff to Tar River, with only occasional traverses inland.

VIII—SUBMARINE CONTOURS IN RELATION TO VOLCANIC HISTORY

The soundings shown on the Admiralty chart indicate clearly that a wide and gently inclined shelf extends around the northern part of Montserrat down to a depth of about 35 fathoms. Beyond the 35 and 100 fm. contours the depths increase rapidly. On fig. 4 are shown the 10, 20 and 100 fm. contours of the Admiralty chart, along with a 35 fm. line that has been newly drawn.

Two features of the contours suggest that the presence of this shelf implies submergence of the margins of the island. The first is the well-marked westerly undersea extension of Bransby Point (south-west of Garibaldi Hill), which is formed by an

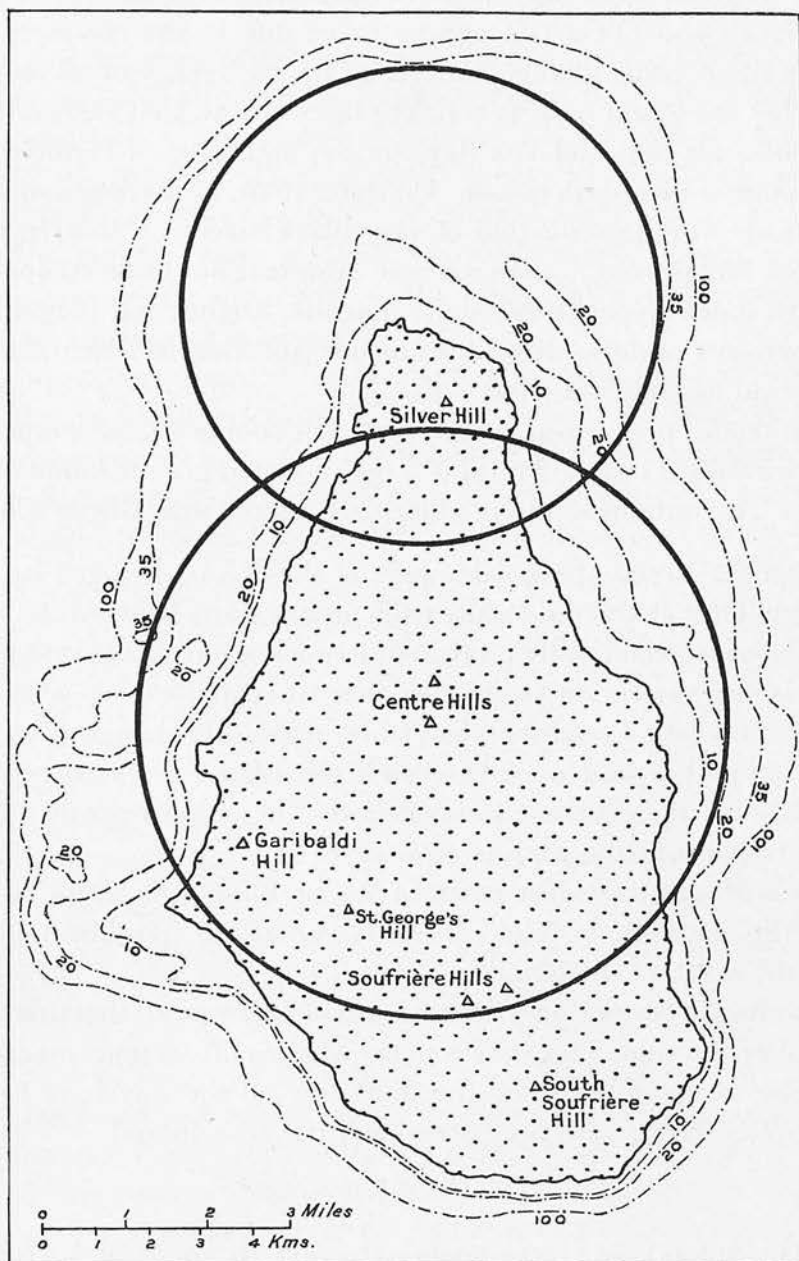


FIG. 4—Submarine contours around Montserrat (depths in fathoms). For explanation see text.

unusually coarse and well-consolidated volcanic agglomerate. The second, which is much more problematical, is the re-entrant affecting the 100 and 35 fm. contours about 2 miles to the north, suggesting a drowned river valley, possibly that of the Balham River. The first feature alone makes it extremely probable that subaerially

formed volcanic rocks of the different volcanoes at one or more periods extended unsubmerged to the neighbourhood of the present-day 35 fm. line.

From the position and configuration of the 35 fm. contour we can infer the approximate diameters of the bases of the older volcanic cones of Montserrat. That of Silver Hill was probably about 6 miles, and that of the Centre Hills about 7 miles, as indicated by the circles drawn in fig. 4. The distance of the 35 and 100 fm. contours from the coast west of Garibaldi Hill is presumably due to the combined effects of the accumulation of volcanic debris from the Centre Hills and Garibaldi Hill volcanoes.

Accepting the evidence for emergence and submergence, we can apply the ideas of Vaughan and Daly (Vaughan 1919*a*, p. 611; Daly 1935, chap. VI), and correlate one stage of low sea-level with the world-wide Pleistocene land emergence of Glacial times. Vaughan and Daly regard this emergence as due to the withdrawal of water from the oceans to form the great continental ice-sheets of the period. The submerged platform and the cliffed coasts would then be due in part (see below) to wave action during the partial submergence that resulted from the return of the water to the ocean on deglaciation (in Recent times).

Daly cites the very similar submarine shelf round Barbuda and Antigua (fig. 1) and that around Anguilla, St Martin and St Bartholomew, which was first interpreted by Vaughan, as examples of this cycle of events (Daly 1935, figs. 104, 106). It seems unnecessary to invoke the hypothetical coral reefs of Davis.

The mature topography and high cliffs of Silver Hill, and the fact that it is largely formed of solid bandaite with some well-consolidated agglomerate, indicate that from this volcano a large amount of more superficial, and less consolidated, volcanic material has been swept away.* This implies erosion that is probably too prolonged and too profound to be attributed to Pleistocene and Recent times. It seems probable that the Silver Hill volcano was active either in the Upper Miocene (which, according to Vaughan, was a period of extensive uplift in the Antillean region), or the early Pliocene, and that its coastal cliffs are in part due to marine erosion during moderate submergence in Plio-Pleistocene time.

If the re-entrants in the 100 and 35 fm. contours north-west of Garibaldi Hill indicate a submerged river valley, it may have been eroded at the time of either Upper Miocene or Pleistocene emergences. The post-Glacial submergence, according to Daly, drowned river mouths to a depth of only 75–90 m. (100 fm. = 183 m.), but concomitant differential crustal movement may have caused local submersion to greater depths.

The tuffs, volcanic sands and agglomerates of the outer parts of the Centre Hills are not well consolidated, and offer little resistance to wave erosion. The building up of the Centre Hills volcano, therefore, most probably took place in Pleistocene times.

* The rocks of Silver Hill closely resemble the prevalent types of the Centre Hills, and there can be little doubt that the superficial eruptive products were of the same nature in both cases (tuffs, volcanic sands, and agglomerates).

It will be shown later that Silver Hill was profoundly eroded before the later eruptions of the Centre Hills (p. 36).

The probable geological and volcanic history of Montserrat is summarized in Table I. In following the sequence of events it must be remembered that very little of the area at present occupied by the island has ever been submerged since Upper

TABLE I. SUMMARY OF PROBABLE GEOLOGICAL AND VOLCANIC HISTORY OF MONTSERRAT

Correlation of events with geological time scale	Geological and volcanic events	Order of magnitude of age of various events
V. (Sea-level as at present day)	Subaerial and (slower) coastal erosion of the island	Present day
IV. Recent (post-Glacial) peripheral submergence	Coastal and subaerial erosion of all volcanoes of Montserrat	↑ 20,000 years ago
III. Pleistocene (Glacial) peripheral emergence	Eruptions of Soufrière Hills (7)* St George's Hill (6) South Soufrière Hill (5) Garibaldi Hill (4) Centre Hills (3)*	↑ 25,000 to 500,000 years ago
II. Pliocene to early Pleistocene peripheral submergence	Eruption of Roche Bluff centre (2)* (early Pleistocene) Coastal and subaerial erosion of Silver Hill	? ↑ 2,000,000 years ago 8,000,000 years ago
I. Late Miocene or early Pliocene emergence	Eruptions of Silver Hill and possibly of early centre now submerged off Roche Bluff (1)	10,000,000 years ago

* The Roche Bluff tuffs may have come from an eruptive centre that was contemporaneous with, or later than, the early activity of the Centre Hills. The eruptions of the Soufrière Hills may have been contemporaneous with, or later than, the post-Glacial peripheral submergence; there is, however, no evidence that necessarily implies eruptive activity within the span of human history.

Miocene times. The Roche Bluff tuffs, which contain marine fossils, and are found only close to the present coastline, indicate local submergence confined to the south-east corner of the island. These tuffs are believed to have been upraised and tilted by volcanic upheaval almost contemporaneous with their formation (p. 23). The absence of fragments of limestones or sediments in the tuffs and agglomerates of the other volcanic centres* shows that, at the time of the Roche Bluff activity, no marine deposits were formed over most of the area that is now concealed beneath volcanic debris. The terrane was probably occupied by eroded volcanic rocks older than the

* Only one was found in the whole island, a thermally metamorphosed sediment fragment in agglomerate of the Soufrière Hills.

Upper Miocene. The last column of the table is intended only to give non-geological readers a rough idea of the general order of magnitude of the time-intervals that separate the present day from the various episodes of the past.

IX. DESCRIPTION OF VOLCANIC CENTRES

The colours on the geological map (Plate 9) show the areas occupied by the various volcanoes, and indicate, to some extent, the nature of their rocks. As a rule any attempt to separate on the map solid igneous rocks (extrusive or intrusive) on the one hand, from tuffs and agglomerates on the other, was quite impracticable. Only in certain favourable localities (near Trant's and Tuit's; Castles Peak; Roche Bluff) was this possible. Solid igneous rocks other than those shown as such on the map, occur, however, only on Silver Hill (intrusive), in the central nuclei of the Centre and Soufrière Hills (intrusive), and on South Soufrière Hill and near Roche's (extrusive).

The positions of the mutual boundaries of the volcanoes are, it is believed, approximately accurate, but to some extent they were sketched in, not fully surveyed. The only line that can be regarded as somewhat conjectural is that separating the north-eastern part of the South Soufrière Hill volcano from the Soufrière Hills to the north.

In order to describe most clearly the field evidence bearing on the relative ages of the different centres, it is convenient to begin with the southern part of the island (Roche Bluff, South Soufrière Hill, St George's Hill, Soufrière Hills); Silver Hill, the Centre Hills and Garibaldi Hill will afterwards be described in turn.

(a) *Roche Bluff centre*

(i) *Possible inlier of Landing Bay Ghaut.* In the bottom of the ghaut that reaches the sea at Landing Bay, and about 600 yards inland, brownish well-bedded tuffs dip *upstream* (west-north-westwards); they are separated by a strong erosional unconformity from an overlying thick bed of pale pumice inclined gently *downstream*. A few hundred yards farther up the ghaut, there is an obscure outcrop of hypersthene-bandaite, or andesite (probably a lava), with a very fine-grained groundmass; it is not very like the South Soufrière Hill lavas, but resembles a fragment in the fossiliferous tuffs of Roche Bluff.* In this lower part of Landing Bay ghaut we thus may possibly have a minute inlier of tuff (and lava?) erupted from a centre in the vicinity of the south-east corner of Montserrat, at some period before the formation of the Roche Bluff fossiliferous tuffs. No more pale pumice was seen anywhere near; presumably it belongs to a late explosive phase of the South Soufrière Hill or Soufrière Hills volcanoes. Unfortunately I collected no specimens from the brownish tuffs below the pumice; the fragments appeared in the field to be bandaite or andesites. The suggested explanation of this doubly anomalous outcrop is by no means free from difficulties. A more detailed study of the area and its tuffs may supply a better solution.

* It also closely resembles one fragment, out of many, collected from the Centre Hills agglomerate.

(ii) *Fossiliferous tuffs*. Apart from the obscure outcrops that have just been described, the oldest rocks of the southern part of Montserrat are (1) the fossiliferous tuffs seen in the coastal cliffs 300 yards north-east of Sweeny's Well, and north-north-westwards of Roche Bluff point, (2) the acid bandaite south-west of Landing Bay. Of these three outcrops, Sapper and Earle saw only the restricted exposure in the cliff just north-east of Sweeny's Well.

The Roche Bluff tuffs contain fossils not older than the Pleistocene (p. 81), and fix a lower limit for the age of the eruptions of the Roche Bluff, South Soufrière Hill and Soufrière Hills centres. Their mode of occurrence will therefore be described in some detail. Sapper's description of the field relations of the Sweeny's Well fossiliferous tuffs is somewhat misleading. Earle, in his unpublished report, states that white limestone with marine fossils is "incorporated in, over- and underlain by, and mixed up in heterogeneous confusion with, the volcanic tuffs".

The results of the writer's more extensive observations may be summarized as follows. There are two series of bedded tuffs in the Roche Bluff area: (1) pale, almost white, tuffs, locally containing fragments and broken masses of fossiliferous limestone; (2) reddish to brown rusty tuffs, locally associated with basalt lava (Roche Bluff Point). The latter (2) belong to the interbedded basaltic lava and tuff series of the South Soufrière Hill volcano, and overlie the pale tuffs (1) unconformably. The pale tuffs were upraised, steeply tilted, and much broken up, and they had acquired an irregular upper surface before the basic series covered them unconformably. These facts were ascertained by inspection from below and from above, by descending the steep slope of lava and tuff at Roche Bluff Point, and by climbing gullies in the cliffs to the north.

Near Landing Bay the chaotic relations of bedding planes in adjacent masses of the pale tuffs, make it obvious that the beds have been uptilted and broken. Locally, rather sandy strata with vertical bedding strike along the beach near the cliff base; a vertical junction between pale tuff and a mass of limestone extends at one place for about 50 ft. up the cliff. North of Roche Bluff Point signs of large-scale brecciation are less noticeable, but in many places the dip of the bedding is between 40 and 45°, and the direction of inclination varies. Locally there is little or no sign of bedding (fig. 18, Plate 2).

Fossils were found only near Landing Bay, and at the northern end of the outcrop beyond Roche Bluff Point. There are broken masses of coral limestone, and highly tuffaceous limestone containing algae, foraminifera, spines of echinoderms, serpulæ, lamellibranchs and ostracods (p. 80).

Many of the accessible parts of the tuff outcrops do not contain either fossils or carbonates; their pale colour is due to a matrix of finely comminuted white mineral matter. In the tuffaceous limestone and pale non-calcareous tuffs, no fragments of the adjacent olivine-basalts were found. Besides detached crystals of plagioclase, augite, hypersthene, and green or brown hornblende, they enclose fragments of acid hornblende-bandaite resembling fairly closely the acid bandaite south-west of Landing

Bay. Other fragments are not unlike more basic hypersthene-bandaïtes, or andesites, that occur in association with olivine-basalt fragments in the agglomerate near the summit of South Soufrière Hill. A fragment of very fine-grained hypersthene-bandaïte, or andesite, has already been referred to in connexion with the Landing Bay "inlier". At one locality the tuff contains pieces of semi-glassy olivine-basalt unlike any lava or tuff fragment found elsewhere in the island (F 4351, p. 58). It is thus probable that the explosive eruptions that gave rise to the pale tuffs disrupted pre-Pleistocene igneous rocks of varied character.

Near Sweeny's Well the details of the geological relationship of the pale fossiliferous tuffs to the adjacent basaltic tuffs are difficult to make out (fig. 17, Plate 2). The southern junction is possibly a fault with a downthrow to the south-west, for the basic tuffs immediately to the south-west have a southerly dip of 75° . The northern junction is, however, almost certainly an unconformity. It looks as if the tuffs and basalt lavas that extend down the face of Roche Bluff to sea-level at Roche Bluff Point are now disposed as they were originally deposited. That is to say, at the time basaltic lavas and tuffs were issuing from the South Soufrière Hill volcano, a steep south-eastwardly facing slope of disturbed and eroded fossiliferous tuffs existed at Roche Bluff, and was covered by the products of the basaltic eruptions. Between Landing Bay and the north side of Roche Bluff Point, there may have been an erosion hollow in the pale tuffs, which was filled up by basaltic tuffs and lavas.

(iii) *Acid bandaïte south-west of Landing Bay.* A few hundred yards south-west of Landing Bay, the cliff section shows the basic lava and tuff series of South Soufrière Hill resting unconformably on a mass of very pale, almost white, hornblende-bearing bandaïte that locally passes into breccia. Rock of this type, locally full of cognate igneous xenoliths (fig. 41, Plate 7), forms the lower part of the cliffs for a considerable distance towards Triangle Rock Point.

This labradorite-dacite (p. 68, and fig. 43, Plate 8), the most acid of the analysed rocks of Montserrat, is easily distinguished from other bandaïtes of the island. It bears, however, a considerable resemblance to some of the small rock-fragments in the pale tuffs of the Roche Bluff area, and is undoubtedly connected with the eruptive period of the Roche Bluff centre. It seems probable that explosions more or less contemporaneous with the consolidation of the dacite (which I regard as intrusive) caused the uptilting and breaking up of the pale tuffs of Roche Bluff, not very long after their formation.

(b) *South Soufrière Hill*

(i) *Lavas and tuffs.* Interbedded basic lavas and tuffs make up the southern, south-eastern and eastern slopes of South Soufrière Hill, and form a capping on Roche's spur, where they extend down to sea level at Roche Bluff Point. The lavas of this area, mainly olivine-basalts, are the only undoubted flows in Montserrat. Dark basic tuffs are conspicuous on the western flanks of the hill (lavas being absent), and, as will be

described presently, they extend a considerable distance westwards underneath the deposits of the Soufrière Hills volcano (Jingo Ghaut inlier).

The radial dips of the basic lava and tuff series, as seen on the outer slopes of South Soufrière Hill and in Jingo Ghaut (Plate 9), indicate an eruptive source somewhere near the summit of the hill.

The higher forested parts of the hill were not examined, but exposures on the Roche's-Galway's track near the summit (2505 ft.) were all in agglomerate with large blocks and small fragments of olivine-basalt, or of hypersthene-andesite, or bandaite, with very sparse olivine.

The lavas form numerous outcrops on the steep hillsides and in the ghauts, but it is impossible to tell how many successive flows are represented. The most westerly outcrop is behind the buildings at O'Garra's; lavas are well exposed on the coast eastwards of this point. They vary from 12 ft., or less, up to about 40 ft. in thickness, and are poorly jointed (no sign of columnar jointing). Many of the flows have slaggy, scoriaceous, and clinkery tops (fig. 15, Plate 2) and bottoms. The vesicles are empty and the lava tops show no trace of contemporaneous decomposition (formation of "bole"). All the flows seem to be overlain and underlain by tuffs. Locally the lower and upper surfaces of flows are exceedingly irregular, and often the cliff sections show thin irregular lava tongues alternating with tuffs.

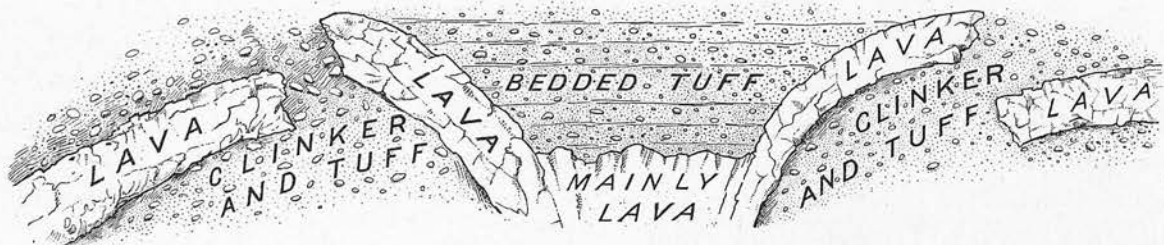


FIG. 5—Broken lava tunnels, south coast South Soufrière Hill.

A lava formation of exceptional interest is seen in the coastal cliffs eastwards of the small point situated about 600 yards west of Shoe Rock. I took Dr Jaggar to see one of these exposures (fig. 16, Plate 2); he suggested that the structure represents a lava tunnel similar to those formed locally where a lava front split into a series of lobes on reaching the coast, during the great eruption of Sakurajima (Japan) in 1914 (Kotô 1916). Kotô describes how lava flowed on in tunnels formed by the solidification of the outer crusts of the lobes, and how the roofs of the tunnels collapsed. Exposures a little farther along the coast make it clear that Dr Jaggar's explanation is correct. Here two adjacent lobes are seen in section; in each case the tunnel roof has broken, and tuffs that were laid down later, on top of the lobes, have penetrated into the tunnel cavity (fig. 5). The axes of the lobes pitch seawards at 25–30°.

The lavas are mainly olivine-basalts, with numerous phenocrysts of basic plagioclase and pyroxene (p. 69). Olivine-basalts were found on Roche Bluff, at Sweeny's Well

and south-westwards to O'Garra's. A few flows are hypersthene-andesites, or bandaïtes, with olivine very sparse or absent (e.g. Savannah Ghaut), and sometimes with traces of resorbed hornblendes.

The dark tuffs are largely composed of dark grey to black slaggy basaltic fragments, and are typically very evenly bedded (fig. 13, Plate 2). They are normal volcanic ashes, easily distinguishable from any volcanic ejectamenta elsewhere in the island. Locally the dark tuffs contain fragments of hypersthene-andesite with traces of olivine, and of bandaïte with some brown hornblende.

Magnificent sections in the dark tuff series are seen in the high walls of White River Ghaut, south and south-east of Galway's. Here, and on the hill slopes to the east, dark tuffs are interbedded with thick bands of pale tuff. Tuff beds of this type were not noticed in the lava area. A specimen was collected from a bed of very pale brownish tuff, fairly well consolidated but very light and porous, and typical of a number of these bands. It is composed of small fragments of olivine-basalts of South Soufrière Hill type, and of bandaïtes with green hornblende, along with detached crystals of plagioclase, hypersthene, augite, green hornblende and olivine. This mixture of types may indicate that the Soufrière Hills volcano (characterized by hornblendic rocks) became active before the South Soufrière Hill eruptions were over, and that some of its eruptive products were blown up by explosions of the latter basaltic volcano. The hornblendic fragments might, however, have been derived from buried rocks older than the South Soufrière Hill volcano (cf. Roche Bluff fossiliferous tuffs). It seems less likely that explosive eruptions of new basalt and hornblende-bandaïte magma alternated rapidly at the South Soufrière centre.

(ii) *Relations to Soufrière Hills.* The right bank of White River Ghaut is capped by bandaïte agglomerate, of the *nuée ardente* type characteristic of the Soufrière Hills volcano, and these deposits form the hill slopes from the Galway's-German's Bay spur northwards.

An inlier of the black slaggy tuffs of the South Soufrière Hill volcano was found in the bottom of Jingo Ghaut, north-east of Reid's Hill (Plate 9). Here they have a westerly dip, and are overlain by a considerable thickness of typical Soufrière Hills *nuée ardente* agglomerate, pale and almost unconsolidated. It is thus clear that the Soufrière Hills volcano is the younger, and that its deposits abutted on the western slopes of South Soufrière Hill before White River Ghaut was eroded.

A small outlier of Soufrière Hills agglomerate, consisting of a rounded knoll covered with large blocks of typical Soufrière Hills bandaïte with brown hornblende (p. 68), lies to the east of White River near the sea (Plate 9). Most of the debris of the Soufrière Hills eruptions appears to have been removed by erosion from the western slopes of South Soufrière Hill. It is probably represented, however, by breadcrust bombs that are found hereabouts. A bed of fairly well consolidated pumiceous tuff, with bandaïte fragments, that truncates the bedding of black tuffs, appeared to me to represent one

of the paler bands of the dark tuff series, locally filling up a contemporaneous erosion hollow (fig. 13, Plate 2). This exposure, on the track leading up the spur about 1000 yards north of O'Garra's, is, I believe, one seen by Dr Jaggar, and regarded by him as providing evidence of a very recent "veneer" of tuff on the hillside. Further field and microscopic study of the tuffs of this area, more detailed than was possible for Dr Jaggar and myself, should settle this interesting point.

(iii) *Area near Galway's soufrière.* About 800 yards down White River Ghaut from Galway's soufrière, olivine-basalt forms a high waterfall. This rock, except for a small irregular exposure of similar type not far upstream, is quite unlike any other in Montserrat. It is an ophitic, ophimottled, augite-rich basalt, with phenocrysts of olivine, plagioclase and pyroxene, and it forms the only outcrop in the island that bears any resemblance to a dyke. If it is a dyke, its trend is S. 15° W.; but I could not get definite evidence of its intrusive nature.

Upstream from this locality, as far as Galway's soufrière, the bottom of the gorge traverses what seem to be xenolithic igneous rocks containing cognate fragments of very fine-grained hypersthene-bandaite, not unlike that of the Landing Bay Ghaut "inlier". In the field the matrix is locally pale greenish, and the exposures have the appearance of agglomerate. It is possible that all the rocks just described are older than the South Soufrière Hill eruptions.

A little way downstream from Galway's soufrière, higher beds of tuff in the left bank have an (original) anticlinal structure that suggests an eruptive source in the soufrière hollow; I was unable either to get at them, or to make out how they are related to the tuffs of high cliff-exposures in the left wall of the gorge further downstream.

It is, however, clear that the agglomerate at the top of the right bank of White River, and to the west and north of the soufrière area, belongs to the Soufrière Hills. South-east of the soufrière, on the track that crosses the col connecting the Soufrière Hills and South Soufrière Hill, the rocks are deeply rotted and their history is indecipherable.

(c) *St George's Hill*

(i) *Structure and rock types.* St George's Hill (fig. 9, Plate 1), as was recognized by Sapper, is a small separate volcano of purely explosive origin. It is divided into two main ridges—a higher one (1180–1200 ft.) on the south-west, and a lower one on the north-east—by a broad curving valley. This depression was probably initiated by explosion during the period of activity.

The steep radial dip of the tuffs can easily be seen in the short deep ghauts that gash the flanks of the hill (Plate 9, and fig. 12, Plate 1). The bulk of the material forming the volcano is fine pale dusty tuff containing many pale dacitic pumice fragments. Stones and boulders of solid grey or dark glassy bandaite are also embedded in the

tuffs, and on the slope west-north-west of Gage's is a great obscured mass of shattered bandaite or bandaite breccia. There are also many bandaite blocks on the top of the hill. To the north-west of Lee's, rusty pumiceous tuff overlies pale tuff, while west of Gage's a thick bed of pale pumiceous tuff, steeply inclined southwards, overlies yellowish and reddish fine-grained bedded tuffs, or volcanic sands.

The tuff fragments that were examined, indicate a mixture of types resembling those characteristic of the neighbouring part of the Centre Hills and of the Soufrière Hills (pyroxene-bandaïtes and hornblende-bandaïtes). The hornblendic types are probably predominant. Some of the specimens are rich in tridymite.

(ii) *Age in relation to adjacent volcanoes.* Sections in the south bank of the Balham River, for instance north of Week's, prove that St George's Hill is younger than the Centre Hills. Here pale pumiceous tuffs overlie Centre Hills agglomerate. The section shows the great irregularity of the bedding of the tuffs on the lower outer slopes of St George's Hill (fig. 30, Plate 5). This irregularity is probably largely due to contemporaneous erosional effects of tropical deluges (cf. p. 38).

The evidence that St George's Hill is younger than Garibaldi Hill is partly indirect. The drainage system of the latter is much more mature, and Garibaldi Hill is believed to be of much the same age as the Centre Hills (p. 39). The St George's tuffs seem to end off against the lower slopes of Garibaldi Hill, near Delvin, and the upper tuff strata of the Richmond-Bransby ridge (of Garibaldi age) are possibly derived from St George's Hill (p. 39).

Three lines of evidence show that St George's Hill was formed before the eruptions of the Soufrière Hills volcano: (1) Pale pumiceous tuff was characteristic of the St George's Hill eruptions. There is, however, no sign of any material of this kind in the excellent sections immediately south of the hill in Fort Ghaut, or in the adjacent fields, where Soufrière Hills *nuée ardente* agglomerate forms the superficial debris. These deposits are therefore younger than St George's Hill. (2) Just to the south-east of St George's Hill the drainage of Gage's Soufrière Ghaut, and of the ghaut immediately to the north of it, is abruptly deflected south-westwards, to form Fort Ghaut. This indicates that the obstruction offered by St George's Hill locally deflected radial drainage initiated on later-formed slopes of the Soufrière Hills. (3) In Fort Ghaut, about 800 yards south-westwards from Gage's, agglomerate containing fragments of bandaite typical of the Soufrière Hills area is separated by a highly irregular erosional unconformity from underlying thinly bedded reddish and yellowish fine-grained tuffs or volcanic sands. These tuffs are somewhat consolidated and are unlike any others seen in the Soufrière Hills area. They locally dip southwards at 25° , and seem to correspond to the somewhat similar beds that underlie pumice on St George's Hill not far northwards. This evidence is not stressed, for it is possible that both sets of volcanic sands are Centre Hills deposits. On St George's Hill there are slight signs of disturbance and the beds there might conceivably have been uptilted by the

St George's outburst. This is a point that could be decided by careful re-examination. I saw the exposures at different times and found no opportunity to revisit them.

The prominence of hornblendic rocks on St George's Hill, and the immaturity of its drainage system, suggest very strongly that the eruptions of St George's Hill were separated by a relatively short period from those of the Soufrière Hills.

(iii) *Recent erosion.* Modern tropical rain erosion sweeps down great quantities of tuff from some of the Ghauts of St George's Hill and spreads it fanwise over the adjacent lower ground. A pond near Richmond is said to have been obliterated in this way during the great cloudburst of 1896, when 3 or 4 ft. of débris was deposited in the vicinity. The flood-waters of Fort Ghaut did great damage in Plymouth at the same time (Sapper 1903). Very recent narrow cañon-like ghauts, with vertical sides, gash the easterly slopes of the hill, near Lee's.

(d) *Soufrière Hills: central nucleus*

The general topographical and related geological features of the Soufrière Hills (3002 ft.) have already been described. This volcano is the youngest in Montserrat; it is of particular interest because it dominates the town of Plymouth, because all the active soufrières are situated on its flanks, and because in many ways it resembles Mt Pelé, in Martinique.

(i) *Gage's Soufrière Ghaut.* The most striking feature of the Soufrière Hills, as seen from near Plymouth, is the great depression that separates the Chance's Mountain spur from another prominent spur to the north (fig. 9, Plate 1). It forms the head of the ghaut on the sides of which Gage's Lower and Upper soufrières are situated. From the western side of Montserrat this great cleft looks somewhat like a breached and eroded crater. Its appearance influenced the American geologist Hovey when he stated that, apart from the absence of crater lakes, the principal volcanoes of Montserrat and Nevis seem to have much the same form as that possessed by Mt Pelé before the eruption of 1902. He says ". . . each presents a great crater whose wall is breached on one side to the base by a cleft that continues into a gorge of erosion" (Hovey 1903, 1905). While it cannot be denied that volcanic explosions may well have occurred near the head of the great cleft, I think that it may owe its origin very largely to erosion. This explanation seems the more probable because: (1) a large crater (English's Crater) has now been recognized on the eastern side of the serrated knife-edge ridge at the head of the great cleft; (2) the hollow has not the roughly circular shape characteristic of a crater; (3) the slopes of the spurs to north and south do not seem quite steep enough for crater walls.

(ii) *English's Crater.* Considerable attention was devoted to the densely forested ground around Chance's Mountain (3002 ft.), the highest point in the island, and to the east of this summit area, where Mr English had reported the presence of a large breached crater containing a central plug. The latter forms a forest-clad hill with one

or two rocky pinnacles, and rises to about 2530 ft.; it is known as Castles Peak, or sometimes as Castor and Pollux (fig. 19, Plate 3). The hill is conspicuous only from the Tar River area, and cannot be seen from the western side of the island.

On the north, the west, and the south, Castles Peak is separated from some of the main ridges of the Soufrière Hills by a deep and continuous semicircular wooded valley. On the east, beyond a small plateau-like area, the ground slopes down irregularly to the sea, and is trenched by several ghauts.

The examination of the area included an ascent to one of the summits of Castles Peak, a complete traverse round the bottom of the encircling valley, and observations from the Soufrière Hills summit ridge to the west.

Castles Peak, so far as can be seen, is all composed of pale grey bandaite with unusually large porphyritic crystals of hornblende. Perfectly fresh specimens were obtained from large blocks in the recently formed great earthquake rock-fall on the eastern side (fig. 19, Plate 3). On the way up through the forest one got the impression that part of the eastern slope was formed of an old accumulation of large broken blocks (cf. the talus slopes of the composite dome of Mt Pelé).

Both on the south, and on the north, the level of the bottom of the encircling valley is reached by climbing abrupt rather steep slopes, situated respectively towards the head of Tar River Ghaut, and towards the head of the main north branch of the Tar River valley. Between these points, for most of the way round the western side of Castles Peak, the bottom of the encircling valley seemed more or less level. The outer wall of the semicircular gorge is very precipitous, but the inner, formed by the slopes of Castles Peak, is much less abrupt (fig. 20, Plate 3). At one part of the traverse a moderately deep crater-like hollow, about 50 yards across at the base, was found to interrupt the regularity of the valley bottom. It was floored by about 2 ft. of mud, in which reeds were growing, and obviously becomes a pond in wet weather. This is clearly a small explosion crater; it is situated approximately north-east of the summit of Chance's Mountain, on almost the same bearing as Chance's Pond on the ridge far above. The two "ponds" are very similar.

Thanks to earthquake rock-falls, the material of the outer wall of the valley could be seen at a few places. The wall is partly composed of agglomerate, but to a considerable extent consists of solid bandaite. This labradorite-dacite must be intrusive, for there are no lava flows on the Soufrière Hills, and the precipitous slopes of the rock wall showed no signs of stratification. There is, however, no indication of the shape of the intrusive body, or bodies.

The features of the encircling valley cannot be attributed to the action of subaerial erosion. I therefore concluded, from what I had read about Mt Pelé, that they had been produced by a dacitic "dome" (Castles Peak) rising within a precipitous crater wall.

Subsequent examination of the summit area of Mt Pelé served to confirm this hypothesis. Here, a very similar semicircular valley ("fosse" or "moat") is bounded

on one side by the precipitous wall of the pre-1902 crater, and on the other by the talus slopes of the great composite dacite dome of the 1902 and 1929 eruptions (figs. 22, 23, Plate 4). In Martinique the evolution of the topography, as the dome rose higher and higher, was a matter of observation. There are, it is true, certain differences between the two areas. At Mt Pelé the crater wall shows distinct stratification, and the dome rises high above its top. In spite of this, I think there can be no doubt that Mr English's interpretation of the forest-clad Montserrat topography was correct, and that its history is, in essentials, similar to that of the topography of the summit of Mt Pelé. In each case the diameter of the breached crater approximates to 1000 yards, but while English's crater is breached on the east side, that of Mt Pelé is breached on the south-west.

(iii) *Chance's Pond*. This "pond" was a small reedy swamp, about 50 yards across, when I visited it after a prolonged drought. It lies in a small crater-like depression in the summit ridge of the Soufrière Hills, about 200 yards north-east of the top of Chance's Mountain. No rock is seen anywhere near, owing to the dense forest growth (fig. 25, Plate 4). In my preliminary report I signified agreement with Sapper's statement that there is no indication of the pond being a crater lake. Since then, however, I have seen an aerial photograph of craters in the summit ridge of Lassen Peak (Day and Allen 1925, fig. 22). This has convinced me that there can be little doubt that Chance's Pond lies in a small explosion-crater with a similar situation.

(e) *Soufrière Hills: deposits of outer slopes*

(i) *Nature of deposits*. The surface of the outer slopes of the Soufrière Hills is, as a rule, littered with bandaite blocks of all sizes, up to masses 12 ft. or more in diameter. In some places these boulders are much more abundant than in others. This is no doubt partly due to blocks having been removed from the fields for building purposes. Practically all the boulders are more or less porous, and thus lend themselves readily to dressing by masons. They have been used in the construction of many local buildings, including the churches, and the numerous windmill towers that were built in the old sugar-planting days.

The gently dipping deposits on which the surface blocks rest, and to which they belong, are almost everywhere practically unconsolidated. Different layers vary in character from aggregates of subangular bandaite fragments with very little matrix, to beds of volcanic sand and dust, usually pale grey, occasionally reddish. The most prevalent type consists of rock-fragments and blocks of various sizes embedded in a friable matrix of pale grey to pale brownish volcanic sand and dust (fig. 31, Plate 5). Some of the embedded blocks are very large (fig. 32, Plate 5). Ill-defined, but very regular, bedding is usually determined by the alternation of beds in which either the average size of the stones, or the proportion of rock-fragments to matrix, is different (fig. 24, Plate 4). Layers of volcanic sand and dust, from a fraction of an inch up to

a foot or so in thickness, occur locally. Often they are laminated, and their upper and lower surfaces, although remaining equidistant, are broadly undulatory.

A very large proportion of both the small rock fragments and of the large blocks, is porous. The porosity may be obvious to the naked eye, but in many instances it can only be detected by careful examination with a pocket lens. In colour the rock-fragments are pale to dark grey and occasionally reddish (oxidized). The term "porous" is here used to describe bandaites that contain small empty* cavities, usually of very irregular shape, and often bounded by rough "hackly" surfaces. Porosity is characteristic of almost completely crystalline rocks as well as of the less abundant types which, except for the phenocrysts, are almost completely glassy. The latter include the pumice fragments that are found locally; they are usually pale, almost white, in colour, exhibit flow-structure under the microscope, and show "fibrous" porosity, the pale glass lining the cavities being drawn out into fibres. "Breadcrust" bombs (fig. 42, Plate 7) with dark grey to black glassy crusts (due to the presence of brown glass), and broken fragments of these, are locally abundant, as for instance in the neighbourhood of Jingo Ghaut, and near Paradise and Tuit's. The interiors of the breadcrust bombs are highly porous, but the cracked glassy crusts are not even vesicular (p. 62). Breadcrust bombs and rock-fragments showing fibrous porosity seem often to occur in association. The bombs found did not exceed a foot or two in diameter.

The large bandaite blocks are almost all porous; they are usually pale to medium grey, often show local colour banding due to flowage (fig. 32, Plate 5), and contain numerous small cognate igneous xenoliths that are also porous. The larger masses are usually traversed by cracks (fig. 32, Plate 5), and, if lying on the surface, have in many instances disintegrated into smaller angular blocks, the shapes of which are defined by the cracks. Reference will shortly be made to the importance of all these details.

As a result of my examination of the débris of the *nuées ardentes* of the 1929-32 eruptions of Mt Pelé, which occupies the Rivière Blanche, or "Avalanche", Valley; I found that the above description applies in every detail to the Martinique deposits. Microscopic comparison of volcanic dusts from the Soufrière Hills and from "Avalanche" Valley has shown that they are of exactly the same character (p. 67). There can therefore be no doubt that the eruptions of the Soufrière Hills volcano of Montserrat were predominantly of the *nuée ardente* type.

(ii) *Gas emission in nuées ardentes.* It is hoped that the above description of the general characters of the *nuée ardente* deposits will prove of diagnostic value in future work on West Indian volcanoes. Similar data will be found scattered through many pages of Lacroix's great volume on Mt Pelé, but to the best of my knowledge the porosity of the large blocks has never been mentioned. The recognition of the prevalence of porosity of varying kinds and degrees and in rock-fragments of all sizes, is,

* There is often a little tridymite or cristobalite forming part of the cavity lining.

I believe, of great importance, because of its bearing on the mechanism of *nuées ardentes*.

Anderson and Flett were the first to suggest that these avalanches to a considerable extent generated fresh supplies of gas during their descent. In St Vincent they seem to have pictured the gases as being liberated during the solidification of discrete droplets of molten magma (Anderson and Flett 1903, p. 508).

Lacroix, from his experience of the dome formation that accompanied the *nuées ardentes* of Mt Pelé in 1902, emphasized the fact that the *nuées* there consisted of an emulsion of *solidified* rock fragments (and detached crystals), in water vapour and gas at high temperature. As far as Martinique was concerned he denied the generation of gas caused by solidification of molten material during the descent of the avalanches (Lacroix 1904, chap. VIII).

In the Valley of Ten Thousand Smokes, in Alaska, where the great eruptive "sand-flow" of 1912 presented many points of similarity to *nuées ardentes*, Fenner postulated continuous evolution of gas during the flowage. The solid particles of the sand were in this case pumice and fragmental glass (Fenner 1923, pp. 60 *et seq.*).

Shepherd and Merwin, following up Fenner's idea, reached the conclusion that fragments in the *nuées ardentes* of Mt Pelé (in 1902) had intumescenced more or less violently in their progress forward. This was apparently purely a laboratory deduction based on a chemical study of the gas content of dacitic specimens (Shepherd and Merwin 1927). Perret, probably independently, reached the same conclusion as the result of his observation of the passage of numerous *nuées* of the 1929-32 eruptions of Mt Pelé. He did not, however, correlate his conclusions with petrographic evidence (Perret 1935, pp. 84, 93).

In the Soufrière Hills of Montserrat, detailed study of the rock of Castles Peak dome, and of the agglomerates of the outer slopes, has furnished petrological evidence supporting the ideas of Shepherd, Merwin, and Perret, and making such conceptions more definite.

The microscopic study of the porous blocks of the Soufrière Hills shows that in the majority of cases a glassy residuum can be recognized. The glass is usually very full of microlites, and very rarely contains recognizable minute circular vesicles; the rocks are nevertheless often markedly porous. The more prominent the porosity, the greater is the proportion of residual glass in the groundmass. The majority of the abundant minute groundmass fragments in the *nuée ardente* dusts are semi-glassy and full of microlites, and only sparse fragments almost free from microlites show any signs of minute circular vesicles (p. 67). It thus seems clear that the *nuées ardentes* of Montserrat contained a considerable proportion of fragments and blocks of bandaite that had been on the point of solidifying as porphyritic rock with a holocrystalline but very fine-grained groundmass.

It is probable, as will be shown later (p. 66), that the more superficial rock of the dome had crystallized, and was slightly porous owing to the presence of minute

miarolitic cavities, before the great explosions blew it to bits.* Blocks of this nature, it is believed, contained highly compressed gas in their pores when they were blown up; and this gas was emitted as they descended as constituents of the *nuées ardentes*.

It is further suggested that there was a very considerable number of blocks which became markedly porous owing to the solidification of the final residuum as glass, and the expansion of gas, during their descent with the avalanches. There seems to be every transition from white pumice, to large grey glassy blocks with marked "fibrous" porosity, and from these to extremely porous semi-glassy blocks that do not appear to have their glass vesiculated or drawn out into fibres.† Gas was also expelled continuously from less abundant breadcrust bombs and pumice fragments (see p. 61).

Thus all the larger constituents of the *nuées ardentes*, crystalline and semi-crystalline, are to be regarded as having emitted gas during their descent with the avalanches. These conceptions will perhaps help to reconcile the apparently conflicting views of Flett and Lacroix, and make more understandable the transport of huge blocks for great distances. The special significance of the pumice fragments and breadcrust bombs (which contain green hornblende) will be considered later (pp. 54, 62, 70).

(iii) *Mode of formation of deposits.* Well-rounded boulders are not found in the Soufrière Hills deposits, and in the numerous ghaat and cliff sections bedding is usually very regular; "washouts" filled up by later eruptive products are very rare, if not entirely absent. In both these respects there is a marked contrast to some of the deposits of the Centre Hills. Contemporaneous tropical rainstorms acting on the *nuée ardente* deposits do not, therefore, seem to have produced beds that show any obvious evidence of fluvial processes having operated during their formation. It seems justifiable to conclude that the bulk of the deposits now exposed on the flanks of the Soufrière Hills were formed during a comparatively short period of violent explosive activity, and that in the main they were formed by direct deposition from *nuées ardentes*.

Judging by what I saw of the surface of the "Avalanche" Valley deposits in Martinique (in dry weather), it seems probable that some of the thinner layers, composed of fine dust, result from the combined action of wind transport and surface rain-washing during intervals in the series of explosions. Some of the layers in the Soufrière Hills deposits may have been formed as mud-flows, such as those observed during the eruptions of Mt Pelé and the Soufrière of St Vincent, but of this no evidence was obtained.

The gentle slope of the ground, and the lowness of the coastal bluffs, near Tuit's and Trant's (figs. 10, 27, Plates 1, 5), and north of Plymouth, probably indicate that the *nuée ardente* deposits of these localities filled up old hollows of considerable magnitude. An inlier of Centre Hills rock below Soufrière Hills deposits near St George's Church

* The groundmass of the rock of the Castles Peak dome is finely holocrystalline.

† See p. 66 for further evidence.

(p. 35), shows that a buried erosion surface there slopes fairly abruptly to the south. Southwards of Bethel the hill slopes, and the bedding of the Soufrière Hills tuffs, become somewhat steeper than near Tuit's and Trant's, and the coast is fringed by high cliffs (fig. 24, Plate 4). If, as is quite conceivable, the deposits near Trant's and Plymouth were formed by the latest eruptions of the Soufrière Hills, it is impossible to infer how recently these occurred.

If Hardy's sketch-map of soil distribution in Montserrat is compared with the geological map (Plate 9), it will be found that the area covered by his "talus" soils agrees very closely with that occupied by the outer slopes of the Soufrière Hills volcano (Hardy 1922). The term "talus soils" is thus to some extent a misnomer, for the deposits are essentially in the position in which they were deposited during the eruptive period.

In a few places the agglomerate of the outer slopes of the Soufrière Hills was found to be well consolidated. The cementation seems to be quite local and irregular; it appeared to be due to local deposition of iron compounds, or of other binding material, by surface waters.

(f) *Soufrière Hills: rock types*

(i) *Central nucleus.* Much of the summit ridge in the neighbourhood of English's Crater is formed of intrusive bandaite with porphyritic plagioclase, resorbed hornblende, hypersthene and sparse quartz; one specimen has traces of olivine. The Castles Peak bandaite, with its exceptionally large dark brown hornblendes (1 cm.), is the most striking rock in the island (fig. 39, Plate 7).

(ii) *Deposits of outer slopes.* Petrographically the rock-fragments of the outer slopes are almost all bandaites rather similar to that of Castles Peak, but often of a less pale grey colour and with smaller hornblendes. Augite frequently accompanies the hypersthene; the hornblende, often unresorbed, is usually brown. Certain of these hornblende-bandaites contain a few small olivines, often accompanied by sparse corroded quartz. Such rocks were found in the Cold River-Tar River area, near Paradise, and near Lee's. Tridymite, or cristobalite, is only occasionally abundant. The cognate xenoliths are porphyritic, glassy, and rich in brown hornblende; specimens containing olivine were found near Broderic's.

(g) *Soufrière Hills: age of eruptions*

We have already seen that the Soufrière Hills eruptions were later than those of St George's Hill and South Soufrière Hill, and thus occurred in Pleistocene or post-Pleistocene times. The supposition that the Soufrière Hills are younger than the Centre Hills, at once suggested by the less mature drainage system, is confirmed by the field relations of the rocks of the two volcanoes. On the north, smooth slopes sweep down from the nucleus of the Soufrière Hills, and their loose volcanic deposits stop abruptly against a ridge that extends from near Hodges, in the west, to Hill 965, near Tuit's (fig. 21, Plate 3; fig. 10, Plate 1). The ridge, and the hilly ground to the west of Bethel

and Trant's, are composed of bandaitic rocks (mainly in the form of well consolidated agglomerate) that differ in character from those of the Soufrière Hills. In the bottom of the ghaut near St George's Church was found an inlier of Centre Hills rock covered unconformably by loose Soufrière Hills deposits.

The northward sweep of the Soufrière Hills *nuée ardente* deposits beyond the corner at Tuit's (fig. 10, Plate 1) should be compared with Perret's panoramic photograph showing the local deflection of the deposits of "Avalanche" Valley in Martinique (Perret 1935, fig. 28). In the neighbourhood of Trant's there is probably some superficial alluvial outwash material from the Centre Hills, as well as the *nuée ardente* deposits of the Soufrière Hills.

(h) *Silver Hill*

(i) *Structure and rock types.* Silver Hill is a maturely dissected volcanic mass rising to 1285 ft. Its rocks are well exposed inland (as the area has no tropical forest) and finely displayed in the coastal cliffs. They consist to a very considerable extent of solid bandaite of a bluish- to greenish-grey colour, containing small phenocrysts of plagioclase, hypersthene and augite, traces of resorbed hornblende, and much tridymite (fig. 40, Plate 7); cognate igneous xenoliths are not uncommon. North-west Bluff is an example of a great cliff of solid bandaite. Close to the most easterly extinct soufrière on the north coast, the sea has formed a fine natural arch in spheroidally weathering bandaite.

Locally and irregularly the solid igneous rock passes into well-consolidated explosion breccia, or agglomerate that has, as a rule, no signs of stratification. Practically the only signs of bedded agglomerate are in the promontory north of Cars Bay and in the cliffs on the east coast at about the same latitude. These outcrops were only seen from the sea.

Silver Hill thus differs markedly from the other volcanic centres of the island in containing a much greater proportion of massive intrusive bandaite. It has already been inferred that its superficial volcanic tuffs have been stripped off by prolonged erosion, and that what is left represents the comparatively deep-seated nucleus of a Miocene or Pliocene volcano. The rocks of Silver Hill therefore probably correspond to the "old volcanic basement", often mentioned in connexion with other islands of the Lesser Antilles (e.g. Lacroix 1904, p. 3).

(ii) *Extinct soufrières; salt springs.* A feature of the Silver Hill area is the presence of a number of centres of former soufrière activity, of which six were located under the guidance of Mr T. R. Allen. The most westerly one was noticed by Dr Jaggar when passing in a steamer in 1902.

Where alteration due to the soufrières is most intense, the bandaite is quite rotted, pale yellow, and seamed with gypsum. Rusty decomposition extends over considerable areas in the neighbourhood of the soufrières at Rendezvous Bay and on the north coast, and the bandaite of North-west Bluff is locally altered, and veined by gypsum.

Springs "salt" to the taste occur close to the sea near the old soufrière on the south side of Rendezvous Bay, and at the most easterly one on the north coast. Another permanent salt spring has its source three or four hundred yards up Valentine Ghaut, the valley that reaches the sea at Rendezvous Bay.

(iii) *Age in relation to Centre Hills.* At a locality just west-north-west of Pinnacle Rock, on the east coast, a hollow has been filled, to a depth of 10 ft. or more, by a series of flat-bedded, and only slightly consolidated, volcanic sands or tuffs, including layers of pale porphyritic pumice. These beds are just like some of the more northerly deposits of the Centre Hills volcano, as seen, for instance, on the west and east coasts just south of the latitude of Cars Bay. The unconformable relation of these semi-consolidated flat beds to the hard rocks of Silver Hill is clearly seen, both from land and sea, at the top of the cliffs near Pinnacle Rock.

The presence, in an erosion hollow in the deep-seated rocks of Silver Hill, of this outlier of fragmentary material derived from the Centre Hills volcano, clearly shows that the Centre Hills eruptions were of very much later date.

(i) *Centre Hills: central nucleus*

The Centre Hills (2450 ft.; fig. 10, Plate 1), and the surrounding lower ground, represent, as we have seen, a large and maturely dissected volcano. On both leeward and windward coasts its irregularly bedded agglomerates and tuffs form precipitous iron-stained cliffs. These beds are consolidated or semi-consolidated, and differ in this and in other respects from the deposits of the Soufrière Hills.

Very little time was devoted to the higher forested parts of the Centre Hills, owing to the great difficulties presented by the terrane; on the high knife-edge ridges nothing could be seen except from tree tops. It was clear, however, that a good deal of the high ground is formed of solid igneous rock (bandaite), which is presumably intrusive because of its high central position, and because lavas are unrepresented on the outer slopes.* Nothing was seen to suggest the presence of an old crater, but a more detailed examination might possibly reveal one.

In the ghaut east of Waterworks, about three-quarters of a mile above the house, solid bandaite has been bleached and altered by old soufrière activity, with the formation of some iron sulphide. This much-obscured exposure was first visited by Dr Jaggar, at the request of Mr Paul Hollander, and was subsequently examined by the writer. Sites of other old soufrières would doubtless be found by careful search.

(j) *Centre Hills: deposits of outer slopes*

The outer slopes of the volcano were completely traversed, mainly by road and track. The cliff sections were also examined from the sea. For descriptive purposes the slopes of the Centre Hills may be divided into two districts presenting somewhat different features.

* The bandaite mass north of Tuit's may possibly be extrusive, but this is doubtful.

(i) *Balham—St John's Church—Statue Rock.* From Balham round the north side of the volcano to near Statue Rock, inland exposures along road and track are to a large extent in tumultuous agglomerate containing stones and boulders of all sizes, up to blocks 6 ft. and occasionally 20 ft. across, embedded in a matrix of semi-consolidated fine-grained tuff, or volcanic sand, which is sometimes abundant, and sometimes very scanty. The hill slopes and fields are usually littered with blocks weathered out of the agglomerate.

The dips shown on the geological map were obtained from the comparatively rare exposures of intercalated fine-grained tuff layers. In colour the tuffs (beds or matrix) are buff to rusty brown, and sometimes greenish or reddish. The rock fragments are pale grey to bluish or greenish grey bandaites. They are not uncommonly reddened (oxidized). The large blocks often contain cognate igneous xenoliths and very occasionally show flow-banding. Fragments of very pale porphyritic pumice ("fibrous" type) are common in the fine tuffs; beds of pumice are especially prominent in road exposures in the north, between St Peter's and Cudjoe Head, and around St John's Church and Braid's. Except in the pumiceous types, porosity is rare. One or two breadcrust bombs, or fragments of these, were seen near Cars Bay.

The coastal cliff exposures show a much greater proportion of fine-grained tuffs and volcanic sands. They reveal marked irregularity of bedding and the lenticular nature of many of the layers. The sections on the west coast are particularly instructive.

In some of the agglomerate beds, both inland and on the coast, certain boulders may show signs of rounding by water action (fig. 29, Plate 5).

(ii) *Bugby Hole area.* In the area on either side of Bugby Hole valley, from near Trant's to near Hodge's, the rocks exposed consist largely of well-consolidated coarse rusty agglomerates, which are locally much rotted. The only indication of dip was found in a fine-grained tuff bed near Hodge's. The bandaite fragments differ in character from most of those collected in the area first described.

A great mass of solid bandaite containing traces of olivine was found near Tuit's (Plate 9), and a smaller outcrop of similar character was located just to the north. Definite evidence of the relation of these masses to the neighbouring agglomerate was not obtained.

(k) *Centre Hills: rock types*

Only two specimens of solid bandaite were collected from the central nucleus; they are both hornblende-bearing, and one contains porphyritic quartz.

From Balham round the north of the volcano to near Statue Rock rather acid hornblende-bandaite are prominent. A good many of the stones are glassy or pumiceous and contain green hornblende; in other types the hornblende is resorbed or oxidized (red-brown). Rocks with abundant brown hornblende, like those of the Soufrière Hills, are not represented. Quite a number of the specimens contain porphyritic quartz, and olivine is very rare. There are also more basic pyroxene-bandaite.

Tridymite is fairly common, except in the glassy types, and a few specimens contain cristobalite.

A typical fine-grained tuff, from Cars Bay, was examined microscopically. It contains minute fragments of highly vesicular glassy pumice and of oxidized hornblende-bandaite, as well as broken crystals of hypersthene and green hornblende, decomposed plagioclase, and some iron ore.

In the Bugby Hole area the rocks are hypersthene-augite-bandaite, usually rich in tridymite, and with only traces of hornblende, or none at all. Olivine, usually very sparse, was found in the solid bandaite north of Tuit's, and in blocks in the neighbouring agglomerate.

Cognate xenoliths are common; they are hornblendic in the hornblende-bandaite, and pyroxenic in the pyroxene-bandaite.

In a great many of the rocks of the Centre Hills, as in those of Silver Hill and Garibaldi Hill, the groundmass has a bluish grey to greenish fine-grained felsitic appearance in the hand specimen. This feature distinguishes these bandaite from most of those of the Soufrière Hills. In some instances the effect is produced by the finer grain of the groundmass, but in many specimens this is not the case, and it may possibly be due to the presence of very abundant tridymite.

(l) *Centre Hills: eruptive history*

The distribution and character of the rocks suggest that those of the Bugby Hole area represent the products of some of the earlier eruptions of the Centre Hills. The character of these agglomerates does not suggest that they were formed by eruptions of the *nuée ardente* type.

The deposits on the other parts of the outer slopes also differ in many ways from those of the Soufrière Hills, for instance in: (1) the rarity of porosity in non-pumiceous fragments and blocks; (2) the irregularity of the bedding; (3) the abundance of lenticular beds of fine-grained tuff or volcanic sand; (4) the presence of water-rounded boulders in some agglomerates.

The coastal sections show clearly that between successive explosive eruptions the slopes of the volcano were much dissected by contemporaneous water erosion, and that the channels so formed were subsequently filled by younger volcanic debris (fig. 28, Plate 5). Water transport has clearly played a part in the formation of many of the beds. To what extent explosive eruption of the *nuée ardente* type occurred, it is very difficult to judge. It seems unlikely that such outbursts played a predominant part in the history of the volcano.

(m) *Garibaldi Hill*

Garibaldi Hill (840 ft.), with its radial drainage system and radially dipping tuffs and agglomerates, is clearly a small separate volcanic centre of the explosive type. Its age in relation to the Centre Hills is not clear. The two volcanoes are thought to

be of about the same age because of the maturity of their drainage systems, and because the rock fragments of the agglomerates of Garibaldi Hill are very similar to pyroxene-bandaite fragments of the Centre Hills. They are rich in tridymite and cristobalite.

Garibaldi Hill consists partly of well-consolidated agglomerate and partly of semi-consolidated fine tuffs, often containing much pale pumice. Minor faulting affects the beds seen in the cliff section between Old Road Bay and Fox Bay.

Bransby Point is formed by an almost horizontal bed of well-consolidated, and exceptionally coarse, agglomerate that overlies fine-grained red pumiceous tuff. Some of the pyroxene-bandaite blocks in the agglomerate are 8 ft. across. The same two layers, dipping southwards, can be recognized in the coast section of Garibaldi Hill a little to the north; here the agglomerate is much less coarse.

From Bransby Point a well-defined ridge extends inland (eastwards) to near Richmond; it is separated from the lower slopes of Garibaldi Hill by a well-marked hollow. Near Bransby the ridge is breached by two ghauts: one leads back to Garibaldi Hill; the other, in wet weather, carries the water of streams draining St George's Hill.

I was unable to arrive at a satisfactory explanation of the geology and physiography of this area. Even the source of the pale tuffs that cap the ridge is not clear (p. 27).

X. ACTIVE SOUFRIÈRES

(a) *General account*

The active soufrières of the island, seven in number, are all situated in agglomerate of the Soufrière Hills. Information regarding them has been summarized in Table II, where they are arranged roughly in order of age. The most important soufrières, Gage's Lower, Galway's, and Gage's Upper, are between 800 and 1600 ft. above the sea; they are the only fumaroles mentioned in previously published descriptions of Montserrat.

It is clear from past records that the general activity of the Montserrat soufrières underwent a marked increase at the time of the 1897-9 and 1933-6 series of earthquakes. According to local observers each seismic "crisis" of the recent series was accompanied by noticeable temporary increase of emission of hydrogen sulphide at Gage's Lower soufrière. The first earthquake shock of the recent series (September 1933) was preceded or accompanied by the emission of abnormal quantities of hydrogen sulphide from this soufrière. In 1934 gas emission and seismic activity both increased. It is obviously desirable that methods be devised for obtaining some measure of the relative increase of gas pressure at soufrières during periods of local seismic activity.

When the expedition reached Montserrat, in March 1936, bubbling pools of water were a feature of Gage's Lower soufrière. By the beginning of May, after a prolonged drought, these bubbling pools had completely disappeared. Although the hot springs of Gage's Upper and Galway's soufrières still persisted, Dr Powell and the writer are of the opinion that the warm water of the soufrières is almost entirely of meteoric

origin; its temperature has been raised by contact with rising volcanic steam, hot gases, and hot rocks (cf. Day and Allen 1925, p. 175).

(i) *Geographical distribution.* The positions of the *soufrières* were fixed as accurately as possible by taking prismatic compass bearings, and by pacing from fixed points. A number of them lie approximately on a line passing across the summit area of the Soufrière Hills in a direction about E. 35° N.; these are Spring Ghaut, Gage's Upper, Cow Hill New, Cow Hill and Mulcair *soufrières* (fig. 3 and Plate 9). Little or no definite evidence of faulting of the surface rocks was found along this zone, but it may well represent a line of deep-seated crustal weakness. It may be significant that this direction is parallel to that followed by the Anegada Passage—regarded by Hess (1937) as determined by a tear-fault—and nearly coincident with the belt of earthquake epicentres included in Powell's "Region II" (Powell 1938).

On another almost parallel line, about 1000 yards to the south-east, lie (1) an old locus of *soufrière* activity in White River Ghaut, east of German's Bay; (2) Galway's *soufrière*; (3) hot springs near Tar River; (4) an alleged *soufrière* on the coast at sea-level, near Tar River. The latter locus of alleged activity was visited with a local guide, but no smell of hydrogen sulphide was noticed and little sign of rock alteration. The guide asserted that quite recently the characteristic odour of the gas had been noticed at this point on the coast. The north-east trend of this line is nearly parallel to the straight south-east coast of Montserrat, from Shoe Rock to Roche Bluff, which is suggestive of a fault feature.

One of the most important active *soufrières*, Gage's Lower, does not lie on either of these lines, but is situated about 500 yards to the north-west of that first mentioned. In the main west-north-westerly ghaut south of Gage's, signs of fumarole activity extend a little way up the ghaut from Gage's Lower *soufrière* (situated in its right bank) and are to be seen again (e.g. hot springs) for some little way before reaching Gage's Upper *soufrière* (located mainly in the left bank). For some way below these hot springs the stream has encrusted its bed heavily with iron oxides.

The existence of another line of crustal weakness is suggested by the fact that Gage's Lower, Spring Ghaut, and Galway's *soufrières* are situated very nearly on a line trending about E. 30° S. from Garibaldi Hill, through St George's Hill to the acid bandaite intrusion of the Roche Bluff centre, south-west of Landing Bay. This direction is parallel to the general trends of the north-east coasts of South America and Cuba.

(ii) *Gaseous products.* Hydrogen sulphide is the most obvious gaseous emanation at all the centres. Steam is also evolved, except at Cow Hill New and Spring Ghaut *soufrières*. Mulcair *soufrière* may also be an exception in this respect; I saw it only once from some distance offshore. At those *soufrières* where it is liberated, the rising steam can, as a rule, be seen from a considerable distance.

When the wind was blowing from the direction of Gage's or Galway's *soufrières*, temporary concentrations of hydrogen sulphide were strong enough to be decidedly

unpleasant in the neighbourhood of Plymouth, even during the comparatively quiet period of my stay in the island. At the soufrières themselves, silver articles are instantly blackened, and even in Plymouth they are very rapidly tarnished. White paint on a visiting liner was blackened by the gas while the ship was lying off Plymouth during one of the more active periods of the recent disturbances.

Sapper records that during the 1897-9 activity, at the time of the last and greatest earthquake, hydrogen sulphide exhalations from Gage's and Galway's soufrières were so great that for a week the whole leeward side of the island was filled with strong sulphurous fumes, and water that stood overnight acquired a thin shimmering skin. He also states that, in 1903, in spite of decreased activity, a noticeable smell of the gas was still sometimes felt in Plymouth (Sapper 1903).

Powell has found that the concentration of hydrogen sulphide in the immediate neighbourhood of the gas and steam vents was about 1 in 5000 in the year 1936. In Plymouth, even when the odour of the gas was very pronounced, the concentration was sometimes less than 1 in 10,000,000. At the soufrières the odour is not that usually associated with hydrogen sulphide. Powell suggests that this may be due to high concentration of the gas and consequent fatigue in the olfactory organs (Powell 1937).

Mr Perret, I understand, will shortly publish the scientific results of his 1934-5 gas and water collecting at Gage's Lower and Galway's soufrières.

(iii) *Mineral products.* Crystalline sulphur forms a local encrustation around all the gas orifices, large and small, but at the present day the total amount is not great. At one time sulphur from Galway's soufrière is said to have been exported in barrels.

Earle reported the presence of alum, gypsum and alunogen [$\text{Al}_2(\text{SO}_4)_3, 16\text{H}_2\text{O}$] at Galway's soufrière, and a mineral that is probably halotrichite [iron alum: $\text{FeSO}_4, \text{Al}_2(\text{SO}_4)_3, 22\text{H}_2\text{O}$] at Gage's Lower soufrière.

I collected samples of some of the encrustations on the rocks at Gage's Upper soufrière. A white silky fibrous mineral, occurring in radial aggregates with hollow centres, was submitted to Dr A. F. Hallimond of the Museum of Practical Geology. By means of optical tests he proved it to be alunogen. The aggregates produce a mammillated surface, which is locally stained in varying shades of brown. Encrustations formed of aggregates of little gypsum crystals were also found at the same locality.

Some of the alunogen is mixed with aggregates of minute greenish yellow crystals with a resinous lustre. Refractive index tests by the writer indicate that the mineral is probably copiapite (hydrated iron sulphate).

The agglomerate affected by the soufrière gases is always much bleached, rotted and locally iron-stained to varying degrees. The most intensely altered rocks are pure white in colour and make the soufrières very conspicuous from a distance. A pure white, light, and porous specimen of altered tuff was examined microscopically and found to be composed almost entirely of various isotropic minerals of very low refringence. Qualitative chemical tests by Mr C. O. Harvey show that the water-

soluble portion of the specimen contains sulphate and some aluminium and sodium, and that the insoluble portion is siliceous and contains probably more than 80% of silica. Dr J. Phemister, petrographer to the Geological Survey, was good enough to carry out tests, with specially prepared oils of low refractive index, on some of the minerals of the water-insoluble part of the rock. He reports that more highly refracting mineral aggregates are set in an isotropic matrix of which the refractive index lies between 1.445 and 1.455. A clear isotropic mineral with a lower refractive index (between 1.428 and 1.437) is also present, and was thought to be possibly fluorite. A quantitative chemical test for fluorine gave, however, a negative result. Moreover, fluorine was sought for in water and gas samples (from Gage's Lower and Galway's *soufrières*) that were sent by Mr Perret for analysis in the Geophysical Laboratory in Washington, in 1934; the results were negative. The identity of this mineral thus remains doubtful; possibly it is water-rich opal, occurring as pseudomorphs after phenocryst fragments in the tuff.

The chemical and petrographic evidence indicate that the white rock is largely formed of opal, with some soluble aluminium sulphates. Opal with about 9% of water has a refractive index of 1.446.

The above conclusions regarding the mineral composition of the rock most highly altered by fumarolic action agree well with results obtained by Day and Allen in the Lassen Peak district of California. Here it was found that opaline silica and aluminium sulphate are final products of the decomposition by acid of the lavas in the hot spring and fumarole areas (Day and Allen 1925). Fluorine-bearing minerals are to be expected in *soufrière* deposits. One of the outstanding characteristics of the fumarolic emanations and encrustations of the Valley of Ten Thousand Smokes (Alaska) was the large fluorine content (Zies 1929).

Jet black, pale yellow and grey muds are striking products at the hot-spring areas of Galway's and Gage's Upper *soufrières*. Qualitative chemical tests by Mr C. O. Harvey have confirmed the supposition that the black muds are largely formed of finely divided iron sulphide, and the yellow muds of free sulphur. The grey muds contain a mixture of these two components. Mr English had previously arrived at this conclusion.

(b) *Notes on individual soufrières*

The positions and general characters of individual *soufrières* are sufficiently indicated by the data of Table II, and by the photographic illustrations. A few additional notes are, however, required.

(i) *Galway's soufrière*. As the Admiralty chart in the neighbourhood of this *soufrière* does not agree with the present location of ridge, stream and track, a map of the locality has been prepared (fig. 6; and fig. 35, Plate 6).

In 1810 Nugent commented on the local destruction of vegetation, the almost daily shifting of the little vents from which sulphurous emanations came, the encrustations

of crystalline sulphur, the rapid blackening of silver coins, the intense local heat, and the "boiling" of the mountain stream that passed through the area. He described the bleached aspect of the rocks, and inferred the presence of alum. He estimated that the devastated area was 300–400 yards long and about 150–200 yards broad (Nugent 1811). These detailed observations are of great importance, for they show that the area of devastation and the nature of the activity have remained essentially the same for at least 125 years.

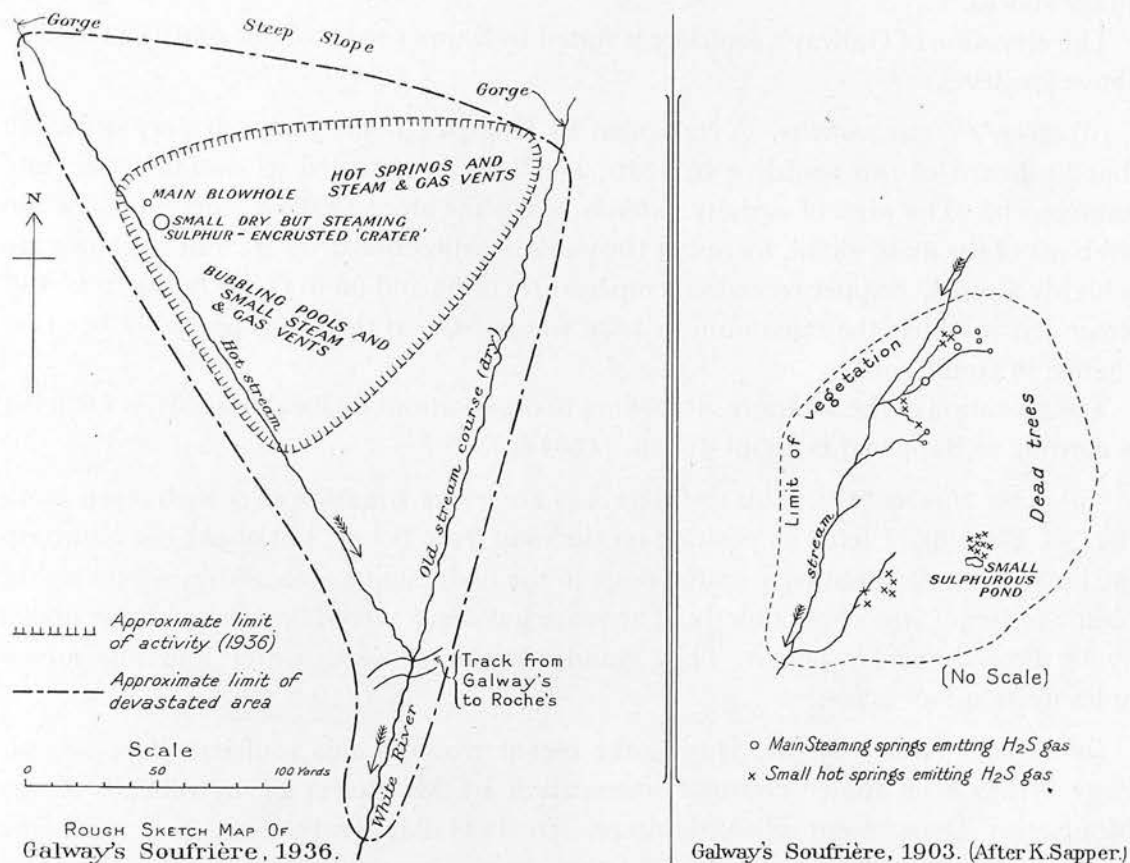


FIG. 6. Galway's Soufrière in 1903 and 1936.

Sapper's sketch of the area of activity in 1903 is reproduced in fig. 6. Since that date the main activity has evidently shifted from near a south-south-westerly stream to the neighbourhood of a south-easterly one; in Sapper's time it was "concentrated at the upper end of the soufrière area".

In 1903 Sapper found the temperatures of hot springs, gas jets, and steam jets, to vary from 34.2 to 93.2° C. At the time of my visits the main orifice was a sulphur-encrusted blow-hole, about 2 ft. across, from which gas and steam issued with a continuous roar (fig. 36, Plate 6). Nearby was a small dry, but steaming, sulphur-encrusted hole (like a small shell-hole crater) a few yards across. The highest

temperature recorded at the main blow-hole was 115° C., and at smaller jets 91° C. In 1935, and later in 1936, 120° C. was registered at the main blow-hole.

The maximum recorded temperature in 1936 was thus higher than in 1903. The results obtained depend on the skill of the observer in inserting the thermometer far down the blow-hole and maintaining it there against the pressure of the upward blast; they depend a good deal on wind conditions. From Mr English's notes it appears that the roaring blast was a feature of the *soufrière* before the recent period of earthquake shocks.

The elevation of Galway's *soufrière* is stated by Sapper to be about 480 m. (1570 ft.) above sea-level.

(ii) *Gage's Upper soufrière*. A statement by Nugent (p. 11) makes it very probable that he heard of this *soufrière* in 1810; locally it is regarded as dating from time immemorial. The area of activity extends along the steep shallow side-gorge, in the left bank of the main ghaut, for about 100 yards in a direction S. 35° E. The agglomerate is highly altered. Sapper recorded temperatures of 95 and 96.6° C. for hot springs and steam jets in 1903; the maximum in 1936 was 95° C., so there has probably been no change in conditions.

The elevation of the *soufrière*, according to observations by local officials, is 1600 ft.; according to Sapper it is about 460 m. (1504 ft.).

(iii) *Cow Hill soufrière*. This *soufrière* has a curious situation in a high steep bank (fig. 38, Plate 6). I fixed its position on the map from below, but could not climb up the bleached and sulphur-encrusted slope to the main active area above, where a thin plume of steam was rising quietly. The main gas vents were later visited from above by Dr Powell and Dr Jaggar. They found a trickle of warm water, and sulphurous holes up to a foot across.

(iv) *Gage's Lower soufrière*. During the recent troubles this *soufrière* (figs. 33, 34, Plate 6) has been under constant observation by Mr Perret or by officials of the Montserrat Department of Agriculture. In 1934 Mr Perret set up a recording thermometer with a buried bulb; the temperature was then 105° C. In 1936 this thermometer registered between 112 and 115° C. Trouble due to acid corrosion had, however, caused the instrument to record erroneous high temperatures in 1935, and, although the mechanism was completely overhauled by the makers, it is possible that the 1936 readings were still rather too high. The highest temperature registered by an ordinary maximum thermometer was 95° C.

In 1903 Sapper's observations ranged from 90 to 97.4° C. Here again there has probably been little or no change since the beginning of the century, for Sapper did not use a buried-bulb thermometer.

This is the only *soufrière* where the eyes and throat are seriously irritated by the gaseous emanations. During his 1934-5 observations Mr Perret spent a night in a hut he had erected in the *soufrière* gorge, and was seriously affected.

TABLE II. ACTIVE SOUFRIÈRES OF MONTSERRAT

Name of soufrière	Date of origin and record of activity	Location referred to	Description (1936)	Temperature of steam jets (1936)	Temperature of bubbling water (1936)	Remarks
Galway's	Known in 1810. Activity probably increased during both 1897-9 and 1933-6 earthquake periods	summit of Chance's mountain $\frac{3}{8}$ mile S.S.E.	In large depression near head of White River Ghaut. Large steam and gas blow-hole, small steam and gas jets, and hot springs	98-120° C.	72-92° C.	Also called Galloway's, South, or Roche's soufrière. Probably oldest active soufrière. Large area (about 5 acres) affected by gases Quite extensive area in south bank affected by gases. Temperature of hot springs some way down main ghaut 53-58° C.
Gage's Upper	Very old. Probably referred to by Nugent (1810). Activity increased just before or during earthquake periods of 1897-9 and 1933-6	300 yards W. 21° N.	In west-north-westerly ghaut south of Gage's, and in shallow side-ravine in its south bank. Small steam and gas jets and hot springs	93-95° C.	Cool, owing to cold water of stream in main ghaut	
Cow Hill	Very old. Activity probably renewed, or increased slightly, just before or during 1933-6 earthquake period	1 mile E. 42° N.	In steep slope of northern bank of first ghaut south of Tar River estate buildings. Small steam and gas jets	96° C.	None	Also called Tar River soufrière. Some years ago described by Mr English as "long extinct"
Gage's Lower	After 1896 cloudburst. Unusually active during 1897-9 and 1933-6 earthquake periods	Almost $\frac{3}{8}$ mile W. 15° N.	In short deep side-ravine in north bank of west-north-westerly ghaut south of Gage's. Numerous small steam and gas jets and (sometimes) hot springs	112-115° C. by thermometer; 95° C. by maximum thermometer	82° C. Dried up by middle of May after long drought	Often called simply "Gage's soufrière". Large area affected by gases. Thermograph readings possibly too high. Gases affect eyes and throat
Mulcair	? between 1896 and 1899. More active since about 1933	2 $\frac{1}{4}$ miles E. 40° N.	At base of cliff on east coast, just south of Hell Hole Bay. Emission of hydrogen sulphide gas	—	—	Accessible only by boat on a calm day. Not seen at close quarters by expedition
Cow Hill New	? about 1933 or 1934	$\frac{3}{8}$ mile E. 42° N.	In bottom of dry ghaut a few hundred yards south-west of Cow Hill soufrière. Emission of hydrogen sulphide gas	None	None	Located 1936. Area affected by gases is small (1250 sq. yd.)
Spring Ghaut	? 1933 or later	750 yards W. 11° S.	In bottom of Spring Ghaut near its head. Emission of hydrogen sulphide gas	None	None	Located 1936. Area affected by gases is very small

When Mr Perret revisited the soufrière in May 1936, after a prolonged drought, the hot springs had completely dried up, and only steam and gas were in evidence. He was struck by the marked decrease of activity as compared with that observed in 1934 and 1935.

The alteration of the local agglomerate begins about 45 yards eastwards up the little side gorge in which the soufrière is situated. The activity in 1936 began at a point 75 yards further east, and was confined mainly to the bottom of the gorge, which was dry below the active area, even before the disappearance of the bubbling pools in May. Bleached agglomerate, highly altered by previous activity, extends beyond the south wall of the side gorge for at least 50 yards south-eastwards from the present gas vents. Decomposed breadcrumb bombs, derived from the adjacent altered agglomerate, are a feature of the area of devastation.

The soufrière is generally believed to have opened up at the time of the great flood of 1896. Mr English has, however, stated that it originated between 1840 and 1850, probably in 1843 (cf. fig. 2).

According to local observers the elevation of the soufrière is 850 ft., while Sapper puts it at 340 m. (1112 ft.).

(v) *Mulcair soufrière*. This very inaccessible soufrière was not reached by any of the scientific visitors to Montserrat. I fixed its position, with the help of a guide, from the cliff top immediately above. There were no signs of soufrière alteration at the top of the cliff, but the odour of hydrogen sulphide was strong.

(vi) *Cow Hill New soufrière*. This small incipient soufrière, situated in dense forest, was located by the strong smell of hydrogen sulphide that emanated from it. An area of dead trees (fig. 37, Plate 6) extended for about 50 yards along the dry watercourse and was about 25 yards wide. The gas was emitted from minute indeterminate orifices. There was no steam, no appreciable heat, and only slight traces of sulphur encrustation.

(vii) *Spring Ghaut soufrière*. This small area of soufrière activity can only be reached after some rather awkward climbing of "dry waterfalls". It is in the bottom of Spring Ghaut about 525 yards above the end of a water pipe. The gorge here is narrow and the walls very steep. Vegetation a little way up the sides has been killed for a distance of about 50 yards along the gorge. The agglomerate was altered, but the orifices from which the hydrogen sulphide escaped could not be located. There was no heat or steam.

XI. HOT SPRINGS

In two widely separated places hot springs occur unassociated with soufrière activity, and at a third locality springs that feed a small pond are said to be sometimes hot.

(i) *Tar River*. Two hot springs are found only 120 yards apart in the Tar River (fig. 3), about 500 yards S. 30° E. from Tar River estate buildings. The Tar River (origin of name unknown) is fed by a cold spring that rises at a higher level, about

200 yards inland from the hot springs. The track from Tar River estate buildings to Roche's at present passes between the two hot springs. On the Admiralty chart the track is shown too far upstream in relation to an important ghaut junction situated just below the lower hot spring.

The maximum temperature measured was 40° C. at the upper hot spring. The lower one comes up through cold water. Each hot spring is associated with stalactitic deposits on the adjacent rocks, and around lianas.

(ii) *Hot Water Pond*. This small shallow pond, held up by beach sand at the mouth of a small ghaut on the west coast 1 mile north-west of Plymouth (fig. 3), is fed by hot springs that are alleged to be, or to have been, "salt". The water is locally just too hot to hold the hand in with comfort. The ghaut above the pond is dry except in the rainy season.

The sand barrier is sometimes breached by storms or floods, and in wet weather quicksands are formed. Along the beach for some way south-eastwards the sand at shallow depth is said often to be very hot.

(iii) *Fox Bay*. The small shallow pond that forms a mangrove swamp at Fox Bay, not far to the north-west, is maintained by seeping springs at its landward end. One of these is said to be sometimes hot. This pond is also held up by a sand barrier that is sometimes breached in wet or stormy weather.

XII. PETROLOGY

The petrological study of the rocks of Montserrat has proved of exceptional interest. Reference has already been made to inferences regarding the mechanism of *nuées ardentes*, that may be drawn from the petrological characters of the rocks of the Soufrière Hills (p. 31); this hypothesis is more fully developed, and extended to dome formation, in connexion with the petrology of remarkable cognate xenoliths in the rocks of the Soufrière Hills. In other sections is incorporated new evidence bearing on the magmatic corrosion of feldspar phenocrysts, on the production of red-brown and brown hornblende by "oxidation", on the "resorption" of hornblende, and on the character and mode of formation of breadcrust bombs of the peléan type. Volcanic dusts from the Soufrière Hills are compared with those of Mt Pelé, and with the "Barbados dust" of 1902, to which they bear a close resemblance.

A special section is devoted to the mode of occurrence and optical properties of tridymite, and of cristobalite (which often forms pseudomorphs after tridymite). The abundance of primary tridymite in the groundmass of many of the rocks, and of cristobalite or tridymite in cognate xenoliths, is an outstanding petrological feature of the island. Cristobalite (as such) is also recorded for the first time in the old and new domes of Mt Pelé.

The close resemblance of the seven analysed Montserrat rocks to volcanic rocks occurring elsewhere in the Lesser Antilles, and in the Lassen Peak District of California,

is brought out by comparative tables of analyses. It is significant that the eruption of Lassen Peak in 1915 was of the peléan explosive type.

(a) *Previous petrological work: Montserrat*

In Section v some notes have already been given on Waller's detailed description of a rock-specimen from the Soufrière Hills (Waller 1883). His observations were detailed and accurate, and notable for the recognition of hypersthene in West Indian rocks.

Lacroix has described four specimens collected by Sapper from the Soufrière Hills (Lacroix 1904). In 1904 he called them dacites, andesites and "andesilabradorites"; he recorded phenocrysts of quartz, plagioclase (labradorite to labradorite-bytownite), hornblende (red-brown and resorbed), hypersthene and augite, and compared them with various types from Martinique. In the groundmass of one of the rocks he found little crystals of quartz. In my slices from the Soufrière Hills I have been unable to be certain of the presence of any free silica in this form. He also stated that a feldspathic basalt from Sweeny's Well was indistinguishable from an olivine-basalt occurring at La Trinité in Martinique.

(b) *Nomenclature of Montserrat rocks*

The nomenclature adopted for the rocks of Montserrat is based partly on their mineral content, and partly on seven new chemical analyses representing the various rock types (Tables III and IV). With regard to the two most basic rocks, olivine-bearing lavas with basic plagioclase phenocrysts and a silica percentage of about 52, there is no difficulty; they are clearly olivine-basalts. The other five analysed rocks, on the other hand, present a problem of considerable complexity. Their silica percentage ranges from 56.75 to 64.21; all contain abundant phenocrysts of basic plagioclase, along with some of hypersthene or augite. The three most siliceous rocks have phenocrysts of hornblende, and sparse porphyritic quartz. Quartz phenocrysts are lacking in the pyroxenic rocks of Silver Hill and Centre Hills, but these have much tridymite in the groundmass.

Analyses A, B, C and D show how closely chemically comparable these rocks are with other West Indian types. Mineralogically they are also very similar. Rock A has been called a "hypersthene-andesite" by American petrologists. According to the revised nomenclature of Lacroix (1919, 1926) rocks B and D are "dacitoïdes", and rock C is a "dacite". Lacroix has defined a "dacite" as a rock of andesitic composition with modal quartz, and a "dacitoïde" as a rock similar chemically and mineralogically, except for the absence of modal quartz (Lacroix 1919, 1926). Rocks F and G, with only about 53.5% of silica, are called by him olivine-bearing "labradorite", and pyroxenic "dacitoïde", respectively. The zoned feldspar phenocrysts of Lacroix's dacites and dacitoïdes approximate to labradorite in composition, and have even more basic zones.

The Montserrat rocks, like Lacroix's dacites and dacitoïdes, are very different from the dacites of Rosenbusch, being, for example, richer in magnesia and lime and poorer in potash (Rosenbusch 1923). To such labradorite-bearing andesitic rocks, including the West Indian dacites and dacitoïdes of Lacroix, the name "bandaite (=labradorite-dacite)" was given by Iddings twenty-four years ago (Iddings 1913). The name was derived from the volcano Bandai San in Japan (Anal. L, Table IV). It will be seen from the norms of the analysed rocks of Montserrat that most of them fall into the sub-rang "bandose" of the American C.I.P.W. classification (Table V).

The term bandaite was rejected by Lacroix because it does not indicate whether modal quartz is present or not; at the same time he proposed to describe individual dacites as oligoclase-, andesine-, or labradorite-dacites (Lacroix 1919). Lacroix does not, however, adhere to this admirable scheme; he has called rocks simply "dacites" (without qualification) although they have labradorite phenocrysts and only 53.5% of silica (Lacroix 1926). This is very confusing, as the traditional dacites of Rosenbusch are so very different chemically and mineralogically.

Johannsen also rejected the term bandaite, his reason being that it was established on a consideration of chemical as well as mineralogical composition (Johannsen 1932). Johannsen, in his "purely mineralogical" classification, would apparently call such rocks quartz-basalts or basalts, according as modal quartz is present or absent. Neither term would convey to the writer the idea of a pale grey to almost white rock, or suggest the possibility of the presence of abundant green or brown hornblendes.

The term bandaite has priority over "peléite" adopted by Tröger (1935) for similar or identical rocks that fall, chemically, into Niggli's peléitic magma type (Table VI).

The writer defines the rock-names used in this paper as follows. The equivalent terms "labradorite-dacite" or "bandaite" describe andesitic rocks characterized by modal labradorite and silica, and agreeing closely with Niggli's peléitic magma type. Similar rocks without modal silica should preferably be called labradorite-andesites. A labradorite-andesite passes into a basalt when it contains less than 10% of normative quartz; the majority of basalts defined in this way have a silica percentage below 55.

The rocks of Montserrat are almost all labradorite-dacites and olivine-basalts; the former include hornblende-pyroxene-bandaïtes and hypersthene-bandaïtes, in either of which traces of olivine are occasionally found. In practically every Montserrat rock, other than olivine-basalts, modal silica is present either as sparse quartz phenocrysts, or as primary tridymite (or cristobalite) in the groundmass. A few basic looking, pyroxenic, but olivine-free, rocks are associated with the olivine-basalts of South Soufrière Hill and are not represented by an analysis; they are either labradorite-andesites or basalts.

(c) *Phenocrysts of Montserrat rocks*

(i) *Porphyritic feldspar*. In all the rock-types the characters of the porphyritic basic plagioclase feldspars are very similar. They are always abundant, and often form 30–35% of the rock.* They show stout rectangular to equidimensional forms, and vary greatly in size—from about 2.5 mm., down to 0.1 mm. (“microphenocrysts”). Internally anhedral glomeroporphyritic groups, sometimes along with hornblende, pyroxene, or iron ore, are common. Fractured crystals and broken fragments are usually present. Oscillatory zoning is usually very pronounced. Many crystal sections show very spongy cores, or exhibit internal sponginess in certain zones.

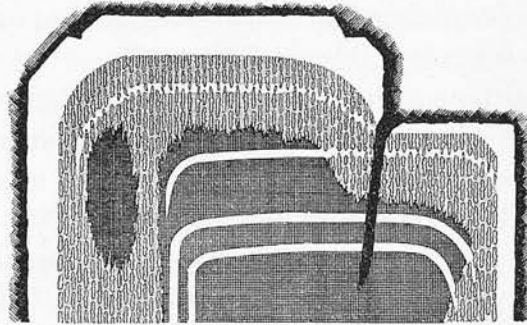


FIG. 7. Corroded phenocryst of zoned plagioclase. For explanation see text.

That this sponginess is in many, if not all, cases due to magmatic corrosion, is shown by the crystal illustrated (as it appears between crossed nicols) in fig. 7. It occurs in the glassy crust of a breadcrust bomb (F 4362).† At a certain stage in the history of this oscillatory zoned feldspar a change in physicochemical conditions caused the residual magmatic liquid to corrode the crystal. The outlines became smoothly rounded, and the corroding liquid, penetrating raggedly into the interior of the crystal along subparallel lines of crystallographic weakness, cut irregularly across pre-existing zones of varying composition. Finally a further change of conditions brought about a renewal of crystal growth, and the external solid rim of feldspar (white in the figure) grew outwards. During the corrosion process, the composition of the residual feldspar of the spongy portion was altered (cf. MacGregor 1930, p. 113), for it now extinguishes in a position different from that of the uncorroded feldspar of the core. The minute cavities in the spongy part of the crystal are filled with brownish glass resembling that of the groundmass of the rock.

In this and other rocks with residual glass in the groundmass, the porphyritic feldspars usually have little isolated irregular cavities (much larger than those of the spongy crystal of fig. 7) filled with brown or colourless glass containing a minute circular gas bubble. These cavities often tend to be subrectangular, with their longer

* Volume percentage.

† Numbers in brackets refer to microscopic sections in the “Foreign” Collection of the Geological Survey and Museum, London.

axis parallel to a crystallographic direction, such as that of the albite twinning. The feldspars also sometimes enclose minute pieces of pyroxene and iron ore, and, especially in the labradorite-dacites, little apatite prisms and needles.

In composition the zoned plagioclase of most of the bandaites approximates largely to labradorite ($Ab_{35}An_{65}$), and no part of a crystal is less calcic than about andesine-labradorite ($Ab_{50}An_{50}$); cores are not usually more basic than labradorite-bytownite ($Ab_{30}An_{70}$). The most acid plagioclase was found in an unanalysed hornblende-pyroxene-bandaite of the Centre Hills; the average composition is labradorite ($Ab_{44}An_{56}$) with zones varying from slightly more basic labradorite to andesine ($Ab_{56}An_{44}$). In the basalts the bulk of the feldspar is labradorite-bytownite ($Ab_{30}An_{70}$) with zones of more basic bytownite and less basic labradorite.

(ii) *Porphyritic quartz*. Quartz phenocrysts are always very sparse, and probably never form more than about 2% of any rock. They are found in practically every specimen from the Soufrière Hills, in most of the hornblende-bandaite of the Centre Hills, and in the hornblende-bandaite of Landing Bay. Part of a broken quartz crystal was found in a slice of hypersthene-augite-bandaite from North-west Bluff (Silver Hill area), which contains traces of resorbed hornblende.

The quartz appears always as rounded, or embayed, corroded relics, usually less than 1.5 mm. across (F 4338, 4347, 4389). It frequently has a rim, or "armour", of little pale green augite prisms around it (F 4339, 4361), but rimmed and unrimmed crystals may occur in the same slice (F 4362). In one instance a narrow zone of tridymite separates the quartz from the augite armour (F 4454).

(iii) *Porphyritic hornblende*. The prevalence of hornblende, very often completely, or almost completely, unresorbed, is a notable feature of Montserrat, more particularly in the Soufrière Hills and part of the Centre Hills. The hornblende-bandaite may contain from 3 to 7% of amphibole. There are three distinct mineral varieties, green, brown and red-brown, and they present features of great petrological interest. In size the crystals range from 1 or 2 mm., down to 0.1 mm. ("microphenocrysts"). Exceptionally they are larger (e.g. Castles Peak, 1 cm.). They often enclose small stout rectangular crystals of basic plagioclase, iron ores, and sometimes small ragged patches of hypersthene (F 4360). Glomeroporphyritic groups, fractured crystals, and crystals showing twinning, are not uncommon. In all cases the optic sign is negative. The more important optical characters are as follows:

Type	X	Y	Z	Z \wedge c maxima in different slices
Green hornblende	Pale yellow	Slightly brownish green	Darkish green (near olive green)	13-24°
Brown hornblende	Pale yellow	Dark, slightly yellowish, brown	Dark brown	13-24°*
Red-brown hornblende	Pale, slightly greenish, golden yellow	Reddish brown	Deep ruddy brown	0° \pm

* In the Castles Peak dome almost all longitudinal sections give straight extinction.



The *red-brown hornblende* occurs only in rocks that are reddened and oxidized. The best examples are in the analysed acid bandaite from near Landing Bay (F 4347; see Tables III and V); the analysis reflects the oxidation, in the excess of ferric over ferrous iron. This variety of amphibole is clearly to be described by the recently introduced term "oxyhornblende" (Winchell 1932, 1933).

Much experimental research has been done of late years on the production of brown or reddish brown hornblende by heating hornblende of a different colour, usually green (Kôzu, Yoshiki and Kani 1927; Barnes 1930; Kennedy and Dixon 1936). A notable optical change in the heated hornblende is the reduction of the extinction angle ($Z \wedge c$), often to 0° . According to the results of Barnes (as restated by Winchell in 1932) the changes are due to the oxidation of ferrous iron, owing to loss of hydrogen (not water), without any addition of oxygen from the air. It will be well to refer to this process as "auto-oxidation", for Barnes's conclusions, as stated by himself, appear to the writer to be expressed in somewhat ambiguous terms. Barnes carried out the heating, in air, to 800° C. He restored heated hornblende to its original colour and optical condition by reheating it in hydrogen. Kennedy and Dixon found that similar changes in an amphibole heated in air to 1000° C. were produced by the driving off of *water* (at several stages), but did not comment on the fact that their conclusions clashed with the views of Barnes and Winchell. Neither did they discuss the ratio of the percentages of ferric to ferrous iron in their analyses; in the unheated amphibole it is 0.54 : 7.99, while in the brown hornblende produced by heating it is 9.70 : 0.17. There has clearly been either oxidation or auto-oxidation. During the heating no precautions were apparently taken to prevent oxidation of amphibole or possible released hydrogen by the air. Kôzu, however, by heating common hornblende in nitrogen at a pressure of one atmosphere, produced reddish brown hornblende in which the extinction angle was reduced to zero.

In Montserrat it is clear that the red-brown type of hornblende results from some change affecting either green or brown hornblende. The fact that the red-brown amphibole occurs only in rocks that show clear signs of oxidation from external sources* suggests strongly that the change of common hornblende into red-brown hornblende, with $Z \wedge c$ approximating to 0° , has not been fully elucidated by the experimental studies. Thirty-three years ago Lacroix attributed the formation of red-brown hornblende (occurring in Martinique rocks reddened by superficial volcanic oxidation) to the effects of volcanic oxidation on green and brown hornblende; he produced a similar result by heating such amphiboles in air (Lacroix 1904, p. 532). These observations appear to have been overlooked by recent writers.

It should be mentioned that in Barnes's very extensive experiments the brown hornblende produced by heating in air is never described as having a reddish tinge. Kôzu and Kennedy, however, used the term "reddish brown". Dr Kennedy was good enough to place at my disposal the slides of his amphibole (a practically colourless

* For instance the production of iron oxide rims around pyroxenes (p. 56).

hydrous pargasite low in total iron). I should describe the colour of his heated material as reddish orange-brown. The Montserrat amphibole is a deep but brilliant ruddy brown. It is suggested that hornblende heated under volcanic oxidizing conditions may acquire a more ruddy hue than amphibole heated by means of an electric furnace, either in air or in a non-oxidizing atmosphere. In any case, it is probable that under volcanic conditions oxidation by air plays a part in the change.

The *green hornblende* of Montserrat is confined to rocks that are glassy or semi-glassy; it is invariably the amphibole found in the glassy breadcrust bombs and pumice fragments. The writer has therefore inferred that the much more abundant *brown hornblende*, which often occurs in holocrystalline or slightly glassy rocks, has been produced by partial auto-oxidation of green hornblende. A number of slices indicate that there are gradations in colour between green and brown.

The extinction angles of the brown hornblendes appear at first sight to be against this hypothesis; they show, as a rule, no change as compared with those of the green hornblendes. Kôzu, however, found that the extinction angles in his heated hornblendes remained unaffected until about 650–750° C., but thereafter fell very rapidly, were almost zero at 800°, and zero at 900°. This change was accompanied by decrease in weight and temporary contraction in volume. Unfortunately it is not made clear at what stage the colour change began. It seems possible that the alteration in colour, from green to brown, corresponds in some way to the change (involving loss of weight) that Kôzu, Kennedy and Dixon found to occur, on heating hornblende to temperatures between 400 and 500° C.* This loss of weight, according to Kennedy and Dixon, is due to the driving off of one portion of water; no information is given regarding the colour or extinction angle at this stage. The experimental results suggest to the writer that, under magmatic conditions, and at a higher temperature, slight relief of pressure produces a colour change (from green to brown) because of partial auto-oxidation of ferrous iron, due to loss of some hydrogen (or water?). An analysis of greenish brown hornblende from Mt Pelé supports this inference. The ratio of Fe₂O₃ to FeO is 6.90:5.85 (Lacroix 1904, p. 507), whereas in unheated green hornblendes the ratio is usually much less than 1, and in strongly heated (originally) green hornblendes it is much greater than 1 (e.g. Barnes 1930, p. 414). It is thought the change is less likely to be caused by reheating of a semi-consolidated or consolidated rock during a period of rising temperature in the preliminary stages of an eruption. The reasons for this opinion are (1) reheating of semi-consolidated rock would take place under very considerable pressure (Shepherd and Merwin 1927, p. 114); (2) some of the rocks with brown hornblende were not fully consolidated at the time they became involved in *nuées ardentes* and show no signs of partial refusion. It is, however, quite possible that the hornblende of the holocrystalline rock of Castles Peak dome was affected after the crystallization of the rock, by remaining for a long time at a high temperature and under very low pressure. This amphibole is very dark brown in colour, and, in the

* The amphibole was heated in nitrogen by Kôzu, but in air by Kennedy and Dixon.

three slices examined, all longitudinal sections, with one exception, show straight extinction. In the glassy rocks the sudden freezing-in of the hornblende crystals would render them immune to alteration. This hypothesis implies that the pumice and bread-crust bombs represent the more deep-seated, gas-charged, and less viscous part of the magma, in which the volcanic explosions originated.

In the rocks of Montserrat brown, red-brown, and (to a limited extent) green, hornblende show *two distinct types of "resorption" phenomena*: (1) a "black" type in which the hornblende is wholly or partly replaced by a very fine-grained aggregate, composed of minute granules of iron ore and pyroxene, and predominantly black and opaque; (2) a "pyroxenic" type in which the hornblende is replaced wholly or partly by a much less fine-grained aggregate of pyroxene (both hypersthene and augite), with some basic plagioclase, and iron ore. In the black pseudomorphs original feldspar inclusions remain unaffected. In the pyroxenic pseudomorphs feldspar inclusions are often unidentifiable, and may have provided much of the plagioclase.

Green hornblende is generally unaltered in the most glassy rocks. A few crystals in certain slices of pumice, or of breadcrust bombs, show "pyroxenic" resorption. Green hornblendes in pumice never show "black" resorption; those in breadcrust bombs show it in only one instance, in the form of extremely narrow rims. Green hornblende showing *extensive* "black" resorption was found only in two rocks, non-glassy intrusions of the nuclei of the Centre and Soufrière Hills.

The "black" type of alteration was fully discussed by Washington in 1896. He stressed the fact that these pseudomorphs are much more common in crystalline than in glassy rocks, and concluded that the alteration is not due to reaction with the magma, but takes place when the mineral becomes unstable under conditions of diminished pressure, and slow cooling from a relatively high temperature (Washington 1896). The rocks of Montserrat provide much evidence in support of this hypothesis. For instance, in one slice the presence of a narrow rim of unaltered hornblende *outside* a "black" core, suggests that the phenomenon is not due to magmatic reaction (F 4423).

In Japan it has been found that on heating brown hornblende in nitrogen at a pressure of one atmosphere, to a temperature between 1040 and 1100° C., it dissociates into a black opaque substance, and expands enormously along the *c* axis; at 1200° C. rhombic pyroxene (?) and magnetite were seen in the aggregates (Kôzu and Yoshiki 1927). The authors suggested that under magmatic conditions "black" pseudomorphs are produced by a change in concentration of the magma, or by rising temperature, or by both. No reference was made to the influence of pressure, or to Washington's views.

Whatever the origin of the "black" pseudomorphs, there is evidence to show that the formation of the "pyroxenic" type cannot be controlled by the same conditions. The aggregate chemical composition must differ considerably. Moreover, the hornblende of the most glassy rocks, including cognate xenoliths, not uncommonly shows

the pyroxenic type of alteration. It is therefore probable that the "pyroxenic" pseudomorphs are formed at greater depths than the "black" type, which are characteristic of more crystalline rocks.

Sometimes the whole crystal is represented by a well-shaped pseudomorph (F 4341). In other cases there is a broad outer zone of alteration (F 4340, 4397). The rhombic and monoclinic pyroxene of the central parts of pseudomorphs is often in the form of close-set little prisms with parallel orientation; at the outer margin the prisms are usually diversely arranged. Exceptionally a narrow hypersthene-plagioclase rim is extremely coarse in grain, and strongly suggests that magmatic reaction has played a part in its formation (F 4390). In some instances a "black" core is succeeded outwards by a "pyroxenic" margin, the line of junction being very irregular, as it is in crystals with unaltered hornblende cores (F 4378, 4337). In this case a relict core of hornblende, left after the formation of the pyroxenic rim, presumably became unstable at a later stage, under conditions of lower pressure.

The pyroxenic type of alteration was apparently very prevalent in the rocks of the Mt Pelé eruption of 1902, in which porphyritic hornblendes were rarely intact. Lacroix inferred that the change is of deep-seated origin as compared with that which produced "black" pseudomorphs, and is due to reaction with the magma. The writer's conclusions were arrived at before reading Lacroix's account (1904, p. 507) and on very similar evidence. Lacroix did not record hypersthene in the aggregates, nor did he describe their structure, or mention the possibility that the plagioclase may be derived from original inclusions.

(iv) *Porphyritic pyroxenes.* Most of the bandaites contain phenocrysts of hypersthene and augite, but hypersthene is often much the more abundant, and sometimes occurs without augite. In the olivine-basalts, augite not infrequently occurs without hypersthene. The total content of porphyritic pyroxene is usually between 3 and 7%. In one of the two analysed olivine-basalts it is 12%; in this rock monoclinic pyroxene is more abundant than rhombic. In size, stout prisms range, as a rule, from between 1 and 2 mm. down to 0.5 mm., and smaller ("microphenocrysts"); exceptionally they attain 4 or 5 mm. The crystals often form glomeroporphyritic groups with some iron ore, or feldspar; they are often broken and sometimes contain small enclosures of iron ore and feldspar. Not uncommonly hypersthene forms a core surrounded by augite (F 4329). The hypersthene is optically negative, with a rather small optic axial angle, and is strongly pleochroic (X = pale pinkish brown; Y = yellowish; Z = pale cold green); it is thus fairly rich in iron. In only one unique type of rock, a semi-glassy olivine-basalt found in the tuffs at Roche Bluff, was magnesia-rich rhombic pyroxene detected; in this case the pleochroism is not very marked, the optic axial angle large, and the optic sign probably positive. The mineral is therefore bronzite or magnesia-rich hypersthene (F 4351). The augite is optically positive with a medium optic axial angle; it is frequently twinned, pale cold green in colour, and only slightly pleochroic

to yellowish (*Y*). The maximum extinction angle in the bandaites is about 45° ; extinctions greater than this were occasionally noted in the olivine-basalts. The augite of these rocks may therefore be somewhat richer in Fe_2O_3 or Al_2O_3 (Winchell 1933); the pleochroism is slightly more marked, from cold greenish grey to a more yellowish tinge for *Y*.

In the oxidized rocks the pyroxenes often have a rim of iron oxide (in many cases largely haematite?). The pleochroism of the hypersthene is intensified close to the edges and in the vicinity of cracks (F 4347). The colour of the augite may also be locally deepened in a similar way (F 4414). Lacroix noticed similar changes in the oxidized rocks of Mt Pelé (Lacroix 1904, p. 531).

(v) *Porphyritic olivine*. Olivine phenocrysts occur in most of the basalts, and appear as sporadic crystals in a few of the pyroxene-bandaïtes and hornblende-bandaïtes. In the basalts they form about $2\frac{1}{2}$ – $3\frac{1}{2}$ % of the rock. They are usually small (0.5 mm. or less) but in some of the coarser basalts approximate to 1 mm. The largest crystal (1.6 mm.) was found in a bandaïte (F 4395). The olivines may be well shaped, or corroded and rounded. Both types of crystal usually have an "armour" of pyroxene prisms, as a rule more or less tangentially arranged. This pyroxene is often hypersthene (F 4359); sometimes it is largely augite (F 4414), frequently both pyroxenes are represented, and sometimes there is no reaction rim (F 4363). In the bandaïtes, corroded quartz crystals (often with a reaction rim of *augite*) are frequently present as well as olivine, and even in such rocks olivine may have no pyroxenic armour (F 4452). In the bandaïtes it is clear, however, that the olivine was not in equilibrium with the magma. Even in the basalts, olivine, although usually having good crystal outlines, almost always has a reaction rim of pyroxene around it. The olivines are very largely fresh, and practically colourless to slightly yellowish, but often have reddish brown iron material at the margins and along cracks. In the basalts the optic axial angle is very high and the optic sign negative. The mineral is therefore a magnesian olivine with not more than about 20% FeO (Winchell 1933). The olivines thus agree closely in character with those of the Tertiary basalts of the San Juan region (Colorado) which also show much magmatic resorption; an analysed sample has 19.84% FeO (Larsen and others 1936). Accessory olivine, characterized by reaction rims of hypersthene, occurs in the rocks of Mt Pelé and of the Soufrière of St Vincent (Lacroix 1904; Flett 1908). The olivine of the bandaïtes is believed to be similar to that of the basalts, but crystals giving decisive results on testing were not found. The olivine may enclose iron ore, but is itself often enclosed in feldspar or pyroxene.

(vi) *Porphyritic iron ore and apatite*. All the rocks contain sparse small phenocrysts of iron ore, that as a rule form 1 or 2% of the rock by volume. The bulk of the ore is magnetite (probably titaniferous), but ilmenite must also be represented, for its presence was proved in the black beach sands. The iron ore is frequently a constituent of glomeroporphyritic crystal groups.

Apatite is an accessory porphyritic mineral found in a good many bandaite slices from all parts of the island. The sporadic crystals are in the form of short stout prisms, about 0.1–0.2 mm. in length, with rounded ends (F 4361, 4374). Dark inclusions, which appear as fine striations parallel to the *c* axis, make many of the crystals pleochroic from reddish brown to very dark brown. The apatites occur alone, or in glomeroporphyritic groups with other minerals, and are evidently of deep-seated origin. They closely resemble dark microporphyritic apatites characteristic of Scottish Carboniferous volcanic rocks (MacGregor 1930, p. 93).

(d) *Groundmass of Montserrat rocks*

Tridymite and cristobalite are scarcely referred to in the following notes; a special section, devoted to their characteristics and mode of occurrence, immediately follows this more general account of groundmass constituents. Breadcrust bombs, which are always formed of hornblende-bandaite, are also treated separately.

(i) *Hornblende-bandaites*. The characters of several of the types of groundmass found in the hornblende-bandaite is sufficiently indicated in the brief descriptions of the analysed rocks of Landing Bay, Old Fort Point, and Castles Peak (p. 68). Only in the Landing Bay rock, which has the highest silica percentage of those analysed, and in some rather similar fragments in the fossiliferous tuffs of Roche Bluff, was any quartz definitely detected. It has already been pointed out (p. 32) that a groundmass with a very meagre amount of brownish or colourless glass (such as that of the rock of Old Fort Point) is the most prevalent type in the porous to miarolitic hornblende-bandaite of the Soufrière Hills. Sometimes there is rather more obvious residual glass (F 4313, 4378, 4407) and some rocks are extremely porous without having the “fibrous” porosity of the very glassy types (F 4375, 4376). The constituents of the holocrystalline “minutely spotty” type of groundmass (such as that of the Castles Peak rock) are largely indeterminable because they are so very small and so much obscured by microlites. The great majority are probably minute squarish sections of plagioclase feldspar; some quartz may possibly be present; there are several examples (F 4311, 4374).

In the pumice fragments the groundmass is a colourless glass with a refractive index well below 1.544. The glass is usually full of minute circular to ovate empty vesicles, and may show contorted flow lines (F 4392, 4411). In very porous rocks (not pumice) with “fibrous” porosity, the glass is often of similar character but may locally be tinged with a brown colour (F 4398). Flow structure sometimes depends on colour banding, but more usually on the alignment of small crystals and microlites of feldspar and pyroxene. Microlites are, however, sometimes diversely arranged, and in pumice fragments they may be absent.

Several of the hornblende-bandaite specimens from the Centre Hills have a non-vesicular colourless glassy groundmass crowded with minute microlites (F 4384). In

others the bulk of the groundmass is of the indeterminate "minutely spotty" type that results from slower cooling (F 4389). A rock of allied type from the central nucleus has numerous minute laths of oligoclase set in a very meagre residual glass (F 4423).

(ii) *Pyroxene-bandaïtes*. The analysed rocks from Silver Hill and from the Centre Hills have groundmasses fairly typical of the pyroxene-bandaïtes (p. 69). Sometimes there is more glassy residuum than in either of these rocks (F 4457), and in one specimen a crystalline groundmass is unusually fine-grained and free from small microphenocrysts (F 4358). There are, however, many specimens showing better examples of the primary tridymite that is so prevalent in rocks of these centres, and also in those of Garibaldi Hill and St George's Hill. It is a notable fact, to which reference will be made later, that, in Montserrat, no pumiceous or highly porous rock was found to be composed of pyroxene-bandaïte without hornblende.

(iii) *Olivine-basalts*. The groundmass of the analysed basalts from near Shoe Rock and O'Garra's are representative of those of many specimens from South Soufrière Hill. A few of the lavas collected have a rather coarser groundmass composed of basic plagioclase, granular to prismatic augite, and iron ore (F 4348, 4352).

Exceptional types are represented by a fine-grained chilled olivine-basalt occurring as a block on the beach near Roche Bluff (F 4350), and by a semi-glassy fragment from the fossiliferous tuffs of Roche Bluff (F 4351). A totally different rock is that which possibly forms the only dyke of the island, in the upper part of White River Ghaut (F 4324). In this basalt, minute laths of basic plagioclase are enclosed ophitically in numerous very ragged patches of pale fawn-coloured augite; between the augite patches the plagioclase is associated with minute olivines. All the olivines, including the phenocrysts, are decomposed (cf. p. 26).

(e) *Tridymite and cristobalite*

(i) *Recent research*. Tridymite and cristobalite have seldom been recorded as occurring in such abundance as they do in many of the rocks of Montserrat. In view of recent research, however, the abundance of the minerals should not be regarded as in any way exceptional. Of late years petrologists have begun to realize that in Tertiary and Recent volcanic rocks tridymite and cristobalite are much more prevalent and widely distributed than was previously supposed. Thus Kuno has found them to be common in Japanese volcanic rocks (Kuno 1933); Burri, who got typical material from Kuno for comparative purposes, has described them in small amount from Nicaragua (Burri and Sonder 1936); Fenner has recently recorded tridymite in volcanic rocks altered by fumarolic action in the Yellowstone Park, where it is regarded as a secondary mineral (Fenner 1936); and Larsen has found much cristobalite and tridymite in lava flows of the San Juan region of Colorado. Larsen has estimated that some of the flows have 20–30% of tridymite in the groundmass, and that the total quantity of tridymite in the San Juan lavas is 350 cubic miles (Larsen 1936).

Kuno suggested that the Japanese tridymite and cristobalite are primary crystallizations belonging to an earlier stage than the glass base. According to Larsen, the tridymite crystallized after the lavas had practically ceased to flow, but during their original cooling and as part of the groundmass of the rock. It tended to concentrate in the last mineralizer-rich part of the magma. To a very small extent it was deposited in gas cavities during the cooling of the rock, but after the crystallization of the groundmass. Larsen was apparently unaware of Kuno's work.

(ii) *Microscopic characters.* The optical determination of tridymite and cristobalite in the rocks of Montserrat presented great difficulties, owing to the fact that diagnostic data concerning these minerals, as given in various papers and standard mineralogical text-books, are either incomplete, ambiguous or contradictory. Kuno's paper is an exception, and his descriptions of tridymite, and his drawings and photographs of cristobalite, are extremely useful. Kuno's determination of cristobalite was confirmed by Kazumoto by means of an X-ray powder photograph.

The writer recognized tridymite by its low double refraction, by its very low refractive index (which gives it marked "relief"), by the straight extinction and negative elongation of numerous lath-shaped sections showing a cross-cleavage, by the frequent occurrence of "arrow-head" or "wedge-shaped" twins (Rogers and Kerr 1933, fig. 133), and by its comparative freedom from cracks. To confirm the determination, Mr F. A. Bannister and Dr G. F. Claringbull, of the British Museum of Natural History, were good enough to separate the supposed tridymite from a crushed rock (F 4379), and take an X-ray powder photograph. The photograph proved to be identical with that of artificial tridymite.

The cristobalite was recognized by means of the descriptions and illustrations in Kuno's paper. It frequently replaces tridymite laths in exactly the same way as described and illustrated by him. As regards double refraction and refractive index it is indistinguishable from tridymite in microscopic sections. In ordinary light, however, cristobalite often has a well-marked system of cleavages that give an appearance resembling nearly square to slightly rhomboidal overlapping tiles on a roof (F 4435). Locally, corners of individual "tiles" are rounded off, and produce a structure resembling rhomb-shaped overlapping roof-tiles with rounded corners (F 4457). In some instances the "cleavage" system can only be described as irregular curving cracks (F 4330). It should be noted that in many instances the cracks or cleavages producing the "tile" effect are not at right angles, as described by Kuno, but make an angle of about 107 or 73° ($90 \pm 17^\circ$). The cristobalite aggregates have an irregular patchy mottled appearance between crossed nicols (best seen on inserting a gypsum plate). The polarization mottling does not necessarily coincide with individual units of the "tile" system, as was apparently the case in Kuno's slices. Well-defined complex twinning seen in some aggregates (F 4435), and in no way corresponding to the tile pattern, is possibly relict from original tridymite, but this is a mere guess.

Rocks containing abundant supposed cristobalite with the above characteristics were submitted to Dr Claringbull for X-ray determination (F 4330, 4435, 4457). Separated material produced X-ray powder photographs indistinguishable from those characteristic of cristobalite. In two of the slices (F 4330, 4457) there appears to be a little residual tridymite that has not changed to cristobalite, but in the separated powder there was not enough present to produce an appreciable effect in the X-ray photograph.

The results of the optical and X-ray examinations raise the suspicion that the traditional description of tridymite as occurring in minute overlapping plates or scales may, in some, or perhaps all, cases refer in reality to cristobalite (cf. p. 72).

I take this opportunity of thanking Mr Bannister and Dr Claringbull for their ready co-operation. Without their assistance decisive results could not have been obtained. The Montserrat slices, deposited in the Museum of Practical Geology in London, will now serve as standard British material for purposes of comparison.

(iii) *Mode of occurrence and origin.* The observations made on the tridymite of the Montserrat rocks fully confirm Kuno and Larsen in regarding tridymite as a primary magmatic mineral. The cristobalite may possibly replace original tridymite in all cases.

Tridymite appears in the groundmass of the pyroxene-bandaïtes as crystals of very variable size; it gives delicate needle-like sections about 0.02 mm. in length, and narrow or stout laths up to about 0.4 mm. long. The delicate needle-like crystals are sometimes embedded in localized patches of residual colourless glass with a refractive index well above that of tridymite, but well below that of the balsam (F 4453, 4454, 4458). Again, the whole groundmass may be permeated by diversely arranged "needles" (F 4359). In the slice just mentioned delicate laths of tridymite have developed in a crack completely traversing a feldspar phenocryst, and in an (apparently) isolated cavity in the crystal. One slice shows particularly clearly that the tridymite is of primary magmatic origin, for sporadic delicate needle-like tridymite crystals, and stout tridymite laths replaced by cristobalite, are embedded in the residual brown glass of the groundmass (F 4457). In other instances, where residual glass is absent, or extremely sparse, abundant tridymite laths form a primary groundmass constituent along with feldspars (F 4366, 4370, 4379). Arrow-head twins, and the larger stout lathy sections, tend to occur together as constituents of patches up to 1 mm. long, but usually smaller; these may represent original rock-pores (F 4395, 4453, 4369). In most of the hornblende-bandaïtes of the Soufrière Hills, and in the basalt lavas of South Soufrière Hill, tridymite was recognized only in small amount; it probably occurs to a considerable extent in partly empty pore cavities, but this is difficult to ascertain as contents of rock-pores tend to break away during the grinding of rock-slices.

The cristobalite, besides obviously replacing tridymite laths or twins (F 4455, 4457), often occurs as innumerable rounded to irregularly shaped spots up to 0.1 mm., or occasionally 0.4 mm. across (F 4307, 4451). Some of these spots may have been formed

directly by cristobalite, but they may equally well have originally been tridymite or even quartz (Sosman 1927, chap. v).

Cristobalite is not so widespread as tridymite and was not detected with certainty in the basalts; hornblende-bandaite fragments collected in the vicinity of Cold River are particularly rich in the mineral. The occurrence of abundant tridymite and cristobalite in cognate xenoliths is referred to in a later section.

Lacroix's observations on the tridymite of Mt Pelé* led him to certain tentative conclusions regarding its mode of origin. Later it will be shown that some of the Mt Pelé "tridymite" of Lacroix may possibly be, in reality, cristobalite (p. 72). He found that until January 1903 the mineral was very rare in fragments ejected from the volcano; by January 1904 it was very abundant in blocks that fell from the dome. The "tridymite" apparently occurred in fissures or cavities; it was not present in rapidly consolidated glassy ejectamenta. Lacroix concluded that the mineral was formed after the solidification of the rocks in which it occurred, owing to prolonged circulation of gases at high temperature. He made the generalization that the production of "tridymite" during the slow cooling of volcanic rocks is a sign of "old age" (Lacroix 1904, p. 519). Subsequently he suggested that the "tridymite" was produced, at a high temperature, by transformation of glass, owing to reheating or the action of water vapour; later on, at lower temperatures, quartz was formed in an analogous fashion (Lacroix 1908, p. 56). As regards Montserrat, it is clear that none of the tridymite or cristobalite originated owing to late reactions of this kind, although some of the material that occurs in pore cavities must be of very late formation. Much of the tridymite of the island is clearly of primary magmatic origin; its crystallization took place as an ordinary groundmass constituent, and before the glass solidified. Larsen's statement that tridymite tends to concentrate in the last mineralizer-rich part of the magma is confirmed by the tendency to localization of especially big laths and wedge-twins in patches that appear to represent pore cavities.

The inversion relations of quartz, tridymite and cristobalite are so complicated that their occurrence provides no useful data regarding the temperatures at which they were formed (Sosman 1927, p. 786).

(f) *Breadcrust bombs*

According to Lacroix, one type of peléan breadcrust bomb was projected into the air in a pasty condition, and was cooled at the periphery with release of gas and the formation of a glassy crust (Lacroix 1904, p. 523). Shepherd and Merwin analysed glassy crusts of breadcrust bombs from Mt Pelé and Lassen Peak and pointed out that, *on the contrary*,† these have retained a large amount of their gases as compared with

* Scales of tridymite were found by Flett in cracks and cavities in some St Vincent rocks (Flett 1908). Lacroix recorded abundant "tridymite" in certain rocks in Guadeloupe (Lacroix 1904, p. 584) and cristobalite in an andesite in St Vincent (Lacroix 1904, p. 593).

† I think it is just possible that Shepherd and Merwin have misunderstood Lacroix; his statements certainly seem to imply expulsion of gas from the crust, but there is a certain element of ambiguity.

the interior (Shepherd and Merwin 1927, p. 109). Further evidence bearing on this interesting point was provided by slices cut from breadcrust bombs of the Soufrière Hills (fig. 42, Plate 7). These show the zone of transition from the dark glassy exterior to the pale grey porous centre (F 4397, 4406). The dark glassy crust is about 0.5–2 cm. in thickness, the transition to the stony looking interior being very irregular, but fairly abrupt. The groundmass of the crust is *quite free from vesicles*, and is a brown glass crowded with little feldspars, pyroxenes and ores, and innumerable microlites. The interior groundmass, on the other hand, is made of paler to colourless glass, containing little crystals and microlites, and *crowded with numberless minute subcircular vesicles*. The chemical deduction of Shepherd and Merwin is thus fully confirmed. Lacroix found the phenocrysts of the crust to be intact and those of the interior often broken. In the Soufrière Hills specimens the phenocrysts of the crust are also often broken. The gases from the interior escaped, of course, through the cracks that developed, as Lacroix pointed out, as a result of the contraction of the glassy crust, and the expansion produced in the interior by vesiculation. It is clear from the study of these bombs, and from the character of the pumice fragments, that extensive loss of volatiles changes the residual glass from a brown to a white colour. Shepherd and Merwin did not comment on the chemical significance of this phenomenon.

The writer regards the breadcrust bombs, which are not of very common occurrence in the *nuée ardente* deposits, as representing comparatively sparse pasty portions of the magma ejected so far upwards by the explosions, that they got temporarily free from the hot gas cloud, and were thus rapidly chilled by the cold air.

At Mt Pelé Lacroix also recognized bombs that were ejected (1) in a semi-consolidated, and (2) in an almost entirely consolidated state. The former have some breadcrust cracks, but the latter only contraction cracks. He restricted the term "bomb" to blocks ejected at high temperatures and characterized by contraction cracks of some kind. Some of the bandaite blocks in Montserrat have developed a crack system on cooling, but show no trace of a glassy crust.

Day and Allen pointed out, after studying the ejected blocks of the 1914/17 *nuée ardente* eruptions of Lassen Peak, that the peléan breadcrust bombs of Lacroix differ from previously described breadcrust bombs in that their shape has not been affected by their flight through the air (Day and Allen 1925, p. 69). This was accounted for by Lacroix as being the result of the lack of ready fusibility of the "dacitic" magma, and the relatively low temperature of the ejected blocks, as compared with the conditions of basaltic eruptions. Day and Allen go on to describe breadcrust bombs ejected from the Lassen Peak volcano as being solid blocks of rock superficially reheated, by gas combustion or otherwise, so that their surface softened (while the interior remained solid and unaltered), and on subsequent cooling developed breadcrust cracks. Their statement is made in such a way as to give the reader the impression that this type of breadcrust bomb had been described by Lacroix from Mt Pelé. As far as Martinique is concerned, I have been unable to find any indication of such an interpretation by

Lacroix of any of the ejected rocks or bombs described by him. In Montserrat there are no bombs, blocks or rock fragments to which it applies.

It has already been mentioned that Shepherd and Merwin found that glassy crusts of breadcrust bombs from Lassen Peak have retained their volatiles to a much greater extent than the interior parts. This clearly shows that there are breadcrust bombs at Lassen Peak to which the hypothesis of Day and Allen does not apply. Day and Allen, who wrote before the publication of the work of Shepherd and Merwin, make no mention of any type of breadcrust bomb, other than those of which they supposed the surface to have been softened by reheating. It is thus impossible to infer to what extent true peléan breadcrust bombs occur at Lassen Peak.

(g) *Cognate xenoliths, and their bearing on the formation of peléan domes and nuées ardentes*

The presence of abundant cognate xenoliths is a striking feature of the hornblende-bandaïtes and the pyroxene-bandaïtes. They are found both in the larger blocks in the agglomerates, and in massive bandaïtes, such as those of Castles Peak and Landing Bay (fig. 41, Plate 7). They are generally irregularly ovate in shape and rather small (up to 4 in. across). The largest one found was a banded xenolith 12 by 9 in.; it was enclosed in a banded labradorite-dacite. The xenoliths are usually darkish grey in colour, and in any case are darker than the rock in which they are enclosed. They look finer grained than the enclosing rock, but this is not the case, but an optical illusion produced by the great abundance of phenocrysts in the latter. They are almost always very porous (much more so than the rock which encloses them), usually contain much vesicular glass, and are very often rich in cristobalite, or sometimes tridymite. The enclosing rock may contain no glass.

(i) *Microscopic description.* Three main types have been recognized, corresponding to three different kinds of parent rock, intrusive hornblende-bandaïte, hornblende-bandaïte blocks in *nuée ardente* deposits, and pyroxene-bandaïte.

The *first type* is represented by xenoliths in the rock of Castles Peak. Xenoliths similar in many ways to one of these were found in the intrusive hornblende-bandaïte of Landing Bay, and in a block of rather similar rock from the Centre Hills. The Castles Peak xenoliths consist mainly of divergently arranged stout rectangular crystals of zoned labradorite, along with dark brown hornblende (F 4507) or pyroxenic pseudomorphs (aggregates of parallel prisms) representing original hornblende (F 4509). The brown hornblende shows only slight magnetitic resorption. In the rock with brown hornblende, the amphibole encloses small feldspars and is moulded on larger ones. In this rock many feldspars are about 0.8 mm. in length, in the other 0.4 mm.; hornblende may attain 2 or 1 mm. respectively. The crystals thus correspond in size to phenocrysts in the enclosing rock. Abundant wide interspaces between the feldspars and hornblendes are largely occupied by brownish spherulitic material, accompanied by brown glass; the glass is sparse in the coarser xenolith, and fairly

abundant in the other. The glass contains minute vesicles, and in one case skeletal feldspar growths. There are also large needle-like prismatic pyroxenes, dark brown apatites and iron ores. There is much cristobalite in the interspaces; it is of earlier formation than the spherulites or the glass (or possibly replaces tridymite that is of earlier formation than the residuum). The coarser-grained xenolith is minutely porous ("sugary"), as is the other. The finer-grained one has locally, in addition, biggish empty cavities with rough "hackly" sides, but apparently lined with glass. There are a few larger feldspars that may be regarded as phenocrysts, and in one case biggish hornblendes replaced by pyroxene and iron ore, two large ophitic crystals of hypersthene, and one large iron ore. In the Landing Bay xenolith (F 4439) there is sparse cristobalite, and probably tridymite; the one from the Centre Hills (F 4383) contains much cristobalite. The enclosing rocks have a very fine-grained, but non-glassy groundmass in all cases; they are somewhat porous ("ragged" cavities), but very much less porous than many of the blocks in the agglomerates of the Soufrière Hills, and infinitely less porous than the xenoliths. Only at Castles Peak was cristobalite (sparse) noticed in the enclosing rock. A third xenolith from Castles Peak (F 4508) is rather similar to F 4507, but the grain size is more variable.

The *second type* of xenolith is characteristic of the hornblende-bandaite blocks in the agglomerates of the Soufrière Hills. In these xenoliths there are well-defined phenocrysts of corroded basic plagioclase (with minutely "spongy" zones or cores), of hornblende (in most instances), and of hypersthene (sparse). Traces of porphyritic quartz and olivine may also be found (F 4399, 4400). The hornblende is usually brown, like the phenocrysts of the enclosing rock, but in one instance is dark brownish green (F 4434). The porphyritic hornblende may be quite unresorbed, or partly or completely changed to the "pyroxenic" type of aggregate (F 4399). There are many feldspars intermediate in size between the phenocrysts and the smallest ones of the groundmass; on the whole the grain size (which varies in different specimens), although fine, is much greater than in the true groundmass of the enclosing rock. The feldspar laths, which approximate to labradorite, are diversely arranged and are associated with little pyroxene prisms (hypersthene and some augite) and iron ores. The most conspicuous, and usually the most abundant, ferromagnesian mineral of the groundmass is hornblende (similar in colour to the phenocrysts); it occurs as minute to fairly long narrow prisms, and gives the rocks a lamprophyric aspect. Between the other constituents is a good deal of interstitial glass, brownish or almost colourless, and containing many minute circular vesicles. All these xenoliths are full of little ragged pores; large empty ovate pores or vesicles are also visible in the hand specimen; often long hornblende needles project into them. One specimen has much cristobalite, partly interstitial (enclosing little feldspar laths and pyroxene prisms), and partly projecting into cavities (F 4380). Cristobalite is also present in the enclosing rock.

The *third type* of xenolith occurs in the pyroxene-bandaite of the Centre Hills (F 4365, 4366). These xenoliths, except for the absence of hornblende, are very similar

to those of the last group. The phenocrysts are basic plagioclase, hypersthene and augite. The groundmass consists of plagioclase, pyroxene (hypersthene and some augite) and iron ores. In one example there is abundant brown glass full of minute vesicles. In the other, interstices are largely filled by coarsely crystallized tridymite, in lath and wedge-twin form. The groundmass of the enclosing rock is also rich in tridymite.

In the olivine-basalts there are no cognate xenoliths corresponding to those described above, but occasionally a glomeroporphyritic group is so large that it resembles a small cognate xenolith of a different type (F 4450). A few basalt specimens from near Roche Bluff contain xenoliths composed of metamorphosed calcareous sediments.

(ii) *Origin.* The origin and magmatic history of these remarkable xenoliths present a fascinating problem of critical importance for the understanding of dome-formation and eruptions of the *nuée ardente* type. The following hypotheses, based on the rocks of the Soufrière Hills, are put forward as a tentative solution, to be tested by future research. They embody some physicochemical conceptions developed by Shepherd and Merwin for Mt Pelé (Shepherd and Merwin 1927).

The dome xenoliths of the Soufrière Hills are very much coarser in grain than the *nuée ardente* xenoliths, and less similar to the enclosing rock in that they are not markedly porphyritic. Moreover, the groundmass of the enclosing rock of the dome is holocrystalline and very slightly porous, while that of the *nuée ardente* agglomerate blocks is semi-glassy to glassy and often markedly porous. Characteristics common to both types of xenoliths are the similar characters of their glassy interstitial residuum, and their vesicularity and porosity.

It is suggested that both types of xenolith represent partly crystallized bandaite magma that once lined the walls of the magma conduit. During renewal of upward movement of similar magma, pieces of semi-crystallized wall-rock were torn from the conduit sides and incorporated as xenoliths in ascending magma, while still under great pressure. The hornblende of the xenoliths is brown (in one agglomerate xenolith very brownish green), and sometimes shows partial or complete resorption of the "pyroxenic" type (p. 54). From these facts we may make the further inference that the wall-rock from which the xenoliths were derived came from a moderate depth in the conduit, but from a higher level than the magma which, when the explosive eruptions occurred, formed the pumice characterized by green hornblende (p. 54).

The large size of the crystals of the dome xenoliths is attributed to the retention of mineralizers during a period of slow cooling under considerable pressure. This period must have been prior to the tearing off of the xenoliths, for we cannot admit that large feldspars grew in a highly viscous medium, or that the xenoliths, on incorporation, contained a large proportion of fluid magma.

Let us assume that the semi-crystallized wall-rock that provided the coarse xenoliths had crystallized more slowly than the wall-rock from which the agglomerate xenoliths came. We may then infer that the coarse-grained, almost non-porphyritic, xenoliths

were torn off the interior part of the conduit wall, where the temperature had fallen slowly, and that later on, as the conduit was enlarged, finer-grained porphyritic xenoliths were derived from a zone further away from the axis of the volcanic pipe, where cooling had been relatively rapid. The magma that was eventually to make the dome was gradually pushed upwards to form a hot, but more or less solid, plug below which enormous gas pressure accumulated.* When the great explosions occurred, the conduit throat was cleared of underlying semi-consolidated and unconsolidated magma, which provided the semi-glassy blocks, and the breadcrust bombs and glassy pumice, of the *nuées ardentes*.

Before their "birth" the xenoliths are to be regarded as being composed of a crystal mesh with a little residual magma entangled in it. Apparently the magmatic residuum and its mineralizers were somehow trapped along with the enclosed xenolith, and these volatile fluxes were retained until the period of final consolidation of the xenolith, when the minutely vesicular glassy residuum was formed. How otherwise can we account for the presence of glassy vesicular xenoliths in the holocrystalline and very slightly porous rock of the dome?

The question now arises: at what stage, and in what way, did release of pressure take place, and bring about the vesiculation of the residuum by loss of volatiles, and the solidification of the glass? In the first place it is probable that vesiculation of the xenolith would only be possible because of previous or contemporaneous formation of pores in the enclosing rock. In the dome rock, which has a holocrystalline groundmass, these pores were probably already in existence in the form of minute "vughs", or miarolitic cavities, filled by gases at high pressure. The release of pressure would come mainly at the time of the great explosions. The explanation of the much more vesicular and porous xenoliths in the agglomerate blocks is not so simple. In this case the groundmass of the enclosing rock, though rarely containing any minute vesicles, is semi-glassy to glassy, not holocrystalline. It is therefore suggested that, in the more glassy and porous blocks at any rate, the final consolidation of the glass of the xenoliths and of the groundmass of the rock took place during the descent of the blocks as constituents of *nuées ardentes*; the xenoliths became highly vesicular and porous, and in the less crystallized blocks the porosity of the enclosing rock was accentuated.

It is clear from Lacroix's description of the *enclaves homæogènes plésiomorphes* of Mt Pelé that they are very similar to, or identical with, xenoliths described above. Among these, the *enclaves amphiboliques* of Lacroix appear to correspond to hornblendic types of the Soufrière Hills. Lacroix inferred that the Mt Pelé xenoliths had been formed as the magma rose, and that they had finally consolidated at the same time as the enclosing rock. I have, however, been unable to understand from his account exactly how he supposed them to have originated (Lacroix 1904, p. 540). It is impossible to tell from Lacroix's descriptions whether, at Mt Pelé, xenoliths in the solid intrusive

* Probably of the order of 100 atmospheres (Shepherd and Merwin 1927).

rock of the dome differ from those of more porous blocks and bombs in *nuée ardente* deposits.

No analysis was made of a Montserrat cognate xenolith. Lacroix, however, has published the analysis of one of the *enclaves amphiboliques* of Mt Pelé, and this is reproduced on p. 74 (Anal. E, Table III). The analysis resembles that of the pyroxene-bandaite from the Centre Hills and that of the Castles Peak hornblende-bandaite. It is, of course, probable that reciprocal molecular transfer took place, to varying extents, between xenoliths and enclosing magma, before the explosions occurred. In this way, richness of the xenoliths in ferromagnesian minerals could be accounted for.

(h) *Volcanic dusts*

In connexion with the interpretation of the deposits of the flanks of the Soufrière Hills as products of *nuées ardentes*, samples of fine dusty agglomerate matrix (F 4500) and of a 2 ft. dust layer (F 4501) were examined microscopically. They are composed of crystals and small fragments of plagioclase feldspar, hypersthene, augite, hornblende (greenish brown, brown and red-brown) and iron ore, along with numerous angular fragments of semi-glassy bandaite groundmass, and sparse bits of glass (brown in one sample); vesicular glass and glassy groundmass are present, but probably in very small amount. There are also some fine-grained holocrystalline groundmass fragments. Tridymite is represented among the more minute fragments. Many of the crystals have shreds of semi-glassy groundmass, or occasionally of brown glass, adhering to them. In one sample, the glass of the semi-glassy bandaite groundmass fragments is practically colourless. Fragments and crystals as large as 0.3–0.4 mm. are sparse, those of 0.1 mm. fairly abundant, and those of 0.06–0.04 mm. very abundant; there are also many as small as 0.01–0.005 mm. or even smaller.

With these samples was compared fine dust collected from the 1929–32 *nuée ardente* deposits of "Avalanche" Valley, Mt Pelé (F 4503). It proved to be almost identical with the Montserrat dust in grain size, mineral constituents and general character. The glass of the numerous semi-glassy groundmass fragments is usually almost colourless. As in Montserrat, fragments of fine-grained holocrystalline groundmass (like that of the dome rock) are in the minority. Hornblende, brown in colour, is less abundant, in accordance with the fact that the mineral is much less common in the Mt Pelé rocks. Some cristobalite was seen.* The general colour of the Martinique dust sample is pale grey, while the Montserrat dusts have a brownish tinge; the difference is probably due to oxidation of iron in the older deposits of Montserrat.

Mounted samples of the volcanic dusts from St Vincent that fell in Barbados in May 1902 and March 1903, and of local St Vincent dusts of 1902, are available in the foreign collection of the Geological Survey and Museum. Descriptions and analyses of these dusts have been published (Flett 1908). On examination they proved to be

* See notes regarding cristobalite of Mt Pelé (p. 72).

essentially of the same nature as the Montserrat and Martinique (1929–32) dusts. The grain size varies a good deal in different instances, and Flett has recorded the presence of olivine. Some of the Barbados dusts contain a good many fragments as large as the largest in the Montserrat dusts, but the proportion of finer material is naturally much greater.

(i) *Analysed rocks of Montserrat*

The following notes on the analysed rocks supplement the very generalized descriptions of sections (c), (d) and (e). The analysed material was carefully selected so as to be free from cognate xenoliths. The modes are shown in Table V; they were determined with an instrument of high precision (the Leitz integrating stage), but the rocks, partly because of the presence of large scattered phenocrysts (e.g. hornblende), and partly because all porphyritic constituents grade by various transitions in size into the groundmass, do not lend themselves to accurate determination in a reasonable time. The mineral percentages given are believed, however, to be approximately correct. The finer parts of the groundmass in all rocks are, of course, quite impossible subjects for micrometric measurements, even when their constituents are fully determinable. Because of differences in the average size of smaller microphenocrysts it was not found practicable to define the size of "phenocrysts" in the same way in all the rocks. All rocks probably have delicate apatite needles in the groundmass.

(i) *Labradorite-dacite; near Landing Bay*. Slice F 4347. A very pale grey rock, slightly reddened by oxidation. Feldspar phenocrysts zoned labradorite, largely about $Ab_{35}An_{65}$; sodic limit $Ab_{50}An_{50}$; calcic limit $Ab_{32}An_{68}$. Porphyritic quartz more abundant and less corroded than in most rocks. Hornblende red-brown, with narrow rims of reddish brown iron oxide, probably resulting from oxidation of narrow magnetite-rich resorption rims. Hypersthene more abundant than augite. Both pyroxenes have red-brown iron oxidation rims, which are also present round small porphyritic iron ores. Very sporadic microporphyritic apatite. Groundmass extremely fine-grained, and "minutely spotty" between crossed nicols; probably dominantly feldspathic (? albite-oligoclase); some quartz associated; some microlites of acid plagioclase, and pyroxene (oxidized and reddish brown), and scattered minute magnetites. Extremely meagre residual colourless "cement" (? glass). The norm (Table V) has been recalculated with the same amount of total iron, but with $Fe_2O_3:FeO=1:2$, corresponding to the ratio in non-oxidized rocks. See fig. 43, Plate 8, and fig. 41, Plate 7.

(ii) *Labradorite-dacite; near Old Fort Point*. Slice F 4342. A pale grey very slightly porous rock. Feldspar phenocrysts as in (i). Sparse corroded quartz. Hornblende brown, partly resorbed to magnetite-rich aggregates. Hypersthene much more abundant than augite. Small porphyritic iron ores and very sparse microporphyritic apatite. Minute microphenocrysts of plagioclase, pyroxene, hornblende and iron ore.

Groundmass fine-grained with sparse residuum of brownish glass. Constituents of predominating microlitic non-glassy part indeterminate, but largely plagioclase feldspar. Quite a number of spots and irregular minute patches of cristobalite.

(iii) *Labradorite-dacite; Castles Peak*. Slices F 4360 and 4360 duplicate. A very pale grey and very slightly porous rock. Feldspar phenocrysts as in (i). Sparse corroded porphyritic quartz. Hornblendes dark brown and unusually large; narrow resorption rims of pyroxene and iron ore; some crystals largely replaced by pyroxenic aggregates with some iron ore. A large proportion of the hornblendes in slices of this rock show straight, or almost straight, extinction. Hypersthene sparse but greatly preponderates over augite. Some small porphyritic iron ores and very sparse microporphyritic brown apatite. Minute microphenocrysts of plagioclase, augite, hypersthene and iron ore. Groundmass holocrystalline and very fine-grained; "minutely spotty" type with microlites of pyroxene and scattered iron ore grains; very largely formed of minute plagioclase crystals; many square cross-sections and some minute laths (? labradorite); possibly ill-defined less basic plagioclase. Very sparse cristobalite and tridymite, possibly in minute pores. See fig. 44, Plate 8, and fig. 39, Plate 7.

(iv) *Labradorite-dacite; Silver Hill*. Slice F 4327. A greenish grey rock with bluish grey mottling, produced by felsitic looking patches of groundmass. Feldspar phenocrysts smaller and less abundant than in other rocks; zoned labradorite, largely about $Ab_{35}An_{65}$; sodic limit $Ab_{36}An_{64}$; calcic limit $Ab_{28}An_{72}$. Minute traces of resorbed hornblende. Hypersthene more abundant than augite. Numerous minute microphenocrysts of plagioclase, and some of pyroxene and iron ore. Groundmass almost holocrystalline aggregate of minute feldspars and pyroxene granules with some iron ore. Extremely meagre residual colourless "cement" (? glass). Tridymite fairly abundant in minute patches of irregular shape. See fig. 40, Plate 7.

(v) *Labradorite-dacite; Centre Hills*. Slice F 4359. A bluish grey rock, rather similar to (iv), but markedly porphyritic. The bluish felsitic aspect of the groundmass is not produced by fineness of grain; it is possibly due to abundance of tridymite. Feldspar phenocrysts zoned labradorite largely about $Ab_{35}An_{65}$; sodic limit $Ab_{50}An_{50}$; calcic limit $Ab_{30}An_{70}$. Hypersthene probably less abundant than augite. Extremely sparse minute relics of olivine. Sparse small porphyritic iron ores, and very sparse microporphyritic apatite. Numerous minute microphenocrysts of plagioclase, augite and hypersthene. Groundmass a fairly fine-grained aggregate of plagioclase and pyroxene, with scattered iron ore grains; possibly very meagre residual glass "cement", but groundmass so permeated by delicate, irregularly orientated, tridymite "needles", that discrimination is impossible. Tridymite also forms numerous irregular straggly patches (up to 0.4 by 0.1 mm.) composed of bigger laths, and aggregates of arrow-head twins. It is definitely a primary groundmass constituent. See fig. 45, Plate 8.

(vi) *Olivine-basalt; near Shoe Rock*. Slice F 4346. A darkish grey rock with innumerable small porphyritic feldspars. Feldspar phenocrysts zoned labradorite-

bytownite, largely about $Ab_{30}An_{70}$; sodic limit $Ab_{44}An_{66}$; calcic limit $Ab_{26}An_{74}$ (bytownite). Hypersthene less abundant than augite. Olivine rather sporadic (up to 1 mm.). Iron ore a constituent of glomeroporphyritic groups. Numerous microphenocrysts of labradorite, pyroxene (augite and hypersthene), and iron ore, grade into groundmass of same constituents. Feldspar of finer parts of groundmass (darkened by iron-ore dust) is indeterminate. A little tridymite, probably mainly in cavities. Groundmass more pyroxenic than in labradorite-dacites. See fig. 46, Plate 8.

(vii) *Olivine-basalt; O'Garra's*. Slice F 4344. A darkish grey rock, aphanitic to the naked eye, and full of minute ragged vesicular pores. Feldspars zoned labradorite-bytownite largely about $Ab_{30}An_{70}$; sodic limit $Ab_{40}An_{60}$; calcic limit $Ab_{20}An_{80}$ (bytownite); unusually small (0.5 mm. and less); very "spongy" and full of included pyroxene and iron ore. Hypersthene subordinate to abundant augite. Olivine forms very minute microphenocrysts (0.2 mm. and less) rounded by corrosion. Sparse small microphenocrysts of iron ore. Groundmass extremely fine-grained dark aggregate of microlites and granules of plagioclase, pyroxene and iron ore. Some cristobalite (or tridymite) as minute spots and in little ragged pores.

(j) *Petrological and chemical summary and comparisons**

(i) *Rock types and magmatic history*. The rocks of Montserrat, with the exception of the olivine-basalt lava flows and most of the associated fine-grained tuffs of South Soufrière Hill, are all composed of labradorite-phyric dacite (bandaite). Intrusive bodies form part of the cores of various volcanoes, but most of the rocks are agglomerates or tuffs. The bandaites range from acid hornblende-pyroxene-bandaites with 64.21% of silica, to pyroxene-bandaites with 56.75%. Green hornblende occurs only in glassy rocks, and the presence of unresorbed brown hornblende is a feature of the Soufrière Hills volcano. The hornblende-bandaites contain sparse porphyritic quartz. Sporadic olivines may occur in hornblende-bandaites along with porphyritic quartz, and in pyroxene-bandaites that have abundant primary tridymite in the groundmass. The prevalence of tridymite and cristobalite is a feature of the rocks of Montserrat, especially of the pyroxene-bandaites.

The pumiceous and most glassy rocks characterized by green hornblende are believed to represent highly gas-charged magma that initiated great volcanic explosions; these explosions blew into fragments semi-consolidated and almost consolidated "magma" lying above them in the magma conduits, as well as more superficial solid rocks. In these less deep-seated zones slow cooling from a high temperature, accompanied by slow release of pressure, had changed the colour of the hornblende from green to brown, and had brought about partial or complete resorption of the amphibole. In Montserrat semi-consolidated magma containing brown hornblende is regarded

* See also opening paragraphs of Section XII, p. 47.

as having reached a state in which it was incapable of initiating great volcanic explosions. Rocks in which hornblende has been almost entirely resorbed to "black" aggregates are also regarded as representing magma that had been at too advanced a stage of consolidation to initiate major explosive eruptions. It is here further suggested that the pyroxene-bandaïtes represent hornblende-bandaïte magma in which the amphibole has been completely, or almost completely, changed to "pyroxenic" or to "black" aggregates (cf. Washington 1896). Chemically they differ little from some of the hornblende-bandaïtes, and many contain minute traces of resorbed hornblende. These hypotheses would account for the facts that, in Montserrat, pumice always contains green hornblende, that highly glassy rocks more often contain green hornblende than brown, and that pyroxene-bandaïtes are very seldom even slightly porous, and never form pumice.

By those who believe in gravitative differentiation, and possibly even by some supporters of the assimilation hypothesis, the olivine-basalt magma of Montserrat, as compared with the bandaïte magma, may be regarded as having been derived from a lower part of the main magma reservoir of the Caribbean arc. Like many other areas, Montserrat provides no decisive evidence on the major problems of differentiation. We do know, however, that the eruption of basaltic lavas and tuffs at South Soufrière Hill was preceded and followed by purely explosive hornblende-bandaïte eruptions that occurred only a very short distance to the east and to the north. Alternation of basic and acid eruptions is a feature of many volcanic regions.

(ii) *Norms and Niggli values.* The tables of Norms and Niggli values are almost self-explanatory (Tables V and VI). They bring out the relationship of the bandaïtes to the sub-rang "bandose" of the C.I.P.W. classification and to the peléitic magma type of Niggli. They also show clearly the contrasted chemical features of the olivine-basalts, which contain only small amounts of normative quartz, and belong to the sub-rang "hessose" of the C.I.P.W. classification and to the leuco-gabbroid magma of Niggli. The rocks have been assigned to Niggli magma types in accordance with the latest revision (Niggli 1936). In his most recent paper Niggli takes the opportunity of making minor changes in some of the magma types (e.g. the peléitic), and of giving detailed rules for applying his classification.

In fig. 8 the normative feldspars of the type "normal quartz-dioritic" and "ossipitic" magmas of Niggli are shown. It will be seen from the diagram that the Montserrat rocks belonging to these magmas are borderline types.

(iii) *Comparisons with Mt Pelé and Lesser Antilles.* Lacroix's great memoir on Mt Pelé, published in 1904, contained a very large number of new analyses of the rocks of Martinique (and of other islands of the Lesser Antilles), which have been widely quoted in petrological literature (e.g. Washington 1917; von Wolff 1929). In 1926 Lacroix brought out an important paper on the petrological and chemical characteristics of the volcanic rocks of the Lesser Antilles (Lacroix 1926). In this publication

he points out that, owing to the use of unsatisfactory analytical methods, many of the analyses of 1904 are unreliable in certain constituents. For the old analyses he substituted thirty-seven new or redetermined ones. In a personal communication, Professor Lacroix has informed me that, as a general rule for the future, the analyses of 1904 should not be used.* Accordingly, in the comparative table of analyses for the Lesser Antilles (Table III) the only analyses quoted from the publications of Lacroix are those of 1926.

It will be seen from Table III how closely comparable are the chemical characters of the rocks of Montserrat with those of others from the Caribbean volcanic arc. There is a close resemblance between the rocks of the Soufrière Hills (Old Fort Point and Castles Peak) and the "dacitoïde à hypersthène" or "hypersthene-andesite" of Mt Pelé. Mineralogically the rocks themselves are more closely comparable than would appear from the mere names, and it is not surprising that the two magmas should have produced the same type of eruption. Lacroix has himself pointed out that the rocks of Mt Pelé have sparse porphyritic crystals of brown hornblende, which are always partly resorbed; they were not found in all specimens. Olivine may also be present as small accessory phenocrysts, as in some of the hornblende-bandaïtes of the Soufrière Hills.

I have examined microscopically three rocks collected from Mt Pelé, one from the old dome of 1902-4, one from the top of the new dome of 1929-32, and one from a late "block and ash flow" of the 1929-32 eruptions, in "Avalanche" Valley close to Morne Lenard. The most striking difference, as compared with the rocks of the Soufrière Hills of Montserrat, is the smaller size of the phenocrysts (1 mm. and less). All specimens contain one partly resorbed phenocryst of brown hornblende, and the specimen from the "block and ash flow" contains a little olivine. In my nomenclature, the rocks are hypersthene-bandaïtes with accessory hornblende, and sometimes olivine. The groundmass resembles that of the Castles Peak rock.

An interesting and important feature is that each specimen contains cristobalite, a mineral not previously recorded from Mt Pelé. In part at least, it is replacing tridymite, and relict tridymite is probably also present in all cases. I believe, however, that some of the Mt Pelé "tridymite" recorded by Lacroix may in reality be cristobalite, for in one place he describes it as occurring "...sous forme de larges plages, individuellement constituées par l'empilement d'un très grand nombre de petites lamelles imbriquées" (Lacroix 1908, p. 51). Cristobalite in my specimens might be described in this way (F 4460, 4461, 4462), but it is similar in character to cristobalite of Montserrat that has been put to the test of modern X-ray analysis (p. 59).

* See also Lacroix 1919. Comparison of old and new analyses suggests that some of the earlier figures differ from the later ones by as much as several units before the decimal point (e.g. Al_2O_3 , MgO , CaO). It is thus to be hoped that none of the old analyses will be used without previous reference to Professor Lacroix.

The rocks of Montserrat represent almost the full range of types known in the Caribbean volcanic arc. Rocks more acid than the hornblende-bandaite of Landing Bay are extremely rare (e.g. the *dacitoïde sphérolitique* of Guadeloupe with 72.72% of silica). A good many rocks are, however, very slightly richer in potash (p. 77). Lavas more basic than that of O'Garra's are found in St Vincent, and there are no representatives of the anomalous "basanitic" lavas of Grenada (cf. Lacroix 1926).

The chemical characteristics of the volcanic rocks of the Caribbean arc have recently been compared with those of dioritic to granodioritic igneous rocks from Aruba (fig. 1), an island lying off the coast of Venezuela (van Tongeren 1934). Aruba is largely composed of a "dioritic" batholith (with associated dykes) intruded in late Mesozoic or early Tertiary times, into folded rocks believed to be of Cretaceous age (Westermann 1932). It is interesting to read of the close magmatic agreement between these relatively old intrusive rocks and the much younger volcanic rocks of the Lesser Antilles. The magma of the Caribbean region appears to have retained the same general characters over a vast period of time.

(iv) *Comparison with Lassen Peak region.* One of the better-known eruptions of *nuée ardente* type is that which took place at Lassen Peak, in California, in 1915 (Day and Allen 1925). From Table IV it will be seen that every rock in Montserrat can be closely matched in the Lassen Peak area. Analogies between the tectonic and eruptive histories of the Lesser Antilles and the Lassen Peak region have already been pointed out (p. 5).

(v) *Normative feldspars.* In fig. 8 are shown the composition of the normative plagioclase of the analysed rocks of Montserrat and the ratio of potash feldspar to plagioclase feldspar, in accordance with Niggli's graphical method (Niggli 1927). It will be seen that the normative plagioclase of the rocks is somewhat less basic than the abundant modal labradorite phenocrysts; this is of course due to the fact that much of the albitic plagioclase is in the groundmass of the rocks.

The diagram shows at a glance two of the most outstanding features of the rocks of the Lesser Antilles—the abundance of lime-rich plagioclase in relatively siliceous rocks, and the unusually small potash content. Fig. 8 also shows part of the "fields" for the normative plagioclase of the Mexican volcanic province (Burri 1930) and of the Tertiary and Recent volcanic rocks of the Sierra Nevada (including Lassen Peak) and Nicaragua (Burri and Sonder 1936). The "fields" for the latter regions are very much the same, and have been shown together.

The diagram brings out two features very clearly. The first is the much wider range of normative plagioclase in the rocks of the American continent as compared with those of Montserrat. This is not due to the presence of more acid rocks in the American "fields", for liparites and rhyolites and allied types have been excluded from the diagram. The differences arise mainly from the fact that many of the continental "dacitoïdes" and andesites, and many of the basalts containing a little normative

TABLE III. ROCK ANALYSES: MONTSERRAT AND LESSER ANTILLES

Island ... etc. ...	Mont- serrat	Martinique		Mont- serrat	Mar- tinique	Statia	Mont- serrat	St Kitt's	St Vincent	Montserrat		Mar- tinique
		Pelé (spine) A	Pelé (1902) B							Carbet massif C	Castles Peak III	
Locality, Nr. etc. ... Landing	Bay I			Old Fort Point II	Carbet massif C			Black Rocks F	Sou- frère G			
Anal. No.												
SiO ₂	64.21	63.53	61.65	60.08	60.12	57.38	58.36	53.74	53.51	52.64	52.00	51.58
Al ₂ O ₃	16.83	17.02	17.80	18.03	17.02	18.20	18.57	18.55	18.85	19.52	19.22	17.86
Fe ₂ O ₃	3.74	2.80	2.20	2.24	1.35	4.21	2.30	3.19	3.37	2.85	2.73	6.42
FeO	1.77	3.25	4.24	4.09	4.09	3.12	4.36	6.35	5.60	5.78	5.54	3.34
MgO	2.22	2.08	3.08	3.04	2.16	2.23	3.26	3.81	4.38	3.76	5.54	4.54
CaO	6.03	5.83	6.62	7.44	8.86	8.22	7.95	9.06	9.15	9.68	10.58	9.64
Na ₂ O	3.40	3.59	3.05	2.91	2.78	4.04	2.28	2.97	3.13	3.23	2.53	3.11
K ₂ O	1.09	1.05	1.08	0.97	1.14	0.80	0.87	0.72	0.51	0.99	0.76	0.85
H ₂ O ⁺	0.17	0.16	0.12	0.34	1.80	0.81	0.66	0.27	0.12	0.27	0.20	1.29
H ₂ O ⁻	0.20	0.09	—	0.30	—	0.54	0.64	0.34	—	0.32	0.15	0.22
TiO ₂	0.34	0.47	0.40	0.45	0.96	0.78	0.43	1.19	1.06	0.86	0.63	0.86
P ₂ O ₅	0.09	0.16	0.11	0.11	0.23	0.12	0.08	0.07	0.05	0.12	0.11	0.39
MnO	0.11	0.14	0.11	0.16	0.11	0.09	0.13	0.08	0.10	0.17	0.11	0.17
CO ₂	Nil	—	—	Nil	—	—	Nil	—	—	Nil	Nil	—
Rest	—	0.04	—	—	—	—	—	—	—	—	—	—
Total	100.20	100.22	100.46	100.16	100.62	100.54	99.89	100.34	99.79	100.19	100.17	100.07

Note: I-V, labradorite-dacites (bandaites); VI, VII, olivine-basalts.

LIST OF ANALYSES: TABLES III AND IV

Except in Montserrat, the rock-names in this list are those applied by the petrologist who described them, and do not necessarily conform to the nomenclature used in this paper.

- I. *Labradorite-dacite (hornblende-pyroxene-bandaite)*. Intrusion. Coast, south-west of Landing Bay, Montserrat (F 4347). Anal. F. Herdsman.
- A. *Hypersthene-andesite*. Part of spine of 1902-3, Mt. Pelé, Martinique. (Shepherd and Merwin 1927, p. 100.)
- B. *Dacitoïde à hypersthène (obsidiennique)*. Eruption of 1902, Mt Pelé, Martinique. (Lacroix 1926, p. 394.)
- II. *Labradorite-dacite (hornblende-pyroxene-bandaite)*. Block from agglomerate. Knoll east of White River, near Old Fort Point, Montserrat (F 4342). Anal. F. Herdsman.
- C. *Dacite à hornblende et hypersthène*. Alma, Carbet Massif, Martinique. (Lacroix 1926, p. 394.)
- III. *Labradorite-dacite (hornblende-pyroxene-bandaite)*. Intrusive dome. Castles Peak, Montserrat (F 4360). Anal. F. Herdsman.
- IV. *Labradorite-dacite (pyroxene-bandaite)*. Intrusion. Summit of Silver Hill, Montserrat (F 4327). Anal. F. Herdsman.
- D. *Dacitoïde*. Statia. (Lacroix 1926, p. 402.)
- E. *Enclave amphibolique*. Mt Pelé, Martinique. (Lacroix 1926, p. 399.)
- V. *Labradorite-dacite (pyroxene-bandaite)*. Intrusion (?). Centre Hills, west-north-west of Tuit's (north of ghaut and road), Montserrat (F 4359). Anal. F. Herdsman.
- F. *Labradorite α à hypersthène et olivine*. Black Rocks, St Kitt's (Lacroix 1926, p. 403.)
- G. *Dacitoïde à pyroxènes*. Old Somma, Soufrière, St Vincent. (Lacroix 1926, p. 403.)
- VI. *Olivine-basalt*. Lava flow. South Soufrière Hill, coast about 500 yards west of Shoe Rock, Montserrat (F 4346). Anal. F. Herdsman.
- VII. *Olivine-basalt*. Lava flow. South Soufrière Hill, at O'Garra's, Montserrat (F 4344). Anal. F. Herdsman.
- H. *Labradorite α à plagioclase*. Morne du Diamant, Martinique. (Lacroix 1926, p. 394.)
- J. *Hypersthene-andesite, with resorbed hornblende (Tonalose)*. Mount Shasta, California. (Diller 1898, p. 228; Washington 1917, p. 378.)
- K. *Hornblende-andesite, with traces of olivine (Tonalose)*. Burney Creek, Shasta Co., California. (Clarke and Hillebrand 1897, p. 195; Washington 1917, p. 380.)
- L. *Augite-andesite; called bandaite by Iddings (Bandose)*. Obandai, Bandai San, Japan. (Iddings 1913, p. 146; Washington 1917, p. 416.)
- M. *Basalt (Bandose)*. Lake Tartarus, near Lassen Peak, California. (Washington 1917, p. 408.)
- N. *Plagioclase-hypersthene secretion in hypersthene-andesite (Bandose)*. South of Suppans Mountain, Tehama Co., Lassen Peak region, California. (Clarke 1915, p. 172; Washington 1917, p. 408.)
- O. *Quartz-basalt; called bandaite by Iddings (Bandose)*. Near west base of Lassen Peak, California. (Clarke 1915, p. 174; Washington 1917, p. 408.)
- P. *Basalt (Hessose)*. Rim of Crater Peak, Shasta Co., California. (Clarke 1915, p. 175; Washington 1917, p. 534.)
- Q. *Basalt*. Pit River, Lassen Peak region, California. (Clarke 1915, p. 175.)

quartz, are richer in soda and poorer in lime than the rocks of Montserrat. In the Lassen Peak region itself, however, there are, as we have seen, many rocks within this range of types that are closely comparable to those of Montserrat and the Lesser Antilles.

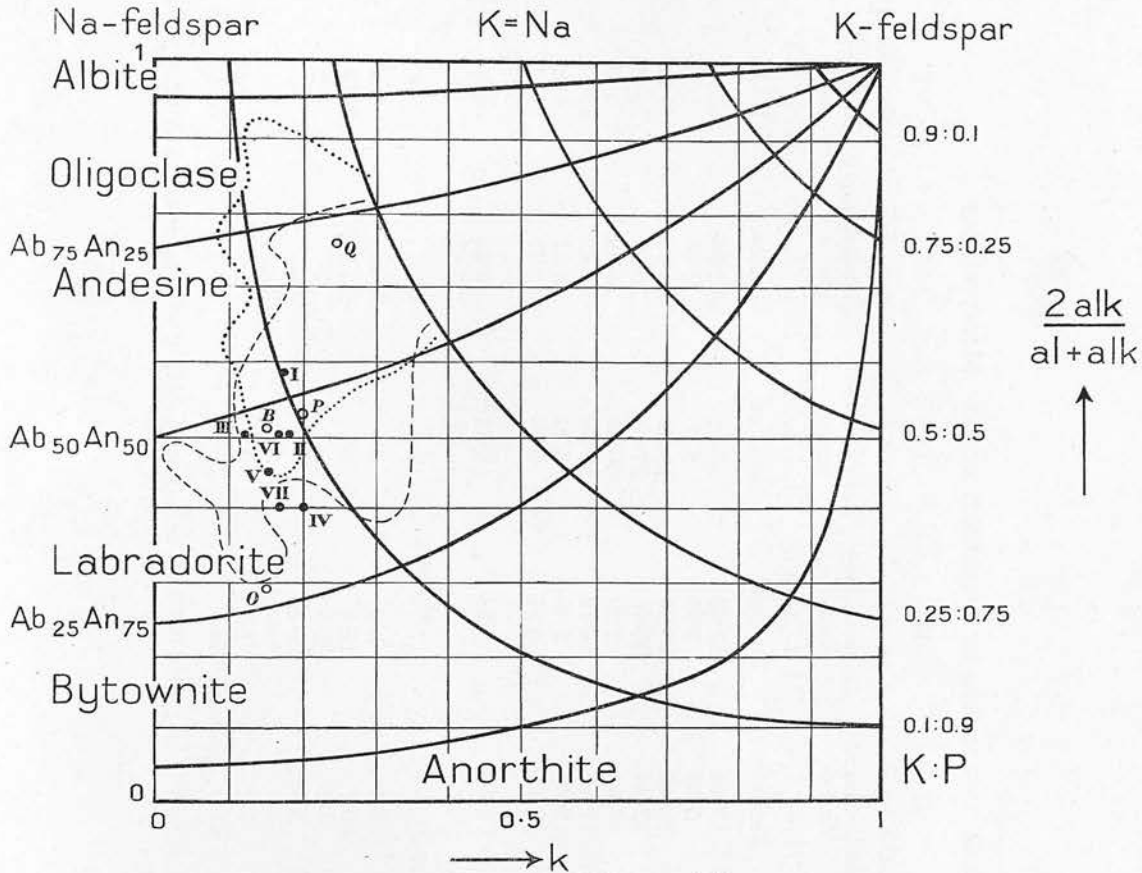


FIG. 8. Normative Feldspar Diagram.

Explanation

Analysed rocks: Montserrat.	Revised Niggli Magma types (1936)
I Labradorite-dacite (normal quartz-dioritic)	Q Type normal quartz-dioritic magma.
II—IV Labradorite-dacites (peléitic)	P Type peléitic magma.
V Labradorite-dacite (belugitic, near peléitic)	B Type belugitic magma.
VI Olivine-basalt (belugitic)	O Type ossipitic magma.
VII Olivine-basalt (ossipitic)	
..... Field of Mexican province.	
----- Field of Sierra Nevada—Lassen Peak, and Nicaragua.	

The other feature clearly indicated is the lower potash content of the Montserrat rocks. This, as Lacroix has pointed out, is a characteristic feature of the Lesser Antilles. The potash content of the Montserrat rocks is, on the whole, lower than the average for the Lesser Antilles. Of the thirty-seven analyses published in 1926 by Lacroix, fourteen have higher potash than the hornblende-bandaite of Landing Bay, but the

TABLE V. NORMS AND MODES OF ANALYSED ROCKS: MONTERRAT

Analysis	I	II	III	IV	V	VI	VII
Locality	Nr. Landing Bay	Old Fort Point	Castles Peak	Silver Hill	Centre Hills	Nr. Shoe Rock	O'Garra's
Name	Labradorite-dacite	Labradorite-dacite	Labradorite-dacite	Labradorite-dacite	Labradorite-dacite	Olivine-basalt	Olivine-basalt
Symbol	(I)II.4.3(4).4"	"II.4."4.4"	"II.4."4.(4)5	II.4.4.4.	II.4."4.(4)5	II.5."4.4"	II".5.4.4"
Sub-rang	Tonalose	Bandose	Bandose	Bandose	Bandose	Hessose	Hessose
<i>Q</i>	24.31	17.46	17.04	17.52	12.66	3.06	3.12
<i>or</i>	6.67	5.56	3.89	5.00	4.45	6.12	4.45
<i>ab</i>	28.37	24.63	26.20	19.39	23.06	28.25	21.48
<i>an</i>	27.24	33.08	33.64	37.81	35.58	35.58	38.64
<i>di</i>	1.50*	2.51	2.29	0.68	5.23	9.55	10.57
<i>hy</i>	4.80*	11.45	11.42	13.58	12.82	11.62	15.71
<i>mt</i>	5.10	3.23	3.48	3.25	3.71	4.18	3.94
<i>il</i>	0.61	0.91	0.91	0.76	1.37	1.67	1.20
<i>hm</i>	0.16	—	—	—	—	—	—
<i>ap</i>	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Phenocrysts†	1.1	0.6	0.3	—	—	—	—
Quartz	31.8	30.1	29.8	19.5	34.3	39.2	32.5
Plagioclase	6.0	4.2	2.8	5.7	7.7	5.2	12.0
Pyroxene	2.9	2.8	7.2	—	—	—	—
Hornblende	—	—	—	—	(Trace)	—	—
Olivine	2.2	1.3	1.5	0.2	1.0	2.4	3.5
Ore	56.0	61.0	58.4	74.5	57.1	1.4	1.0
Groundmass	—	—	—	—	—	52.0	51.0

* Iron-free. † Recalculated norm. ‡ "Phenocrysts": in I, ± 0.0016 sq. mm.; in II-VI, ± 0.04 sq. mm.; in VII, ± 0.0004 sq. mm.

TABLE VI. NIGGLI VALUES OF ANALYSED ROCKS: MONTSERRAT

Anal. no.	Rock name and locality	<i>si</i>	<i>al</i>	<i>fm</i>	<i>c</i>	<i>alk</i>	<i>k</i>	<i>mg</i>	<i>ti</i>	<i>p</i>	<i>c/fm</i>	<i>qz</i>	$\frac{2 \text{ alk}}{\text{al} + \text{alk}}$	Magma type*
I	Labradorite-dacite (nr. Landing Bay)	223	34.5	29.0	22.5	14.0	0.17	0.40	0.8	0.2	0.78	+67	0.58	Normal†
II	Labradorite-dacite (Old Fort Point)	187	33.0	31.0	25.0	11.0	0.18	0.46	1.0	0.2	0.82	+43	0.50	Quartz-dioritic Peléitic†
III	Labradorite-dacite (Castles Peak)	184	33.0	31.0	25.0	11.0	0.12	0.43	1.0	0.2	0.82	+40	0.50	Peléitic†
IV	Labradorite-dacite (Silver Hill)	178	33.5	32.0	26.0	8.5	0.20	0.47	1.0	0.2	0.82	+44	0.40	Peléitic†
V	Labradorite-dacite (Centre Hills)	162	31.0	33.5	26.5	9.0	0.15	0.47	1.5	0.2	0.79	+20	0.45	Belugitic‡ (near peléitic)
VI	Olivine-basalt (nr. Shoe Rock)	137	30.0	33.0	27.0	10.0	0.17	0.44	1.7	0.16	0.82	- 3	0.50	Belugitic‡
VII	Olivine-basalt (O'Garra's)	128	28.0	37.0	28.0	7.0	0.17	0.55	1.2	0.15	0.75	0	0.40	Ossipitic‡

* According to Niggli's 1936 revision.

† Quartz-dioritic magmas.

‡ Leuco-gabbroid magmas.

greatest recorded percentage of K_2O is only 1.57 (two rocks in Guadeloupe and one in St Lucia).* Again we find an analogy with the Lassen Peak region, where many rocks are low in potash.

XIII. PALAEOLOGY

The first record of fossils in Montserrat, that of Duncan in 1863, is believed to be based on a misconception (p. 11). The presence of fossiliferous tuffs close to Sweeny's Well was first recorded by Sapper (1903). He collected specimens, but his fossils were never determined (p. 11). Earle visited the same locality in 1923; in his unpublished report on Montserrat he mentions the presence, in white marine limestone, of corals, lamellibranchs, calcareous algae, terebratulids, and spines and fragments of tests of echinoids. Before I left for the West Indies, Dr Earle informed me that he regarded these fossils as being most probably of Pleistocene age.

The fossiliferous tuffs close to Sweeny's Well were recollected by the writer, and a number of corals were obtained from a new locality, 350 yards south of the mouth of Cold River.

Soon after my return from Montserrat, Dr J. Pringle, Dr Dighton Thomas and Mr A. G. Davis were good enough to provide a brief report based on a preliminary examination of the fossils. They stated that my collection includes algae, foraminifera, corals, spines of echinoderms, serpulae, lamellibranchs and ostracods, and that the fauna and conditions of preservation suggest a Pleistocene age.

A more detailed examination of the corals and of the limestone specimens has since been carried out by Dr H. Dighton Thomas of the Department of Geology, British Museum (Natural History), and by Mr C. D. Ovey, who have supplied the following notes.

(a) *Notes on the Corals from the Fossiliferous Tuffs of Roche Bluff*

By H. DIGHTON THOMAS, M.A., PH.D., F.G.S.

The collection of corals comprises six specimens and was made from the cliffs on the shore about 350 yards south of the mouth of Cold River (1500 yards north-west along the coast from Roche Bluff). They are all preserved in a white or pale matrix, while the skeletons tend to have a "sugary" appearance.

The specimens have been identified as follows (the field collection numbers being indicated):

M. 161.	<i>Dichocoenia stokesi</i> Edwards & Haime	(B.M., R. 31770)
M. 163.	<i>Stephanocoenia intersepta</i> (Esper)	(B.M., R. 31771)
M. 164.	<i>Solenastraea hyades</i> (Dana)	(B.M., R. 31775)
M. 192.	<i>Diploria labyrinthiformis</i> (Linn.)	(B.M., R. 31772)
M. 193.	<i>Phyllocoenia</i> [<i>Orbicella</i>] <i>cavernosa</i> (Linn.)	(B.M., R. 31773)
M. 195.	<i>Phyllocoenia</i> [<i>Orbicella</i>] <i>annularis</i> (Ellis & Solander)	(B.M., R. 31774)

* Biotite is recorded only in the Carbet Massif of Martinique and in the Petit Piton of St Lucia (Lacroix 1904, pp. 557, 591).

A few specimens [now in the British Museum (Nat. Hist.)] were also collected in Montserrat at Sweeny's Bay, Roche's, by Dr K. W. Earle (in 1923). They include *Phyllocoenia cavernosa* (R. 30902), *P. annularis* (R. 30909) and *Diploria clivosa* (Ellis & Solander) (R. 30905, R. 30907).

None of the broken coralla shows any indication of an area of attachment; but it is clear that, even if, before fossilization, they had become detached from their original position of growth, they could not have drifted far.

All the species thus known as fossils from the island are common forms now living in the shallow waters of the West Indies. The specimens from Montserrat would indicate that similar conditions prevailed during the formation of the coral-bearing limestones, the age of which, both from the specific identifications and the state of preservation of the fossils, would appear to be not earlier than Pleistocene.

References: Matthai 1928; Vaughan 1919*b*; Wells 1936.

(b) *Notes on the Foraminifera from the Fossiliferous Tuffs of Roche Bluff*

By C. D. OVEY, B.SC., F.G.S.

The following samples were examined:

(1) From cliffs on shore 195 yards north-east of Sweeny's Well, Landing Bay:

- M. 149. Fossiliferous tuffaceous limestone
- M. 150. " " "
- M. 151. Limestone

(2) From cliffs on shore about 350 yards south of the mouth of Cold River (1500 yards north-west along coast from Roche Bluff):

- M. 162. Part of a coral colony (M. 161) showing matrix
- M. 165. Fossiliferous limestone
- M. 194. " "
- M. 196. " "

It was not possible to extract the foraminifera from the matrix. Hence it has been necessary to cut thin sections. From these the following identifications have been made:

- | | |
|--|--|
| <p>M. 149. <i>Amphistegina radiata</i> (Fichtel & Moll)
 <i>Archaias</i> sp.
 <i>Biloculina</i> sp. cf. <i>subsphaerica</i> d'Orb.
 <i>Dentalina</i> sp. cf. <i>communis</i> (d'Orb.)
 <i>Globigerina</i> sp.
 <i>Operculina venosa</i> (Fichtel & Moll)
 ? <i>Polymorphina</i> sp.
 <i>Quinqueloculina seminula</i> (Linn.)</p> | <p><i>Biloculina</i> sp.
 <i>Bolivina</i> sp.
 <i>Cancris</i> sp.
 <i>Globigerina bulloides</i> d'Orb.
 <i>Globigerina</i> sp.
 ? <i>Globorotalia</i> sp.
 ? <i>Heterostegina</i> sp.
 <i>Nodosaria</i> sp.
 <i>Nonion</i> sp. cf. <i>depressulus</i> (Walker & Jacob)</p> |
| <p>M. 150. <i>Amphistegina radiata</i> (Fichtel & Moll)
 <i>Anomalina</i> sp. cf. <i>ammonoides</i> (Reuss)
 <i>Archaias</i> sp.</p> | <p><i>Operculina</i> sp. cf. <i>venosa</i> (Fichtel & Moll)
 <i>Operculina</i> sp.—fragmentary</p> |

- M. 150. ? *Peneroplis* sp.
Planorbulina mediterranensis d'Orb.
Textularia sagittula DeFrance
Triloculina tricarinata d'Orb.
Triloculina sp.
- M. 151. *Archaias* sp.
Globigerina bulloides d'Orb.
- M. 162. *Amphistegina radiata* (Fichtel & Moll)
Asterigerina carinata d'Orb.
? *Fronicularia* sp.
Globigerina bulloides d'Orb.
Globorotalia sp.
Operculina venosa (Fichtel & Moll)
Quinqueloculina sp.
- M. 165. *Amphistegina radiata* (Fichtel & Moll)
Globigerina dubia Egger.
- M. 194. *Amphistegina radiata* (Fichtel & Moll)
Archaias aduncus (Fichtel & Moll)
Globigerina sp.
Marginulina sp.
Textularia saggittula DeFrance
Textularia sp.
- M. 196. *Amphistegina radiata* (Fichtel & Moll)
Archaias sp.
Operculina venosa (Fichtel & Moll)

The assemblage, in which *Amphistegina radiata* Fichtel & Moll is the predominating species, is typically of a tropical shallow-water nature. The fauna compares well with records, both from Tertiary and Recent rocks, of other authors from the West Indies and neighbourhood. It is not earlier than Miocene in age, and is in accord with a Pleistocene or Recent date for the containing deposits. Calcareous algae are also abundant.

[Added 10 February 1938. Since the completion of this contribution, a further sample (M. 154) from the same locality as M. 149, M. 150 and M. 151 has come to hand containing the following species: *Amphistegina radiata* (Fichtel & Moll), *Globigerina bulloides* d'Orbigny, *Globigerina cretacea* d'Orbigny, *Globigerina ? triloba* Reuss, ? *Orbulina universa* d'Orbigny and *Sphaerogypsina globulus* (Reuss). Algae are also present.]

References: van den Broek 1876; Cushman 1919, 1922a, 1922b, 1926; Goës 1882; Jones and Parker 1876.

XIV. GENERAL SUMMARY AND CONCLUSIONS

(i) *Volcanic history of Montserrat.* We have seen that, since late Miocene or early Pliocene times, at least seven distinct series of volcanic eruptions have occurred in Montserrat, and that the centre of activity has oscillated between northerly and southerly parts of the island. Four of the volcanic centres lie roughly on a central line that runs slightly west of north and does not conform to the local north-west trend of the volcanic arc; the three others lie on a line that crosses the southern part of the island in a west-north-westerly direction. The Soufrière Hills, the youngest, and at the present day the loftiest, volcano is situated at the intersection of these two lines. Lavas were erupted at only one centre.

The Silver Hill volcano, in the north, is thought to be of late Miocene or early Pliocene age. All the other centres are believed to have been active in Pleistocene or Recent times; in three instances this is proved by fossil and stratigraphical evidence. It has been shown that the eruptions of the Soufrière Hills were of the peléan explosive type and that they occurred in Pleistocene or Recent times, that is to say within the

last one or two million years. Since the last eruptions, erosion has been very considerable. It is therefore inferred that after these volcanic outbursts, a long period, to be measured possibly in thousands of years, elapsed before the island first became known to the civilized world (1493). No eruption has been recorded since this date, and I saw no evidence necessarily suggesting even minor eruptions within the span of human history.

The presence of seven active soufrières on the flanks of the Soufrière Hills indicates clearly, however, that below this part of the Caribbean arc, as elsewhere, there is molten or semi-molten magma, and that below the Soufrière Hills in particular it lies at no great depth in the crust.

The Montserrat earthquake series of 1897-9, which is locally said to have lasted till 1902, was accompanied by increase of soufrière activity. These seismo-volcanic disturbances were not renewed after the great eruptions of the Soufrière of St Vincent and of Mt Pelé in May 1902. The recent series of earthquakes was heralded, at the end of 1933, by increased gas emission at the soufrières. Temporary intensifications of soufrière activity have been correlated by local observers with the "seismic storms" of the present series of earthquakes. It has been shown by Perret and Powell that the recent shocks were mostly of shallow local origin, the majority of the foci being below the island.

Both series of earthquakes are therefore clearly "volcanic"; that is to say they are intimately connected with the local soufrière activity, and with general magmatic conditions along the Caribbean volcanic arc.

(ii) *Records of activity in the Caribbean volcanic arc.* Prediction in regard to future events in Montserrat and the Lesser Antilles is made very difficult by the almost complete lack of continuous scientific records of past soufrière activity and local earthquake shocks, and by the vagueness of many of the accounts of isolated disturbances. We even lack such elementary data as the number and location of active and extinct soufrières. Seismo-volcanic phenomena were in fact largely ignored until 1902. To a large extent they are still disregarded unless attention is called to them by alarming events.

From the facts at our disposal, however, there are important conclusions to be drawn. We know (fig. 2) that since 1692 the longest period that has elapsed without the occurrence of a volcanic disturbance somewhere in the arc, is forty-seven years; that since 1766 the longest period of tranquillity has been twenty-eight years; and that on seven occasions the interval between eruptions or minor volcanic activity has been seven years or less. There is thus every reason to believe that eruptions or earthquakes will be renewed in the volcanic arc at no very distant date, and probably more than once in the lifetime of the present generation.

As to the violence of the probable disturbances, no prediction can be made. The three major recorded outbursts have occurred since the beginning of the century; it is

impossible to say whether that is a good or a bad sign. We know, however, that such violent eruptions are preceded by warning symptoms, such as increase in local earth tremors, rise in temperature at *soufrières*, and change in the nature of gases emitted at *soufrières*. These may pass unnoticed, or be ignored, if competent observers suitably equipped are not on the look-out for them. Warning symptoms are likely to be of short duration, and if events are not to be left to chance, observation should be continuous and observers well informed.

The graphical representation of past records (fig. 2) brings out the fact that the main centre of activity has tended to oscillate back and forth along that part of the volcanic arc between St Kitt's and St Vincent. We also know that minor disturbances in one island have been the precursors of violent activity elsewhere; and that exceptional activity in one island has been accompanied by sympathetic minor disturbances in another, often some distance away.

Records of the recent disturbances in Montserrat, when considered in relation to certain previous volcanic episodes, have given information that may be of great service in the future (cf. Powell 1937). There is a strong suggestion that, in the Lesser Antilles, seismo-volcanic disturbances tend to be particularly violent at certain periods of the year—early in May, and between October and December. The evidence is as follows.

The major outbursts in St Vincent and Martinique, in 1902, occurred on 7 and 8 May respectively.* In Montserrat in 1934, 1935 and 1936, increased earthquake and *soufrière* activity were experienced early in May. After the May eruption of 1902 the most violent recrudescence of activity at the *Soufrière* of St Vincent was in the middle of October of the same year (Anderson and Flett 1908). At Mt Pelé in 1929 a series of particularly violent eruptions occurred between the middle of October and the middle of November (Romer 1936). In Montserrat increase of seismo-volcanic activity occurred in November of 1935 and in December of 1934.

It is not implied that minor disturbances or violent eruptions may not occur in the future, as they have in the past, at other periods of the year. Serious eruptions have, for instance, taken place in March, and between 30 August and 31 September. Nevertheless it will be wise to regard the beginning of May, and the last quarter of the year, as periods especially liable to unrest.

(iii) *Future possibilities in Montserrat.* Events in Montserrat in 1936 and 1937 give good reason for the belief that the recent seismo-volcanic disturbances are on the wane. The recrudescence of activity in May 1936 was very mild.

The recognition in the island of an old crater with a central *peléan* dome has some bearing on the probability of future eruptions. Perret has expressed the opinion that dome-building marks a late decadent stage in the evolution of a volcano such as

* Sapper, followed by von Wolff, has erroneously recorded subsequent eruptions at the *Soufrière* of St Vincent between 21 and 30 May 1903 (Sapper 1927; von Wolff 1929). The time of this activity was between 21 and 30 *March* 1903 (Anderson and Flett 1908, p. 293). May was a critical time at Lassen Peak, the main outbursts occurring in that month in 1914, 1915 and 1917.

Mt Pelé, characterized by acidic lava, and that this fact is valuable in volcanological diagnosis and prediction (Perret 1935, p. 106). Some other volcanologists hold similar views. The duration of such a "late stage", although short from a geological point of view, may of course be protracted when regarded from the human standpoint. Thus we know that at Mt Pelé the explosive dome-building of 1902 was renewed in 1929; and there is no guarantee that it will not recur.

Castles Peak is a peléan dome in the crater of a volcano which, apart from soufrière activity on its flanks, has been long inactive. It would thus appear, from Perret's hypothesis, that the danger of recrudescence of violent explosive activity in Montserrat is small. Although I believe this is most probably the case, it must be pointed out that absolute reliance cannot be placed on Perret's generalization. It is known to be true for several volcanoes of peléan type, but according to Williams, who has written an account of all known volcanic domes, there are a number of exceptions to the rule (Williams 1932, p. 146). The Soufrière of Guadeloupe might be cited as an instance. According to Hovey and Lacroix it has a crater containing a peléan dome (Hovey 1903, 1905; Lacroix 1904, 1908). Several eruptions of a minor character have occurred since 1696 (fig. 2). Since, however, there have been no *violent* eruptions during this long period it may be argued that the volcano supports Perret's generalization.

From the tendency of the centre of disturbance to swing back and forth along the arc, it seems probable that the next manifestation of activity will be in Guadeloupe or St Vincent, or in one of the intervening islands.

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- Zies, E. G. 1929 The Valley of Ten **DESCRIPTION OF PLATES** and II (Pumariolic encrustations

All photographs taken by the author, with the exception of those of hand-specimens and microscopic sections of rocks.

PLATE 1

FIG. 9. Panorama looking eastwards from the road between Plymouth and St Anthony's Church. On the left, part of St George's Hill; in the centre, Soufrière Hills; on the right, South Soufrière Hill. Chance's Mountain, the highest point of the island, forms the right-hand (south) peak of the Soufrière Hills. Note numerous earthquake landslips (white streaks) on the steep forested slopes of the central nucleus of the Soufrière Hills, and the great central cleft. The foreground is formed of cultivated fields (*nuée ardente* deposits of the Soufrière Hills). The small white patch, immediately in front of the left-hand (north) spur of the Soufrière Hills, is the cliff behind Gage's Lower soufrière.

FIG. 10. Panorama looking northwards from near Mulcair and Hermitage, on the eastern outer slopes of the Soufrière Hills. In the far distance, about the centre, Silver Hill is just seen. In the middle distance are the Centre Hills. In the foreground, are cultivated *nuée ardente* slopes of the Soufrière Hills. These deposits abut on the well-consolidated agglomerates, etc., of the Centre Hills, and, on the right, sweep round northwards to the sea at Trant's.

FIG. 11. The biggest earthquake rock-fall in Montserrat. "Scree" of large blocks derived from solid bandaite, below "Hill 2600", south-south-west of Tar River estate buildings. The photograph does not indicate the steepness of the slope; incautious movement will set the blocks in motion.

FIG. 12. Earthquake landslips on the side of the big ghaut on the south-west slopes of St George's Hill. Note the well-bedded nature of the tuffs.



FIG. 9



FIG. 10



FIG. 11



FIG. 12

PLATE 2

FIG. 13. Exposure beside track, about 1000 yards north of O'Garra's, South Soufrière Hill. Well-bedded fine-grained basaltic tuffs (left) separated by an erosional unconformity from overlying fairly well-consolidated pumiceous tuff with bandaite fragments. The younger tuffs are believed to represent one of the paler bands that are interbedded with the dark tuffs not far away; here they appear to fill up a contemporaneous erosion hollow (p. 26).

FIG. 14. View looking eastwards along south coast of South Soufrière Hill, from near the O'Garra's-Sweeny's Well track. Well-bedded basaltic tuffs are seen on the hillside dipping southwards at about 25° . The point is formed by an underlying basaltic lava flow.

FIG. 15. Vesicular and clinkery top of olivine-basalt lava flow, O'Garra's, South Soufrière Hill. Note the loose rusty clinkers, resembling volcanic bombs.

FIG. 16. Part of basalt lava tunnel, south coast of South Soufrière Hill, about 600 yards west of Shoe Rock. The photograph shows part of a lava lobe, as seen in section on a steep slope close to the sea. The tuffs on the left are bedded up against the steep side of the roof of the lava tunnel, and fill a hollow between this lobe and another one not far to the left. Cf. fig. 5.

FIG. 17. View looking northwards at the pale fossiliferous tuffs of Roche Bluff, just north-east of Sweeny's Well (Landing Bay). The spur is capped by basaltic lavas and tuffs of the South Soufrière Hills volcano; these extend down the steep slope to sea level, on the right of the photograph, and overlie the pale fossiliferous tuffs unconformably. The left-hand (western) junction is probably a fault, for the dark basaltic tuffs on the nearest part of the shore are inclined at 75° towards the observer.

FIG. 18. Pale fossiliferous agglomerate containing fragments of igneous rocks, and broken masses of coral limestone; east coast of Montserrat, about 350 yards south of the mouth of Cold River. Note absence of bedding at this locality. An irregular mass of coral limestone extends across most of the picture, and lies just above the heads of the figures on the right.

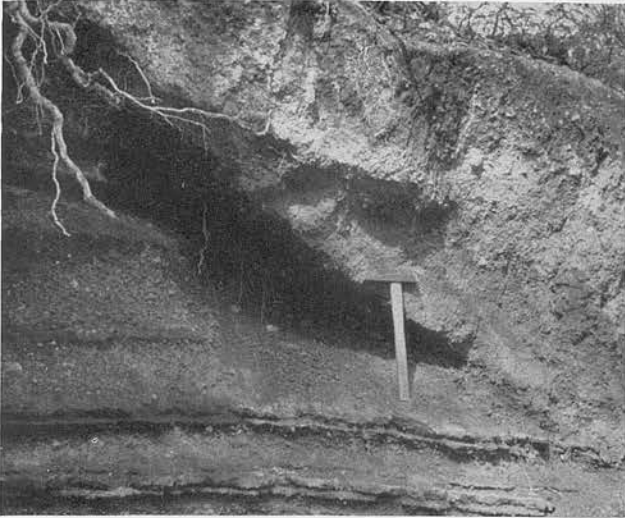


FIG. 13



FIG. 14



FIG. 15



FIG. 16



FIG. 17



FIG. 18

PLATE 3

FIG. 19. Castles Peak (about 2530 ft.) and English's Crater, Soufrière Hills, from the north-east, near Tar River. Castles Peak, the central forest-clad hill with two rocky pinnacles, is regarded as a *peléan* dome within a breached crater. The "fosse" between the dome and the crater walls completely encircles the far (western) side of Castles Peak. The analysed hornblende-bandaite of Castles Peak was collected from the great earthquake rock-fall that shows up as a pale streak in the dark forest about the middle of the slopes facing the observer.

FIG. 20. View across part of English's Crater, looking north-eastwards from ridge near summit of Soufrière Hills. The photograph shows clearly the "fosse" between the precipitous crater wall, on the left, and the much less abrupt slopes of Castles Peak, on the right. In the background, on the left, rise the cloud-capped Centre Hills, and on the right the *nuée ardente* deposits of the Soufrière Hills slope gently down to the sea near Trant's.

FIG. 21. Soufrière Hills from the north. View taken from a ridge (right foreground) forming part of the Centre Hills volcano. Note how a smooth slope of *nuée ardente* deposits sweeps down from the mountainous nucleus of the Soufrière Hills, and stops against the older rocks of the Centre Hills ridge. Castles Peak is almost entirely concealed, but the outline of its summit stands out against the clouds towards the left of the skyline.

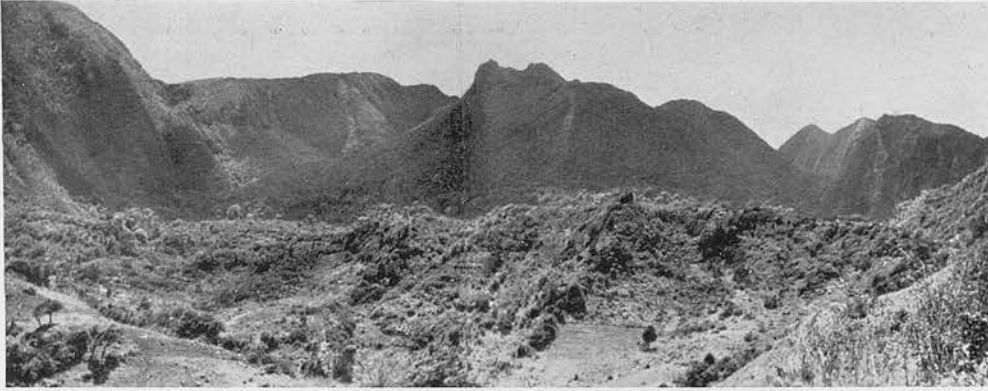


FIG. 19



FIG. 20

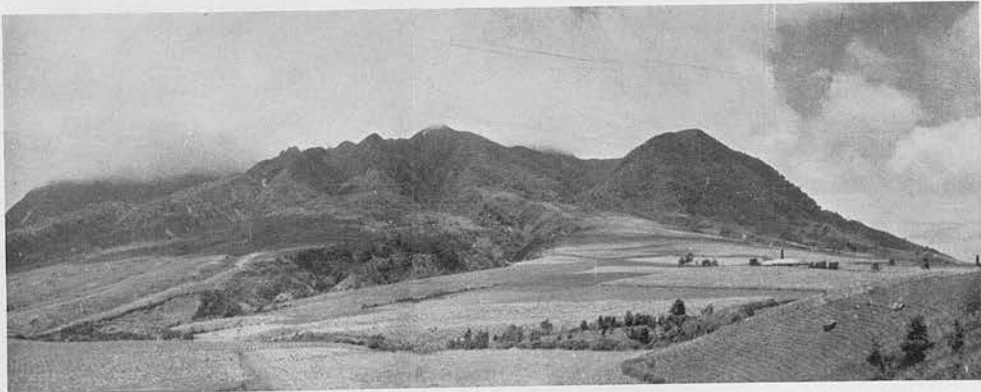


FIG. 21

PLATE 4

FIG. 22. View looking north-north-westwards along the "fosse" of Mt Pelé, Martinique, towards Morne La Croix. Slope of new dome (1929-32) on left; crater wall on right. Photograph taken May 1936.

FIG. 23. View looking southwards in "fosse" of English's Crater, Soufrière Hills, Montserrat. Slope of Castles Peak dome on left; crater wall on right.

FIG. 24. View of cliffs on east coast of Montserrat, looking south from Tar River. In foreground Soufrière Hills agglomerate of *nuée ardente* type. In the distant promontory (Roche Bluff) are seen the pale steeply inclined fossiliferous tuffs that are capped unconformably by basaltic lavas and tuffs of the South Soufrière Hill volcano.

FIG. 25. View in the small explosion crater of Chance's Pond, looking south-westwards to the mist-shrouded summit of Chance's Mountain, the highest point in Montserrat. The pond was almost dry when the photograph was taken, on 21 April 1936, after a prolonged drought; it is situated on one of the high ridges of the Soufrière Hills.

FIG. 26. View of west coast of Montserrat, looking south-eastwards to Plymouth from Hot Water Pond. Illustrates the gentle inclination (less than 10°) of the outer slopes (*nuée ardente* deposits) of the Soufrière Hills.



FIG. 22



FIG. 23



FIG. 24



FIG. 25



FIG. 26

PLATE 5

FIG. 27. East coast of Centre Hills, looking south from near Statue Rock. In foreground note dip of agglomerate in truncated spur, and hanging valley on the right. In the background, on the extreme left, are seen the *nuée ardente* deposits of the younger Soufrière Hills, where they reach the sea near Trant's.

FIG. 28. Truncated spur on west coast of Centre Hills, near St Peter's Church. Illustrates the complex history of the Centre Hills deposits. Agglomerate forms a wide U-shaped outcrop, as seen in section on the cliff face, and extends from side to side of the photograph, with its lowest part near sea-level. The hollow outlined by the agglomerate erosion surface was subsequently filled by the series of well-bedded volcanic sands that form the main component of the cliff. Still later, drainage channels were eroded to left and to right of the centre of the old depression, and eventually the summit of a new spur was formed vertically above the bottom of the old valley. Finally marine erosion cut back the spur and revealed the complex history of deposition and erosion.

FIG. 29. Coarse well-consolidated agglomerate of the Centre Hills. View looking southwards at south end of Cars Bay on the west coast. Note large water-worn boulder in left foreground, and the cracked surface of a prominent block in the vertical face of agglomerate.

FIG. 30. Cliff section in left bank of Balham River, near Week's. Shows the very irregular bedding of the pale pumiceous tuffs of the lower outer slopes of St George's Hill.

FIG. 31. Tumultuous *nuée ardente* agglomerate of the Soufrière Hills, as seen on coast road leading from Plymouth to O'Garra's.

FIG. 32. Large porous block of bandaite embedded in *nuée ardente* agglomerate of the Soufrière Hills, by the side of track from Tuit's to Tar River. Note local flow-banding, cooling cracks and irregular fracture.



FIG. 27

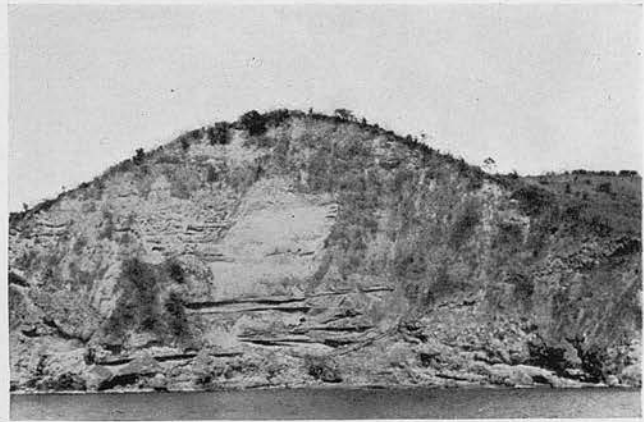


FIG. 28

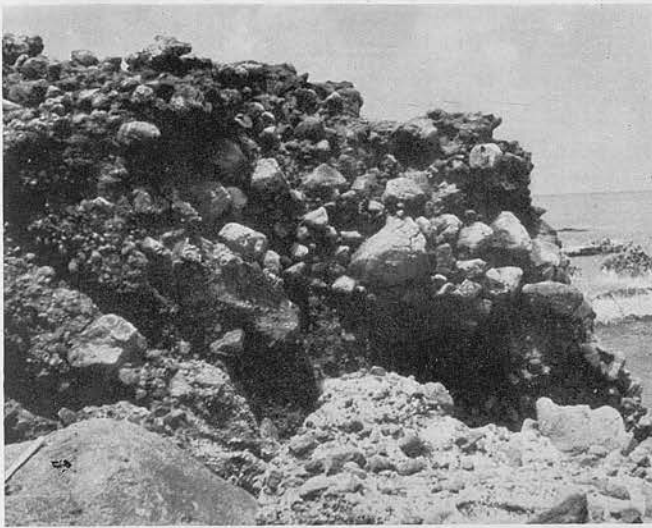


FIG. 29

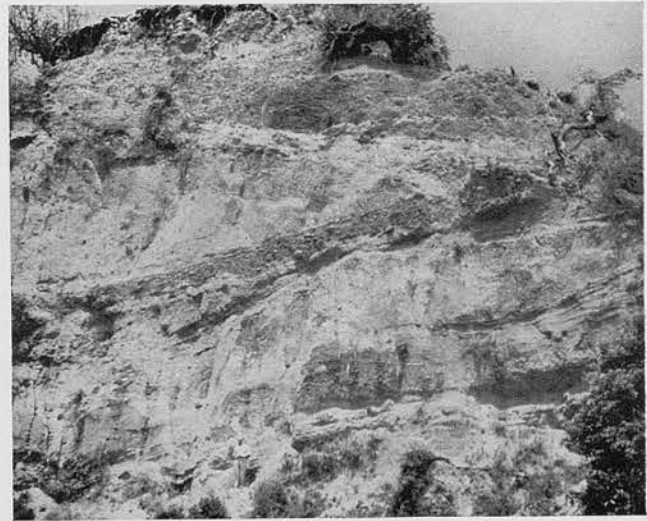


FIG. 30



FIG. 31

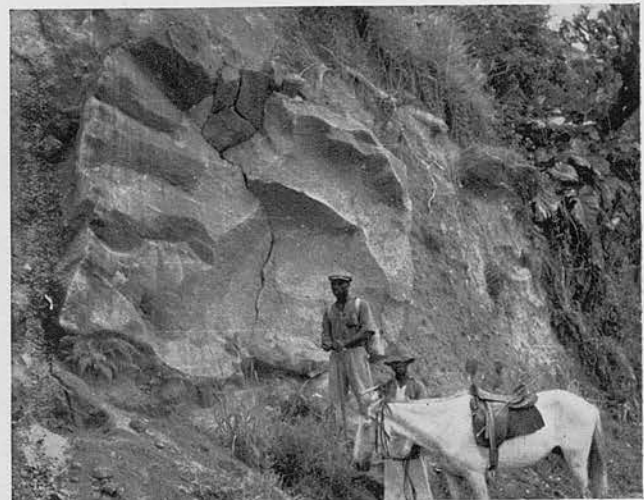


FIG. 32

PLATE 6

FIG. 33. View looking eastwards up Gage's Lower soufrière gorge. Note Mr Perret's hut on slope on the right. The recording thermometer is in the steam and fumes in the bottom of the gorge.

FIG. 34. Bird's eye view looking west down Gage's Lower soufrière gorge. Photograph taken from top of high cliff behind (at east end of) the little gorge. Note Mr Perret's hut on left, in middle distance, and the sharply limited area of devastation.

FIG. 35. Bird's eye view of Galway's soufrière from the track leading to Roche's. The observer is looking north-westwards along the little gorge with the hot stream, to the east of which the main activity was centred in 1936. In the background are mist-shrouded ridges of the Soufrière Hills. Cf. fig. 6.

FIG. 36. The main blowhole at Galway's soufrière, 12 March 1936. Steam and hydrogen sulphide were issuing with a continuous roar, like that caused by a locomotive letting off steam. Note the sulphur encrustation (pale) around the lip of the hole.

FIG. 37. Cow Hill New soufrière, 18 March 1936. Illustrates the incipient stage of soufrière formation, during which vegetation is killed.

FIG. 38. Cow Hill soufrière as seen from the slopes of Castles Peak. In 1936 the main activity was near the top of the steep bank. In the distance are the *nuée ardente* deposits of the Soufrière Hills, in the neighbourhood of Trant's and Bethel.



FIG. 33



FIG. 34



FIG. 35



FIG. 36



FIG. 37



FIG. 38

PLATE 7

FIG. 39. The hornblende-bandaite of Castles Peak, the peléan dome in English's Crater, Soufrière Hills. The large black crystals are brown hornblendes.

FIG. 40. The pyroxene-bandaite of Silver Hill.

FIG. 41. The acid hornblende-bandaite of the intrusion south-west of Landing Bay. The photograph shows one of the cognate xenoliths that are found in all the bandaite of Montserrat.

FIG. 42. Part of the outer surface of a breadcrust bomb (originally about 9 by 12 in.) found embedded in *nuée ardente* agglomerate near Tuit's (Soufrière Hills).

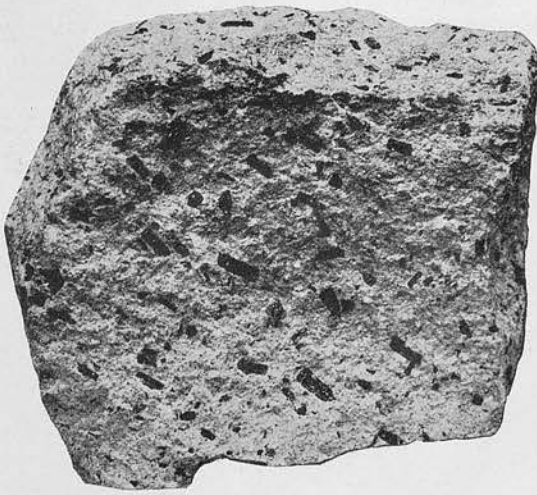


FIG. 39

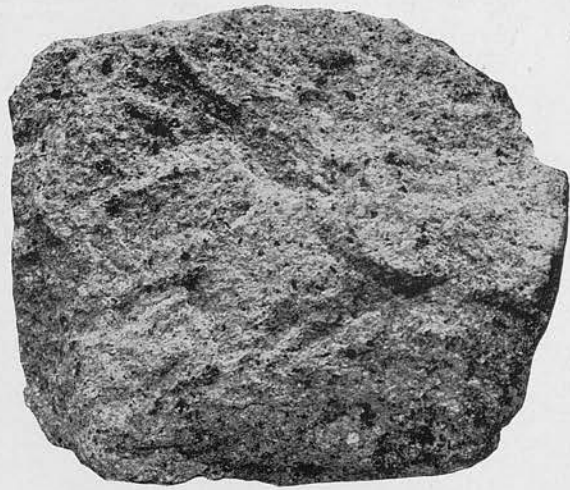


FIG. 40

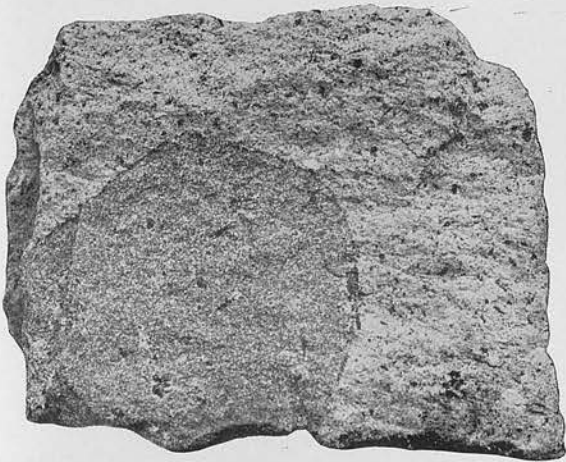
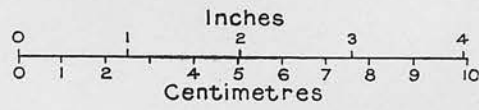


FIG. 41

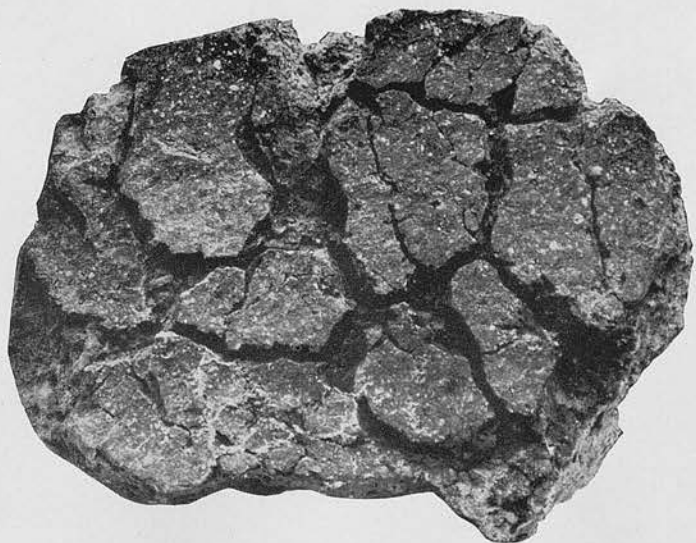


FIG. 42

PLATE 8

(Photomicrographs: ordinary light, magnified 14 diam.)

FIG. 43. Acid hornblende-bandaite, south-west of Landing Bay. Phenocrysts of brown hornblende (dark grey), hypersthene and augite (grey), plagioclase feldspar and quartz (white), and of iron ore (black). A corroded quartz phenocryst is seen just below and to the left of the large hornblende on the right of the photograph. Note narrow iron-oxide rims (due to oxidation) around pyroxene phenocrysts.

FIG. 44. Hornblende-bandaite of Castles Peak dome, Soufrière Hills. Phenocrysts of brown hornblende (dark grey), hypersthene (pale grey: very sparse and small), plagioclase feldspar (white), and iron ore (black). In the left-hand lower corner is a brown hornblende partly resorbed to a pyroxenic aggregate. The sparse quartz phenocrysts are not represented in the field.

FIG. 45. Pyroxene-bandaite of large igneous mass in Centre Hills, north-west of Tuit's. Phenocrysts of augite and hypersthene (grey), plagioclase feldspar (white), and iron ore (black). The groundmass is rich in tridymite.

FIG. 46. Olivine-basalt lava, near Shoe Rock, South Soufrière Hill. Phenocrysts of augite and hypersthene (dark grey), plagioclase feldspar (white with dark inclusions) and iron ore (black). A group of porphyritic olivines, partly enclosed in pyroxene and locally altered to iron material (black in photograph), is seen to the right of the large feldspar phenocryst in the centre of the field.

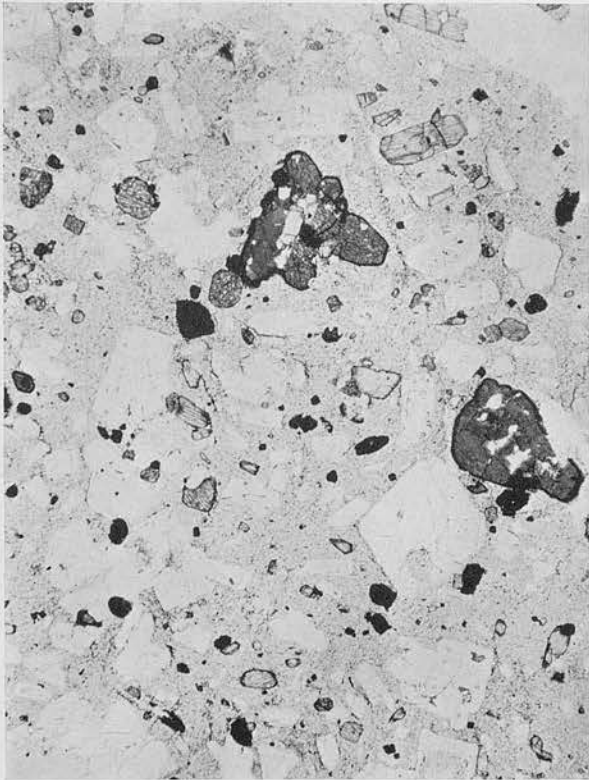


FIG. 43

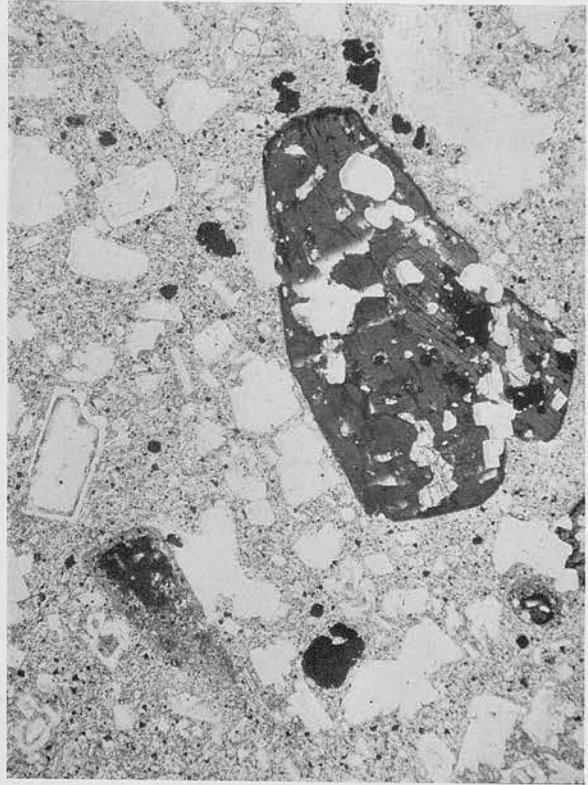


FIG. 44

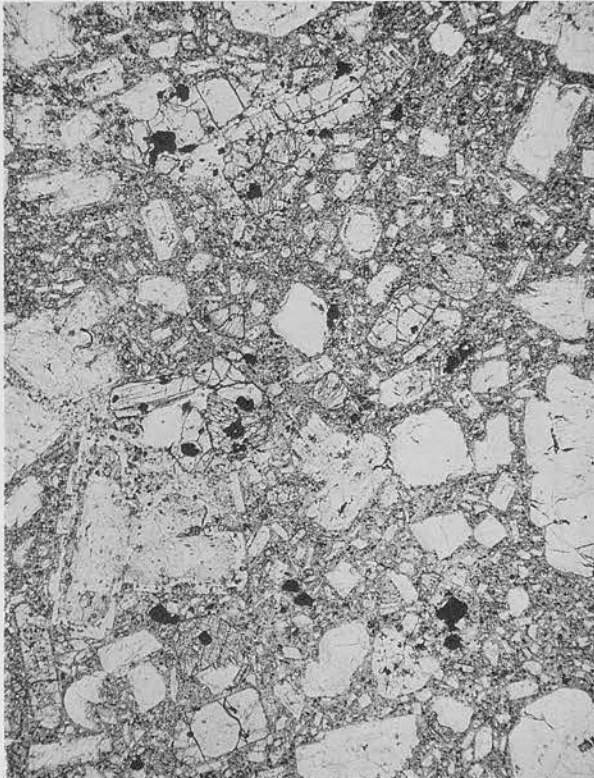


FIG. 45

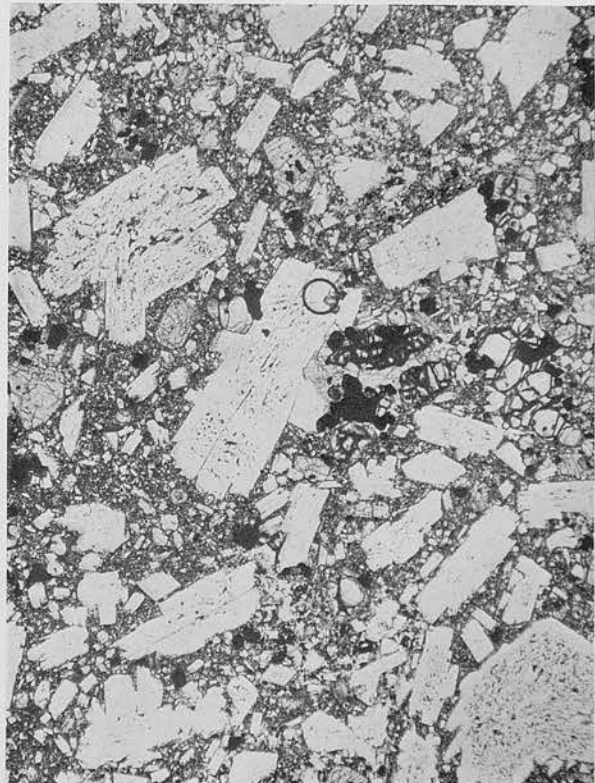


FIG. 46

PLATE 9

Geological map of Montserrat.

