1. Introduction

Mr. D.P. Robertson of the United Nations in a Mission Report dated 1972 recommended a visit to Montserrat by a geothermal expert. The Report included a brief note prepared by Tsvi Meidav on geothermal potential in Montserrat. The report *assumed* favourable potential of the natural resource and concentrated on aspects of economic demand.

A report by Dr. G.R. Robson, (1974), United Nations contained proposals for systematic geothermal investigations designed to result in a development (conservative estimate) of 360 KW. A third UN document by I.A. Innes (1974) listed drilling equipment etc. suitable to drill five slim holes to 1500 feet.

A further proposal followed a two day visit by Messrs. Wood and Shaw of Merz and Maclellan in July 1974. The report on the visit suggested the possibility of a 1 MW development by 'tapping boiling water in a borehole sited on flattish ground between Lees and Gages estates'. Estimated costs of 2/3 exploratory holes are given as £150,000. The proposed drilling site is on a general line between the inland soufrieres and sites of coastal hot water emissions near the Emerald Isle Hotel, and the assumption is of an interconnecting fissure between these locations.

The present series of investigations are being undertaken by the Institute of Geological Sciences on behalf of the Ministry of Overseas Development. Following a short visit by D. Buckley of the Hydrogeological Department in February 1975, a resistivity survey of part of the area of main interest was carried out in April 1975 by geophysicists of the IGS Applied Geophysics Unit (Tombs and Lee, 1975). The study showed a low resistivity anomaly occurring to immediate south of Gages Lower soufriere. In a geothermal context, such an anomaly could indicate hot water. No evidence to support the concept of an interconnecting fissure between the soufrieres and the Emerald Isle Hotel on the west coast was obtained although the possibility is not thereby excluded.

The visit by the present authors Dr. E.P. Wright and K.H. Murray of the Hydrogeological Department in May/June 1976 had the objective of carrying out a basic (hydrogeological/geochemical) survey of the geothermal occurrence in Montserrat with a view to assessing likely potential and if possible to propose suitable locations for deep drilling. Preliminary indications are not unfavourable but recommendations are made for further temperature gradient and heat flow studies to be carried out prior to consideration of a deep drilling programme.

2. Topography, Climate and Water Resources

Montserrat is a mountainous island with elevations attaining 3000 feet on the highest point, Chance Mountain (Figure 1). It is strongly dissected by numerous straight, steep-sided and narrow valleys - called ghauts - leading off from the interior hills. There are only two perennial watercourses of any significance - White River and Belham River. All others flow only occasionally following heavy rains. There are a number of fresh springs on the island (Walter, 1965). The springs are found at elevations between 350 and 1700 feet asl with the majority occurring in the interval between 800 and 1000 feet asl. Discharge varies considerably from less than 50 to more than 700 m^3/day and seasonal veriations commonly occur. Variations may also occur in relation to periods of seismic disturbance.

The climate of Montserrat is tropical lying as it does between latitudes 10° 40' and 10° 50' North. It has also maritime influence with rainfall and temperature closely correlated with topography. Rainfall is distributed moderately well throughout the year but with generally higher values in the period July to December (Figure 2).

Water resources for domestic use are derived from springs and some wells. Total spring flow has been estimated at 900,000 gpd (Walker, 1965) which represents about 1% of total precipitation. On the assumption of a likely availability of large subsurface supplies, a programme of drilling was carried out in the late 1960's as part of the Technical Aid from the Canadian Government. More than 200 boreholes were drilled to depths in the range 40 to 380 feet with the majority in excess of 100 feet (Figure 3). Drilling was concentrated almost entirely in the agglomerates and tuffs but the results were very disappointing. The majority of holes were dry or of negligible productivity. Almost the only wells which gave any significant production were those in the vicinity of the Lower Farms River where the formations include significant components of fluviatile origin.

The drilling results must be considered in terms of possible infiltration. Infiltration is said to be very rapid on the South Soufriere glacis (agglomeratic rocks surrounding the central laval pile) and rapid in the Soufriere Hills glacis and slower elsewhere (Land, 1967). This assessment is essentially qualitative since there are no rain fall-run-off data available. The variable high level spring occurrences and the poor permeability of the Soufriere glacis along the coastal stretch between Richmond and O'Garras deduced from the drilling results do not support the idea of deep infiltration to a continuous water table. Of the wells drilled close to the coast, most encountered a water table a few feet only above sea level. A water table at 12 feet asl was encountered at Grove and at 38 feet asl at Elbertons. More inland wells at higher elevations at Rymans and near Lees did not encounter a water table although drilling depths did not reach sea level. Gradient considerations cannot therefore be included, but the general evidence would not indicate significant submarine discharge of fresh water. The surface outcrops of the Soufriere Hills agglomerates and tuffs donot give the appearance of possessing high permeability. They are composed of poorly sorted material including generally considerable proportions of fine ashy matrix. These features combined with the occurrence of steepsided youthful valleys, common surface erosional features and the various otherindications discussed above would suggest that infiltration must represent a fairly small proportion of total rainfall over large areas of Montserrat.

Water resources aspects are not an important consideration in this investigation but it seems clear that groundwater resources are not likely to be high. Drilling into the South Soufriere Hills glacis might hold out more chance of encountering adequate supplies but there is then the conveyance expense to be considered. Deeper drilling in the inland locations in the Soufriere Hills glacis could also be considered but it must be conceded that available evidence is not favourable. Consideration of the likely distribution of deposits of fluviatile origin could be valuable. If further drilling proved unsuccessful, consideration might be given to impounding surface run-off even though the general characteristics of the valleys are obviously not too favourable.

3. Geology

The rock types composing Montserrat are almost entirely of volcanic origin. The most important geological studies are those by MacGregor (1938) and Rea (1970a, 1974). Reference to the 1974 publication of Rea will provide information on the most significant other sources of information. Geological details given below are mainly based on Rea's work.

There are five major volcanic centres in Montserrat with three subsiduary parasitic developments (Figure 4 and Table I). Their ages range from Pliocene to Recent and detailed sequences have been established only for the younger centres, those of the South Soufriere and Soufriere Hills. The active soufrieres all occur in association with the latter unit. Detailed discussion will be limited to this unit.

The Soufriere Hills (Figures 5 and 6) volcano is composed of a central nucleas of massive andesite lava surrounded by fragmental deposits dipping away mainly at low angles. The central nucleas consists of an irregular group of four steep sided domes truncated by a large breached crater containing a central dome. The four older domes are regarded either as erosional remnants of a large strato-volcano (Robson and Tomblin, 1966) or an individual extrusive masses (Perret, 1939; Rea, 1974). Rea has discussed the various arguments in favour of the latter origin. They may be summarised as follows:-

(i) Exposures of the nucleus rocks are rare but are invariably of solid lava.

(ii) Boulders on each hill are composed of a uniform petrographic type with slight but distinct individual differences.

(iii) The domes form distinct topographic units.

(iv) It is difficult to imagine the nature of the individual unit which on dissection would result in the present configuration.

Rea concludes therefore that the individual units probably formed as endogenous domes by expansion from within. The order of emplacement is believed to be Gages - Perches - Chances - Galways. The evidence is indirect being based partly on occurrences of the distinctive individual rock types in associated agglomerates and an physiographic expression and degree of weathering. There is thought to have been at least one further dome associated with the main four but subsequently destroyed; and the Castle Peak Dome may have been the last in a series of domes to fill English's Crater.

The associated fragmental rocks occurring on the Soufriere Hills glacis include both primary and secondary deposits. Agglomerate is used by Rea to describe deposits of block rich material of uncertain origin. The main characteristics of the different types are as follows:-

A. Primary Deposits

(i) Pyroclast falls:- pyroclastic material initially carried upwards from a volcanic vent. Pyroclast falls are well stratified, well sorted deposits which mantle older topography.

(ii) Pyroclast flows:- pyroclastic material which with gaseous material is carried downwards away from an eruptive vent. Such deposits are unstratified and unsorted and infill topographic depressions. On Montserrat, they include two types - pumice flows of pumiceous blocks in a fine pumiceous matrix and which are considered to have been erupted from an open crater; and pelean type pyroclast flows which contain both vesicular and non-vesicular blocks and fragments and are considered to have been erupted from craters containing domes.

B. Secondary Deposits

(i) Mudflows:- a dense suspension of fragmental material in water. They are unsorted deposits which can be very difficult to distinguish from pelean type pyroclast flows. Very heterogeneous rocks and those with a very high proportion of non-vesicular nature are more likely to be mudflows or talus deposits. A close occurrence with primary volcanic deposits is indicative of pyroclast flow origin. Pyroclast flows are geographically restricted to a small segment of a volcano.

(ii) Fluviatile deposits:- as above but with a higher proportion of water. They are better stratified and better sorted than mudflows and may include rounded deposits.

(iii) Talus deposits:- formed on flanks of volcanic domes and blocks are generally non-vesicular.

The fragmental deposits of the Soufriere Hills volcano are composed predominantly of pyroclast flows and mudflows. Stratigraphic grouping of occurrences is generally difficult and there are inevitable uncertainties. Three main groups have been recognised which are as follows:-

1. The oldest - two pyroxene pyroclast flows and mudflows (associated with Gages and Perches Domes).

2. Older hornblende - hypersthene andesite pyroclast flows, pyroclast falls and mudflows (pyroclast flows associated with Galways and Chances Domes).

3. Younger hornblende - hypersthene andesite deposits including pyroclast flows and falls and mudflows. The pyroclast flows are associated with English's crater. Most recent deposits are associated with the Castle Peak Dome. A recent thin pyroclast with charcoal has been dated at 320 ± 54 years which is some 150 years after Columbus discovered Montserrat. Absence of historical records to the contrary would indicate that the Castle Peak Dome was intruded earlier, possibly in late Pre-Columbian times.

Recent Events

The recent pyroclast flow, the occurrence of volcano-seismic crises in 1897-98, 1935-37 and 1966-67 during which periods there were sharp increases in solfatoric activity and the presence of seven live soufrieres all suggest the existence of a dormant and not an extinct volcano.

The seven soufrieres (Figures 1 and 6) all occur in association with the Soufriere Hills volcano and the majority cluster around the central nucleus. The linear patterns expressed by their groupings suggest that they are sited along planes of crustal weakness although no surface confirmatory evidence has been noted, other than some structural trends apparent on aerial photographs which have concordent alignments. The photograph trends are shown in Figure ~~6~~.5

Significant trend lines suggested by the soufriere locations are as follows:-

a) East 30° North. Soufrieres on this trend include Spring Ghaut (1 and 2), Upper Gages, New Cow Hill, Cow Hill and Mulcairs. An obvious concordant trend is the steep scarp slope following the line between New Cow Hill and Cow Hill. This trend is generally co-incident with that of the belt of earthquake epicentres recorded by Powell during the 1935-37 seismic crisis (Figure 7) MacGregor noted that the direction is also parallel to that of the Anegada Passage regarded by Hess as determined by a tear fault.

b) East 45° North. On this line occurs the extinct soufriere in White River Ghaut, Galways, the Hot Spring on the Tar River and an alleged soufriere on the east coast south of Mulcairs.

c) East 30° South. Lower Gages, Spring Ghaut (1 and 2) and Galways. The trend is sub-parallel to the line of volcanic centres associated with the Soufriere Hills volcano including St. Georges Hill, the central nucleus of 5 Domes and Roches Bluff. Three rock scars noted on the air photographs of St. Georges Hill might possibly be sites of old soufrieres. The trend is also parallel to the zone of epicentres recorded in the 1966-67 seismic crisis (Figure 8).

Structural trends on aerial photographs exist but are comparatively few. The majority occur either in association with Galways soufriere or to the east of Castle Peak. The latter are of two trends ENE-WSW and E-W and include a marked ridge below which New Cow Hill and Cow Hill soufrieres occur. The trends associated with Galways soufriere appear to have primarily local significance and Rea (1970) has suggested that Galways is sited within a pre-existing crater. The NNE-WSW trend is along a steep scarp face which could have a fault origin.

The seven active soufrieres occur in outcrops of Soufriere Hills agglomerate with the possible exception of Upper Gages which is marginal to Chances Dome and adjacent to Gages Domes and associated agglomerates. Steam emission and hot springs occur at Galways and Upper Gages and steam emission only at Cow Hill and Lower Gages. Hot springs were known in 1935-36 at Lower Gages. Mulcairs and New Cow Hill were not visited but the former is said to be virtually extinct. Gas emission is mainly steam with small percentages of non-condensable gases (mainly CO_2 and H_2S) according to analyses carried out of the emissions during the 1966-67 seismic crisis (Shepherd, 1971). The temperatures of the emissions are currently around 97°-98°C which indicates saturated steam at existing atmospheric pressure. Super heated steam was recorded with temperatures up to a maximum of 112°C in 1967-67.

Fumerolic emanations rot and bleach the affected rocks and render them susceptible to weathering. Consequent repeated land-slips, possibly combined with the heat and gas emissions inhibit vegetational growth around the soufrieres which therefore stand out as bare devastated areas. Continuous addition of fresh material occurs from the higher hill slopes above the soufrieres and eventually become incorporated also. The material includes both rock and wood. The majority of the soufrieres occur within stream valleys. The location is at least in part an effect of the susceptibility of the altered rocks to weathering which allows the associated streams to entrench themselves. Structural controls could also be related although the primary control of the stream courses is topographic.

Other than the seven active soufrieres, there is also an extinct soufriere referred to by MacGregor located on the White River. Additional locations of rock scars observed in aerial photographs which could be sites of old soufrieres are shown in Figure 6. One occurs in the Spring ghout to the SW of the known soufriere but higher up on the south side of the valley. Three occur on the south and west slopes of St. Georges Hill. There are no records of soufriere occurrences on this Hill but it was a local centre of seismic disturbance during 1934-36 (Figure 7).

Soufriere activity notably increased during the three recent periods of seismic disturbances in 1897-98, 1933-36 and 1966-67. In the second period, notable increases in steam temperatures occurred as well as obvious increases in volume of gas emissions, particularly apparent in the proportions of H_2S, (for a fuller description of this event, see Powell 1938, MacGregor, 1938 and Perret, 1939). Powell's measurements indicated foci at depths of 1-2 km and related the seismic events to magmatic intrusion at deeper levels. More detailed observations were carried out during the 1966-67 earthquake series (Shepherd et al, 1969). 189 hypocentres were determined strongly concentrated in a belt trending WNW-ESE beneath the Soufriere Hills (Figure 8) at depths of less than 15 km. During the crisis heat flow increased to a maximum and then declined. Heat flow was calculated from fluid and steam discharges and heat loss from fluid surfaces. The method employed is somewhat subjective and also takes no account of heat loss from the ground surface. The values determined are probably less than actual values but comparisons are presumably valid in relative terms.

The main soufrieres have been described in some detail by MacGregor (1938) and Martin-Kaye (1959). New mineral products include sulphur in the vicinity of fumerolic vents and also alum, gypsum, alurogen, pyrite, holotrichite and copiapite. Not all this suite are present at every soufriere. The associated rocks are bleached and rotted and locally iron-stained to varying degrees. Alteration products include kaolinite and a fine-grained pure white material which appears to be predominantly opaline silica. The hot spring effluents in Gages and Galways soufrieres are variable coloured yellow, white, black or gray, according to the nature or proportions of suspended matter which includes sulphur, clay and iron sulphide.

Table II is from MacGregor (1938) and gives details of individual soufrieres. Table III provides additional data including recent measurements.

Geothermal Prospects

The requirements of a geothermal system suitable to permit practical utilisation include a source of heat and an associated fluid phase. All currently utilised geothermal systems result from naturally occurring hydrothermal convective processes whereby high temperature fluids are developed relatively near the surface and within a sufficiently permeable formation to permit practical development. The resevoir should ideally be overlain by an impermeable cap rock which will prevent dissipation of the heat. There are two principal types of convective system, one, vapour dominated in which superheated steam occurs and the second, water dominated in which the prevailing conditions of temperature and pressure are such as to maintain a fluid phase.

A source of near surface heat is implied by the existence of the active soufrieres and hot springs. The heat flow rate calculated by Robson and Willmore in 1954 of 3×10^5 cal/sec for the combined Galways and Upper Gages soufrieres is not large and considered in energy terms is equivalent to 1.25 MW (megawatts). Observations made during the 1966-67 volcano seismic crisis indicated the likely presence of magma, albeit in relatively small volumes, occurring at comparatively shallow levels (c.10 km) below the Soufriere Hills.

No definite information exists of the existence of a permeable reservoir of hot fluid although some deductions of its likelihood can be made from indirect evidence. In the majority of currently exploited geothermal systems, the fluid phase has proved to be of meteoric origin. It seems very probable that the hot springs at the soufrieres are of meteoric origin and it is clear that the study must take account of the basic hydrogeology considered in terms of recharging meteoric water and the possible roles of rising hot fluids (superheated water or steam) which could be derived from meteoric, connate or sea water.

A detailed measurement and sampling programme was carried out on the springs, streams, fumeroles and boreholes in the southern half of Montserrat. Observations included temperature, flow rates (where applicable), ground elevations, geological occurrence etc. and the data is shown graphically and in tables (Figures 9, and Tables IV and V and Appendix A). Samples including stream condensates were collected suitable for analyses of major, minor and trace elements and radioactive and stable isotopes. Additional measurements were also made to detect the presence of mercury or radon in the soil air. Shallow holes were drilled by a portable Craelius coring rig for temperature gradient and fluid sampling purposes. Four holes were completed for these purposes (Figure 3 and Appendix B).

Steam fumeroles occur at the four main soufrieres with current temperatures of emission in the general range 97-98°C which at these altitudes correspond to saturated steam. Periodic records exist for steam temperatures at Galways, Upper and Lower Gages since 1903 (Table IV). Maximum temperatures of 126°C indicative of dry superheated steam have been recorded at Galways in 1936 during the seismic crisis. Maximum values corresponded with maximum earthquake intensities (and presumably shallow level magma intrusions) during this period. In subsequent periods there appears to be no seasonal or other correlation of the smaller ranges recorded, and some of the differences could relate to instrumental or other error.

'Boiling' or bubbing pools occur at Galways and Upper Gages. Current temperatures of the main pools actually indicate boiling and compare with steam temperatures. Outflows from the majority of pools occur and they are in a more strict sense springs. Other springs occur of varying temperatures in the range from 32 to 92°C at Galways and 52°C to boiling at Upper Gages. The spring waters as mentioned above can vary in appearance due to suspended matter and it is significant that the springs containing suspended sulphur particles are the hottest and have presumably been in closest contact with fumerolic steam vents.

Hot springs occur at two other locations, on the Tar River on the eastern side of Montserrat and at the so-called Hot Pond on the west coast close to the Emerald Isle Hotel. The Tar River Spring at the time of the recent visit was flowing at a low rate c.15 gpm with a temperature of 32.5°C. There was then no flow in the main stream. The site of the spring appears to be structurally controlled and on the aerial photographs a clearly defined trend from Cow Hill soufriere extends across the Tar River at the spring location. The Hot Pond spring occurs at an elevation only slightly above sea level emerging in the valley floor of a small ghaut trending southwards from Elberton's. The spring had a low flow of less than 5 gpm at the time of the recent visit with a temperature of 92°C. A slight flow was apparent for a short distance (c. 200m) upstream of the spring and temperatures of the flowing stream were high but lower than the spring. It would seem that discharge is occurring over a small section of the valley floor as well as at the site of the most obvious spring. The valley below the spring is commonly backfilled with sea water after high tides which flood over the beachsand bar at the outlet of the valley which is presumably only cut by storm runoff following heavy rain. No structural control is apparent in the site of the Hot Pond Spring other than its location on an extension of the line between the Upper and Lower Gages soufrieres which approximately follows the zone of maximum earthquake epicentres during the 1966-67 seismic crisis.

Hot water was found in a number of boreholes drilled by Keith Engineers on the west coast between the Emerald Isle and Gingoes. Boreholes included those at Emerald Isle, Sturge Park, Grove, Kinsale and Gingoes. Temperatures recorded (of the discharge) are in the range 33° - 71°C with highest temperatures in those boreholes closest to the Hot Pond Spring (i.e. first three of list above). Details of these and other significant boreholes are given in Appendix I. Temperatures of the discharge waters from the Richmond wells were not recorded which is unfortunate and the information would have been valuable. All borehole sites in the southern part of the island were visited and any that were accessible were opened and temperature logged to the maximum depths possible. (In most cases the wells had collapsed below casing levels). Details are also included in Appendix I. The Emerald Isle borehole had a temperature of discharge of 43°C when the casing was set at 90 feet bgl and 71°C after the casing had been jacked to 70 feet. Recent logging to maximum possible depth of 67 feet gave a bottom hole temperature of $87,5^{\circ}$C, higher than that of the recorded discharge.

The most southerly borehole with hot water recorded by Keith Engineers was at Gingoes. A shallow hole drilled to 37 feet during the current investigation recorded bht of 37°C at St. Patricks thus extending the anomaly even farther southwards.

A schematic sketch section from the interior hills to the west coast is in order to illustrate possible groundwater ?o flaws is shown in Figure 11. The variable high level cold fresh water springs are presumed to be related to local aquicludes intersecting the valley sides (notably Aymers Ghaut). A water-table is shown extending inland from the coast. It is shallow near the coast and grades upwards inland but to elevations below these of the springs which are thus regarded as probably 'perched'. Groundwater discharge occurs into the sea and if a Chyden-Herzberg relation holds a fresh-water to sea water interface should occur at a depth some forty times that of the fresh-water head above sea level. Some anomaly exists here since both the Hot Pond Spring/Craelius hole 1 and the Emerald Isle borehole are clearly contaminated with sea water at relatively shallow depths despite static water levels in one instance +3 and the other +6 feet above sea level.

The theory for the soufriere springs suggests a discharging system in a local groundwater reservoir formed from the permeable altered fumerolic rocks. Some evidence for this type of system occurs in the stream valley below Upper Gages. When the stream reaches an extinct soufriere, it disappears underground and re-appears again farther downstream below the fumerolic rocks accurrence with apparently little difference in flow rate. The springs at Upper Gages occur at the base of a steep slope of altered fumerolic rocks. The situation is less compatible at Galways where some of the major springs occur at a relatively high level within altered rocks although others are known lower down nearer the junction with unaltered rocks. Springs were recorded at Lower Gages in 1935 by Perret but subsequently dried up following a long drought. Seasonal controls of the other soufriere spring flows probably also occurs although no data are available. The information would be valuable in relation to the size of the groundwater reservoir and possible depths of penetration and it is intended to set up flow recording apparatus on the main streams from Galways and Upper Gages soufrieres. At the time of the visit, the stream flows at both locations was warm at all points and could be regarded as base 'soufriere' flow. During periods of heavy rain there is doubtless some stream flow from run-off in the valleys above the soufrieres.

The question of temperature distribution must now be considered. The warm water discharging along the west coast could have moved from a locus of heat in the vicinity of the soufrieres as shown in the schematic figure. A heat source extending underneath the coastal occurrences - which could also extend inland - is also possible with heat being transmitted by conduction to the fluid in the discharging aquifer. The moderate temperatures of most of the borehole waters make both possibilities feasible but further light on the situation is provided by the geochemistry which is discussed in a later section.

The much higher temperatures of the Hot Pond and Emerald Isle Borehole do not favour transmission from the vicinity of the central soufrieres but a much nearer heat source seems to be required. The most likely explanation seems to be an associated fracture up which ascends hot water or even steam. No fumeroles occur but gas emission has been noticed at the Hot Pond Spring and when Emerald Isle b/h uncapped. The ascending hot water could be sea water which would account for the anomolous composition of the fluid in the Hot Pond Spring and Emerald Isle Borehole. The observed piezometric heads, notably at the Hot Pond Spring imply a driving head above sea level but the difference is not great and ascending hot sea water must still be accounted a possibility. Alternatively steam with entrained sea water could account for the chemical anomalies referred to.

The occurrences at the soufrieres must explain emission of saturated steam as well as a series of hot springs of varying temperatures. A meteoric source of the springs seems a virtual certainty and the range of temperatures indicate a mixed system. The permeable fumerolic rocks are believed to be a discharging spring system but the soufrieres are clearly the termination of fracture systems which descend to greater depths. These fractures could be the channels up which boiling water and/or steam are moving. The discharge elevation implies meteoric water of sufficiently high head above the present elevation to permit a driving force.

The resistivity traverses carried out by the Applied Geophysics Unit of the IGS (Tombs and Lee, 1975) are shown in Figure ~~14~~ 12. A low resistivity anomaly was noted to the west and south of Upper Gages which in the context of a geothermal system could represent hot or mineralised water. The anomaly could represent the locus of the ascending fluids (superheated water which flashes but cooled to saturated steam) associated with the Gages soufrieres. Alternatively it could represent the permeabile reservoir with which the stream disappears in the vicinity of the extinct soufriere since the anomaly accurs in that general position. A shallow hole was drilled on the anomaly but the bht at 24 feet were cold c.25°C. Deeper drilling is clearly required but the clay horizons encountered could not be readily drilled with the small coring rig available.

Geochemistry

Results for 17 water samples and six samples of condensed fumarolic steam are shown in Table V. PH, conductance and temperature were measured in-situ or shortly after collection. Samples were acidified with HNO_3 prior to shipment.

Results to date for tritium and oxygen and hydrogen stable isotopes are shown in Table VI. Tritium analyses are represented as tritium units (TU); stable isotope ratios are given as δ-values:

$$\text{eg.} \quad \delta^{18}O = \left(\frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}}{(^{18}O/^{16}O)_{standard}} \right) \times 1000 \text{ per mil } (‰)$$

In the case of water samples, the SMOW standard (Standard Mean Ocean Water) is used as the reference at 0‰ for both $\delta^{18}O$ and δD.

Major element chemistry. The samples listed in Table V may be grouped into three classes on the basis of their chemistry and occurrence:

(i) Spring and hot pool samples from the thermal manifestations (soufrieres) and also those collected from springs on the flanks of the Soufriere hills (i.e. Amersham, Tar River and Lindsay springs). Amershams and Lindsay are cold springs, Tar River spring is warm. All of these waters show relatively low mineralisation (Na^+, K^+, Ca^{2+}, Cl^-) except in the case of sulphate levels in the warm waters. It is possible that a small part of this sulphate component arises from oxidation of dissolved H_2S to SO_4^{2-} on acidification with nitric acid. However all these samples may be classified as Na^+-Ca^{2+}-(SO_4^{2-}) waters. This clear sulphate-rich (low chloride) nature of all the waters associated with the soufrieres, and the relatively low surficial flow of fluids away from them, is strongly suggestive of vapour-dominated system(s) (White et al, 1971). The variability in net mineralisation of samples from the two soufrieres (76/422-425 from Galways and 76/430-433) may be explained partly by the effects of evaporation from near-boiling surface (and possible shallow sub-surface) pools. For instance, sample 76/424 from a pool at Galways appears to have undergone slight evaporative loss relative to the nearby "spring" waters; the molar K/Cl ratios in Table VII show the basic similarity between these sources, although the variation in Ca/Cl and Na/Cl molar ratios may be explained as the result of accelerated leaching of country rock as the various sources near the surface. Lowering of solution pH due to sulphide oxidation would be the principal agent in this process. Ca^{2+} and Na^{+} would be the principal reaction products in solution from the alteration of the anorthite-rich andesitic pyroclasts which predominate locally (Rea, 1974). The samples from pools at Gages Upper (76/430 and 432) have been enriched in Na, Ca and K by this process.

(ii) The series of samples taken from springs and borings on or close to the west coast of Montserrat between Emerald Isle and O'Garras Estate (76/426, 434, 435, 440, 458, 639, 640). These are Na-Cl type waters, of highly variable salinity ranging from 20000 mg/l Cl^{-} at the Craelius boring close to the Hot Pond, to 46 mg/l Cl^{-} in the well at Elberton. The chemical affinity between these samples is demonstrated by the molar ratios shown in Table VII. Na/Cl ratios lie in the range 0.65-1.03, K/Cl ratios in the range 0.005 - 0.06 (except for 0.57 in the Sturge Park b/h sample), and Ca/Cl ratios lie in the range 0.06 - 0.27. These ratios are all lower than those in the first group of samples. They may be compared with the values for sea-water : Na/Cl 0.864, K/Cl 0.018, Ca/Cl 0.019, and are thus seen to be scattered around these values except for Ca/Cl which shows enrichment of Ca^{2+} in all cases. It is therefore suggested that the dominant chemistry of these coastal waters is that of a marine component: in the case of the Emerald Isle B/h and Hot Pond Craelius bore (76/639) this component is very large (compare with marine values of 19500 mg/l Cl^{-}, 10900 Na^{+}, 391 K^{+}, 417 Ca^{2+}). The observed relative enrichment of Ca^{2+}, and depletions of Na^{+} and K^{+} may be attributed to base exchange reactions with country rock which are seen to have greatest effect in the sources showing highest temperatures.

A trilinear plot (Fig. 13a) of percentage equivalent cation contributions shows that the compositions of the low-salinity coastal sources lie on a trend between the high-salinity (marine-dominated) waters (Na-type) and the thermal springs and pools (Ca-Mg type) from the soufrieres and their vicinity. This may indicate the latter as being the source of the fresh water component in the coastal waters, though the predominance of the andesitic host-rock probably assures this compositional trend for all of the fresh ground waters on the southern part of the island.

(iii) The samples of steam condensate from Galways and Gages (Upper and Lower) all have low mineralisation, the level of which is reflected in the conductance values in Table V. Condensate from Galways Vent 2 (76/441) is an acid-sulphate water, due to oxidation of dissolved H_2S.

<u>Trace element chemistry</u>. To date, only Li, B and S_iO_2 have been determined on selected samples (Table V). Molar ratios of Li^+/Cl^- and Cl^-/B appear in Table VII (marine values are 0.045×10^{-3} and 1324 respectively).

Li^+ is obviously enriched in the samples taken from the hot 'pool', but it also shows considerable local variation in spring sources. In all the coastal samples, Li/Cl is considerably higher than the marine value. It has previously been suggested that Li^+ might be a good pathfinder element in hydrothermal systems (Brondi et al, 1973), and in the present case there is sometimes apparent a correlation between apparent Li enrichment and measured temperature.

B also appears to be enriched in the coastal samples (76/426, 434, 435) with respect to sea-water. The variation of Cl^-/B in these three cases over a small area suggests that the boron is not being enriched in the marine component prior to its dilution.

SiO_2 values and their relevance to geothermometry will be discussed subsequently.

Tritium and oxygen/hydrogen stable isotopes. The interim ^3H analyses for six samples shown in Table ~~V~~ VI are all significantly positive values, i.e. all of these waters (4 from soufriere streams/pools, 1 of steam condensate, and 1 from a coastal well) have significant post-1953 contributions. The range of values for soufriere waters, 6.4 - 19.0, probably reflects the effects of evaporation on a uniform recharge water which could be largely very recent water (1 - 2 years) or a pre-1953 water with a small contribution of high-^3H water (from the mid- 1960's for instance). A similar conclusion may be applied to the 31.8 TU value for Hot Pond Spring, though this is more remarkable in view of the very high component of sea-water found for this sample. Marine ^3H is roughly at the 1TU level. It is therefore reasonable to conclude that the non-marine component must have a moderately high ^3H value, possibly between 100 - 200 TU. A model which is consistentwith these observations is that of a local recharge-discharge system operating in the vicinity of the soufrieres, heating taking place during the relatively rapid transit of water (Figure 11). On the other hand, the travel time for water discharging as the 'fresh' component of the coastal wells is considerably longer (of the order of 10 years possibly). This water therefore probably originates also from infiltration in the high ground inland.

The stable isotope results are flotted in Fig. ~~15~~ 14. The Emerald Isle B/h water is close to SMOW, as expected. The other samples lie on or to the right of the precipitation line ($8\,\delta^{18}O + 10 = \delta D$) (Craig, 1961). Water from Galways Spring E2 (76/435) and Sturge Park B/h (76/434) are on this line, reflecting the predominance of meteoric water; in the latter case, the presence of a marine (SMOW) component suggests that the 'fresh' component has an isotope composition more depleted (i.e. down-slope) than the mixture. Sample 76/432 from a pool at Gages Upper is unimportant - the isotopic enrichment being mainly due to evaporative loss (cf. also the ^3H value of 19.0 TU for the same sample). The steam condensate from Vent 2 at Galways has similar δD to the warm spring sample 76/425, but a higher $\delta^{18}O$. The feature could indicate deeper infiltration of the source groundwater permitting greater reaction with country rock in the hot zone and consequent enrichment in $\delta^{18}O$ from the silicates.

Silica and K/Na/Ca geothermometry. Calculated temperatures from solution compositions are listed in Table VIII. In the case of K/Na/Ca, the calculated temperature is that of an assumed equilibrium of a base exchange reaction between feldspars. Since the calculation used elemental ratios, the method is less susceptible to error by dilution of the thermal water with cold waters. The silica calculation assumes a solution equilibrium with a phase of SiO_2 at the zone of highest temperature, and the maintenance of a supersaturated state during upwards migration and cooling, (Fournier & Rowe, 1966). This method is highly susceptible to the effects of dilution or precipitation of SiO_2. Fournier & Truesdell (1973) suggest values of $\beta = 4/3$ and $\beta = \frac{1}{3}$ for source temperatures of $< 100^\circ C$ and $> 100^\circ C$ respectively for use in their empirical equations (the difference is explained by the temperature-dependence of the importance of Ca^{2+} in the exchange reaction).

The K/Na/Ca temperatures are all sub-100°C, with the exception of those for the coastal samples, which all have, as previously discussed, marine contribution. Since sea-water is not in equilibrium with feldspars, these results must be discounted as meaningless. The only feature of note is the anomalously high K^+-value for the Sturge Park sample (76/434) which causes the calculation to yield such a high temperature.

The quartz temperatures are all high as a consequence of high SiO_2 levels in solution. A clue to the real cause of this is given by the calculated temperatures assuming amorphous SiO_2 to be the equilibrating solid phase; these values are mostly fairly close to the measured temperatures. It is suggested that the observed SiO_2 levels in solution are almost invariably the result of equilibration with amorphous SiO_2 deposited as sinter on the surface and near subsurface (cf. XRD analyses of soufriere deposits by Morgan-Jones & Edmunds 1974).

Conclusions

The geochemical and hydrogeological evidence are in general accordance. The inland hot and cold springs have basically similar chemistry. Differences and variations in the compositions of the hot springs can be related either to local rock-water interactions or evaporation effects. Neither the chemistry nor the isotope data indicate a deep level of circulation or contribution from other than meteoric sources. The geothermometry data (S_1O_2; K/Na/Ca compositions) confirm a probable shallow SiO_2 ×
circulating system. The S_1O_2 compositions and observed temperatures are SiO_2 ×
in equilibrium with low temperature amorphous silica; the K/Na/Ca compositions have not even attained equilibrium with the observed temperatures. The combined evidence suggests therefore a shallow, rapid circulating system with the water of recent age. The only possible indication of a deeper circulation is the higher ^{18}O of the steam condensate.

The chemical compositions of the hot coastal spring and boreholes indicates varying proportions of sea water, the proportions apparently increasing with temperature (cf. Hot Pond spring and Emerald Isle bh.). The location near the coast provides general accessibility to sea water but the positive hydraulic head in normal circumstances would have resulted in a fairly coherent fresh water body extending down to a saline interface at appreciable depth (approximately 40 times positive head: Ghyden-Herzburg relationship). The occurrence of sea water occurring at these comparatively high levels seems likely to be due to convectional processes whereby hot sea water is rising and mixing with the cold meteoric water draining from the interior of the island. Minor compositional features such as the presence of H_2S in some wells can readily be related to rock interaction with hot sea water. The meteoric component in the Hot Pond spring appears to be older than the fresh water inland springs which is consistent with normal groundwater flow patterns.

The remote source of heat can be readily attributed to probable magma occurrences below the Soufriere Hills (Shepperd et al, 1969). The process of heat input to the shallow groundwater is more problematic. The chemistry of the soufriere waters indicates little likelihood of addition of heat in a rising water phase and the two feasible alternatives are addition of heat by conduction or by rising steam. No chemical criteria have been established to date which can provide a reliable distinction between the alternative processes but a closer appraisal of the chemical data will be made when all the analytical results become available. On the assumption of a deep remote magmatic heat source addition of heat by conduction would probably imply a relatively high level hydrothermal system resulting in high temperatures in the shallow subsurface and separated from the very shallow groundwater system by an impervious cap rock. Addition of heat by rising steam would occur along fracture systems which are likely to be associated with the soufriere locations (see earlier discussion). The steam would stem from a deeper seated hydrothermal system. This alternative hypothesis does not require a high level hydrothermal system although the feature is not precluded. It does however imply recharge to the latter by meteoric water since the hydraulic head must be well above sea level.

In the coastal areas between Elbertons and St. Patricks, heat input to the sea water with subsequent upward convection and mixing could be in accordance with either of the two processes discussed. It could also include heat input by a fluid phase since the chemical criteria used to discount the occurrence in the inland areas would possibly be masked by sea water. As far as can be deduced from the trilinear plots, only two fluid phases appear to be involved one corresponding to sea water and the second to normal meteoric water. In any event, a deeper hydrothermal system is likewise implied which would provide heat at more shallow levels by conduction or in the form of liquid or vapour phases. Localised higher heat inputs obviously occur in the vicinity of the Emerald Isle/Hot Pond spring area and rising fluid or vapour up a fracture system is clearly indicated. The higher temperature of the discharge in the Emerald Isle borehole when the casing was set at 70 feet as compared with the casing set at 90 feet suggests some lateral flow from a fracture. The current gradient to 60 feet bgl (see No.25, Appendix A) seems a little anomolous since it is linear and more consistent with conductive flow. However the gradient is very steep (41 - 88°C in 50 feet) and could perhaps be interpreted in convective terms.

The deeper hydrothermal system providing heat to the soufrieres and the coastal region could be a single system. If heat addition by conduction is occurring, then a fairly extensive system is implied; if heat addition is by rising steam along a fracture system, a more localised hydrothermal nucleus is possible. It is now necessary to obtain further information on the extent and if possible the maximum temperatures of the deep hydrothermal system. The extent can perhaps be evaluated by the geophyisical data, possibly with some additional work. The results to date do imply a fairly localised occurrence below the Soufriere Hills. Shallow temperature gradient drilling to 2/300 feet could also provide information and a programme is strongly recommended. Unfortunately, it seems likely that the deep temperature data cannot be obtained without deep drilling unless fissure sources should be tapped by the gradient drilling.

Results of the survey of radon and mercury in the soilair will be included in the final report of which this is a draft. More geochemical data will also be available shortly and the results incorporated. A note on availability of suitable drilling rigs for gradient drilling will also be included.

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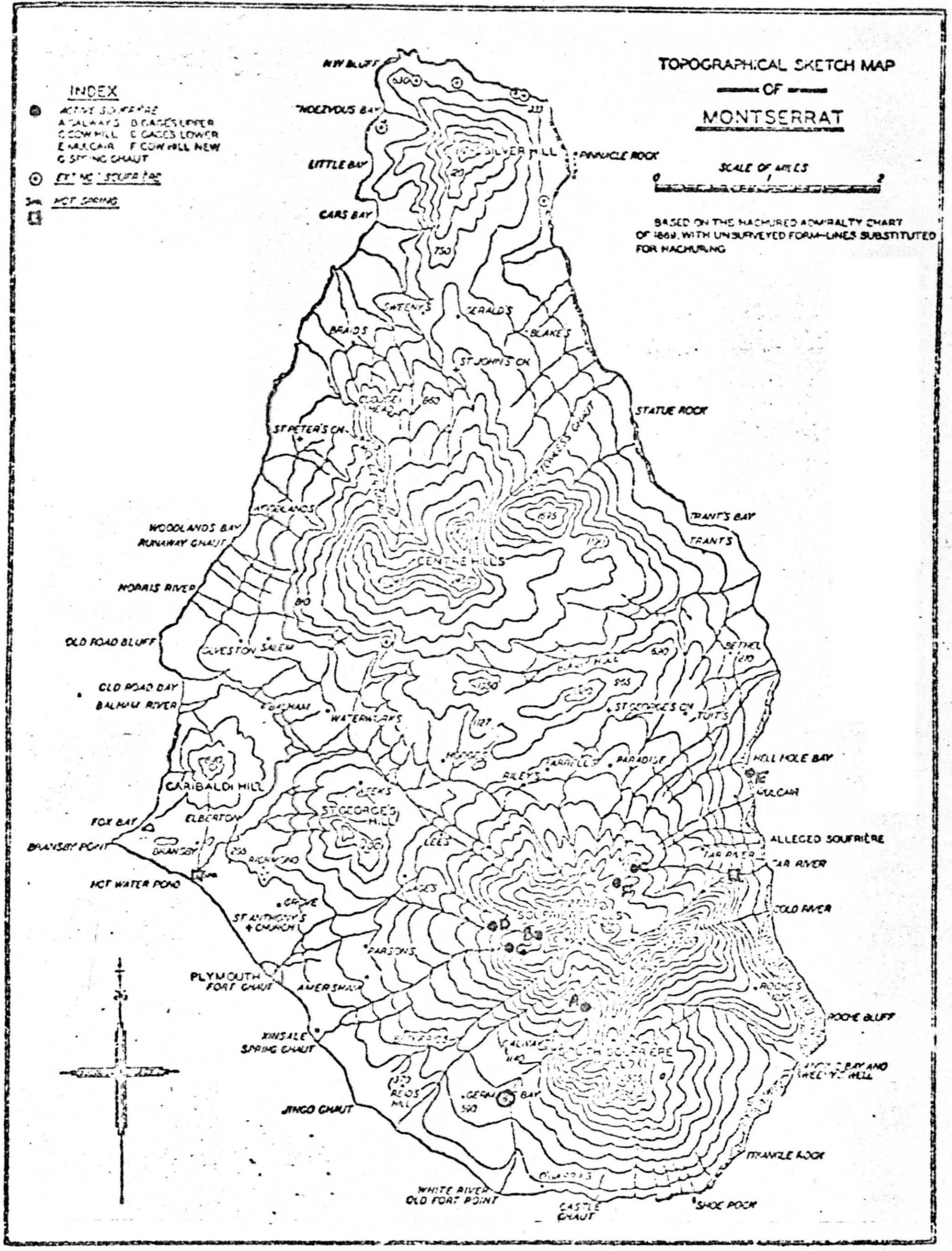
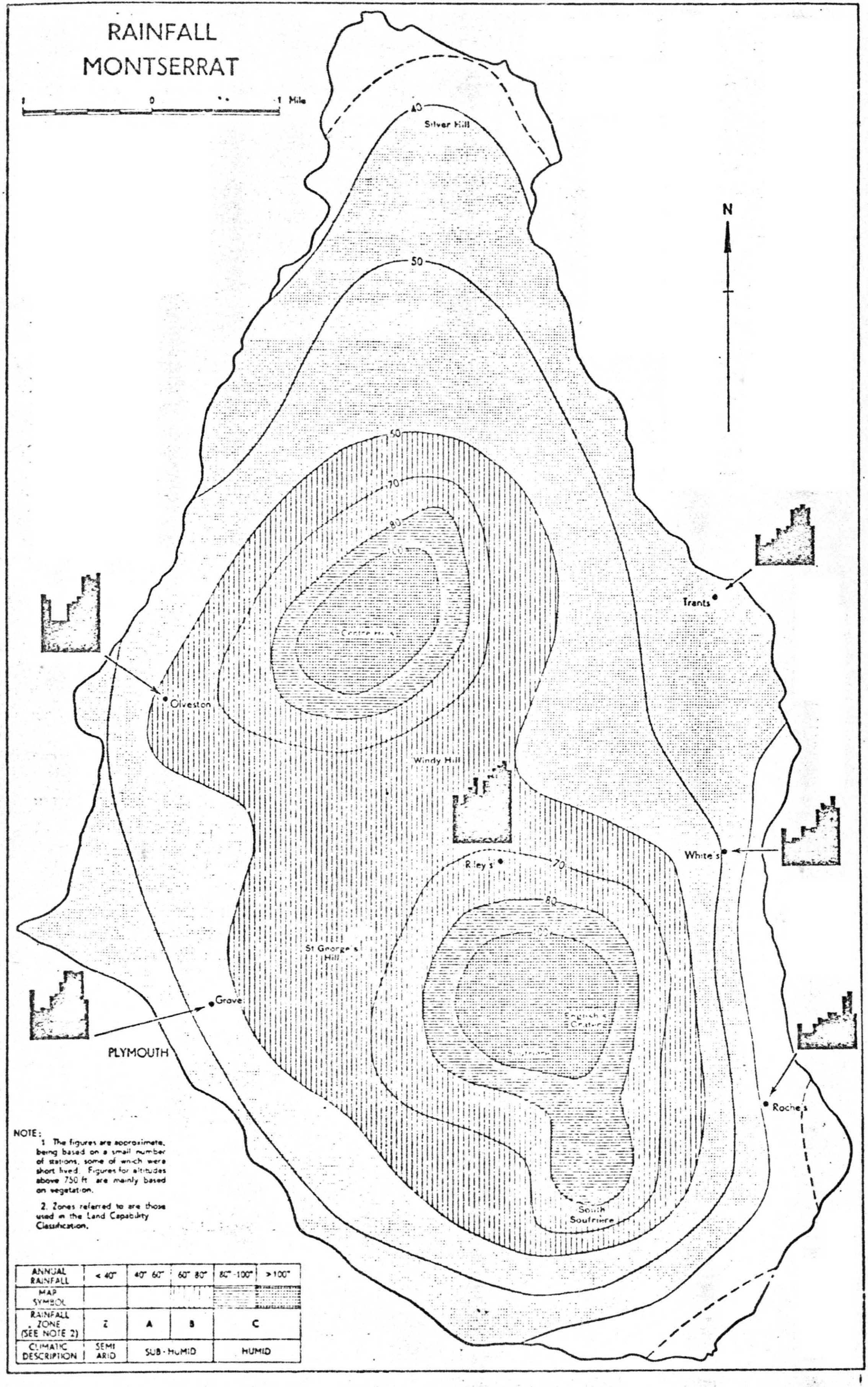


FIGURE 1. (Heights are shown in feet, e.g. 3002.)

Topographic sketch map of Montserrat showing locations of soufrieres and hot springs



NOTE:

1. The figures are approximate, being based on a small number of stations, some of which were short lived. Figures for altitudes above 750 ft are mainly based on vegetation.

2. Zones referred to are those used in the Land Capability Classification.

ANNUAL RAINFALL	< 40"	40"–60"	60"–80"	80"–100"	> 100"
MAP SYMBOL			▥	▤	▦
RAINFALL ZONE (SEE NOTE 2)	Z	A	B	C	
CLIMATIC DESCRIPTION	SEMI ARID	SUB-HUMID		HUMID	

FIGURE 2 (from Lang, 1967). Annual rainfall, Montserrat.

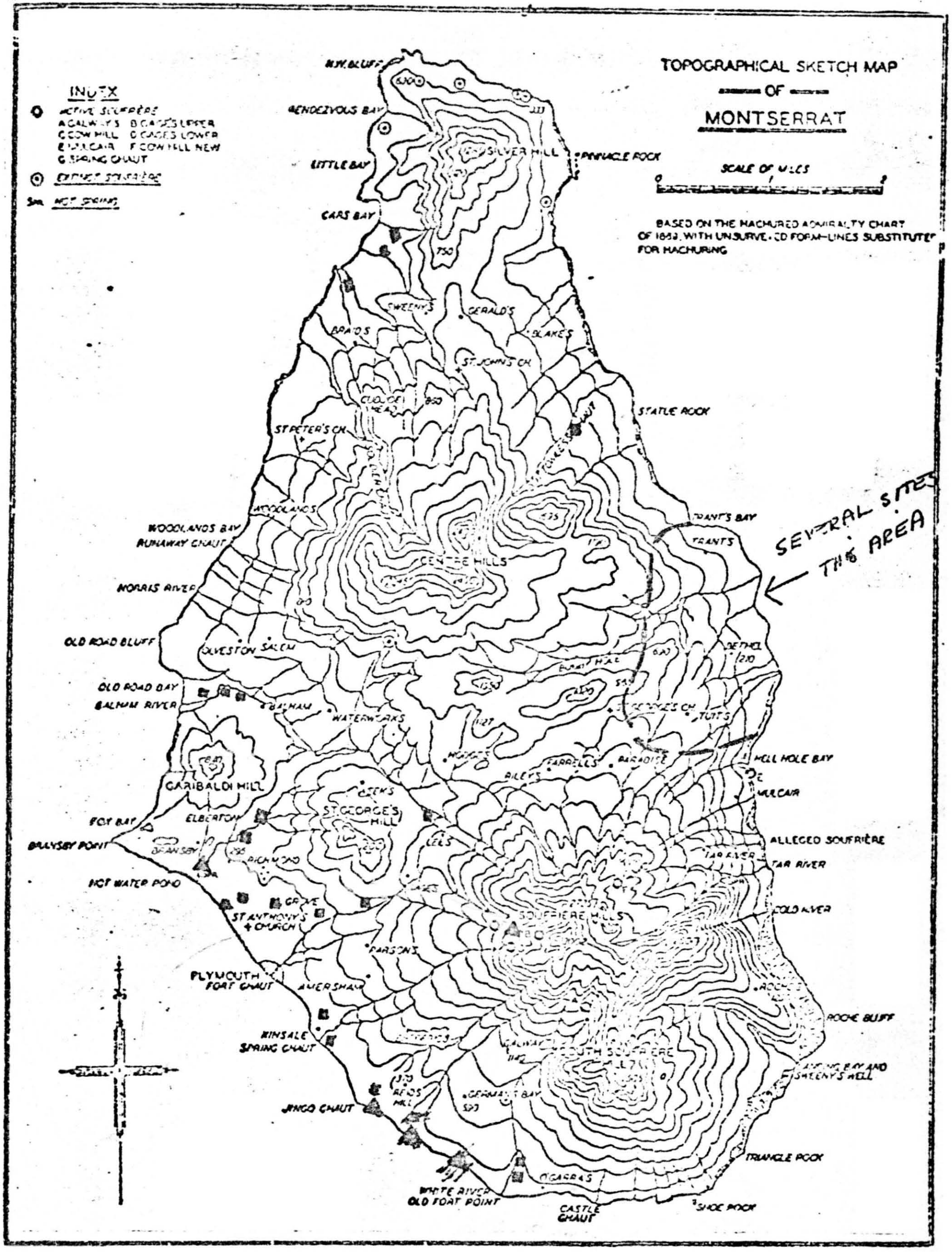
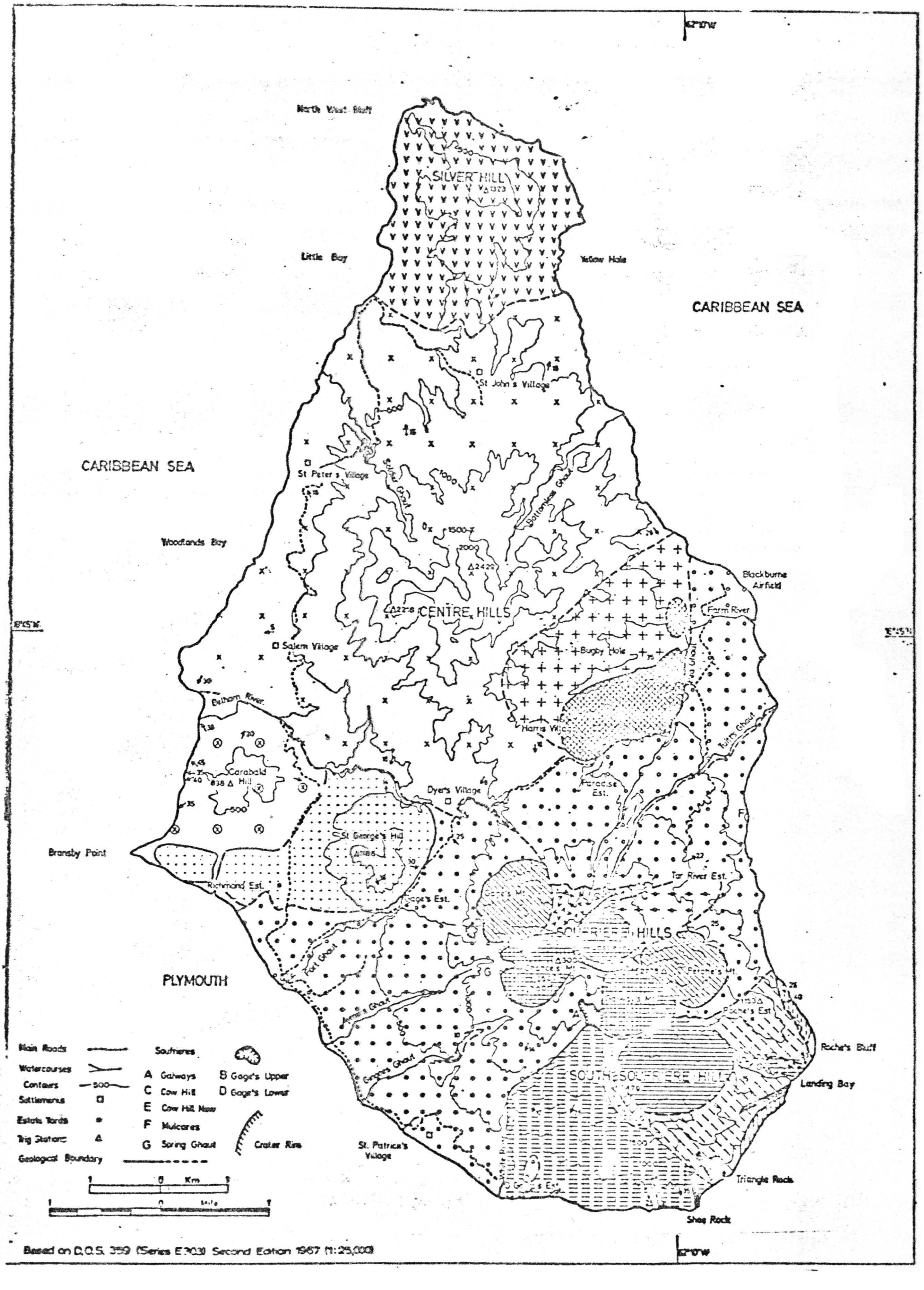


FIGURE 3. (Heights are shown in feet, e.g. 3002).

Location of drill sites ▨ in programme by Keith Consulting Engineers Ltd. Drilling included test holes, test wells, gauge holes (for pump testing) and final wells and one or more of these types may exist at any one of sites shown. For full details see map by Engineers dated January 1974.

Location of Craelius holes ▲ drilled by IGS in May/June 1976.



Based on D.O.S. 359 (Series E803) Second Edition 1967 (1:25,000)

FIGURE 4 (from Rea, 1974). Geological map of Montserrat.

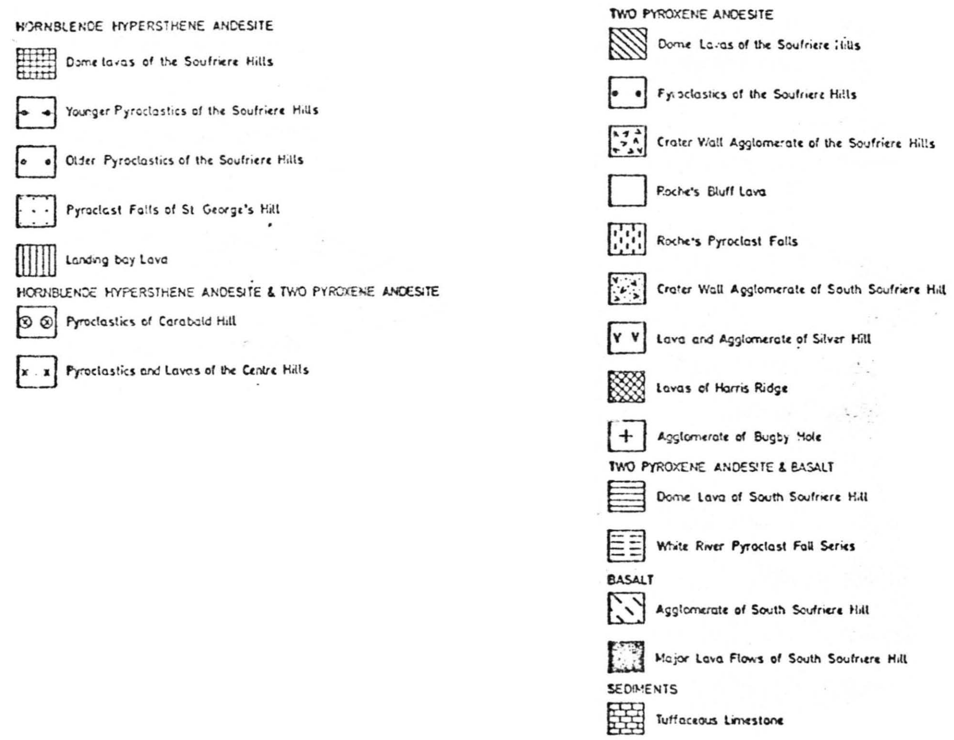


FIGURE 4b Legend

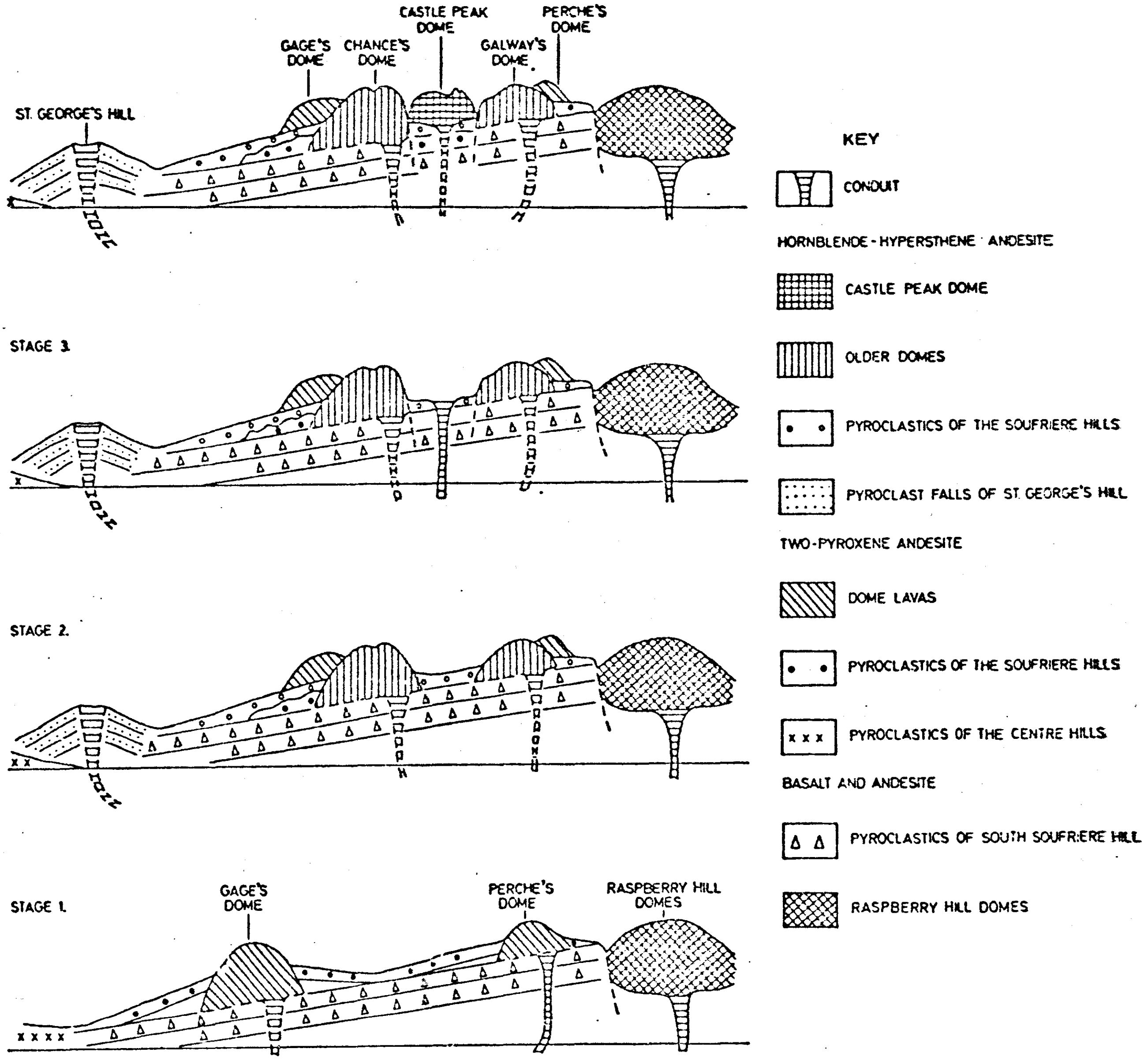


FIG. 6. The Development of the Soufrière Hills. (Diagrammatic sections running approximately NW–SE.) *Stage 1.* Eruption of two-pyroxene andesite domes and associated pyroclastics. *Stage 2.* Eruption of hornblende-hypersthene andesite domes and associated pyroclastics. St. George's Hill was probably active at this stage. *Stage 3.* Formation of English's Crater, accompanied by eruption of hornblende-hypersthene andesite pumice flows. *Stage 4.* Extrusion of the Castle Peak dome within English's Crater probably resulting in breaching of the crater wall. (from Rea, 1974).

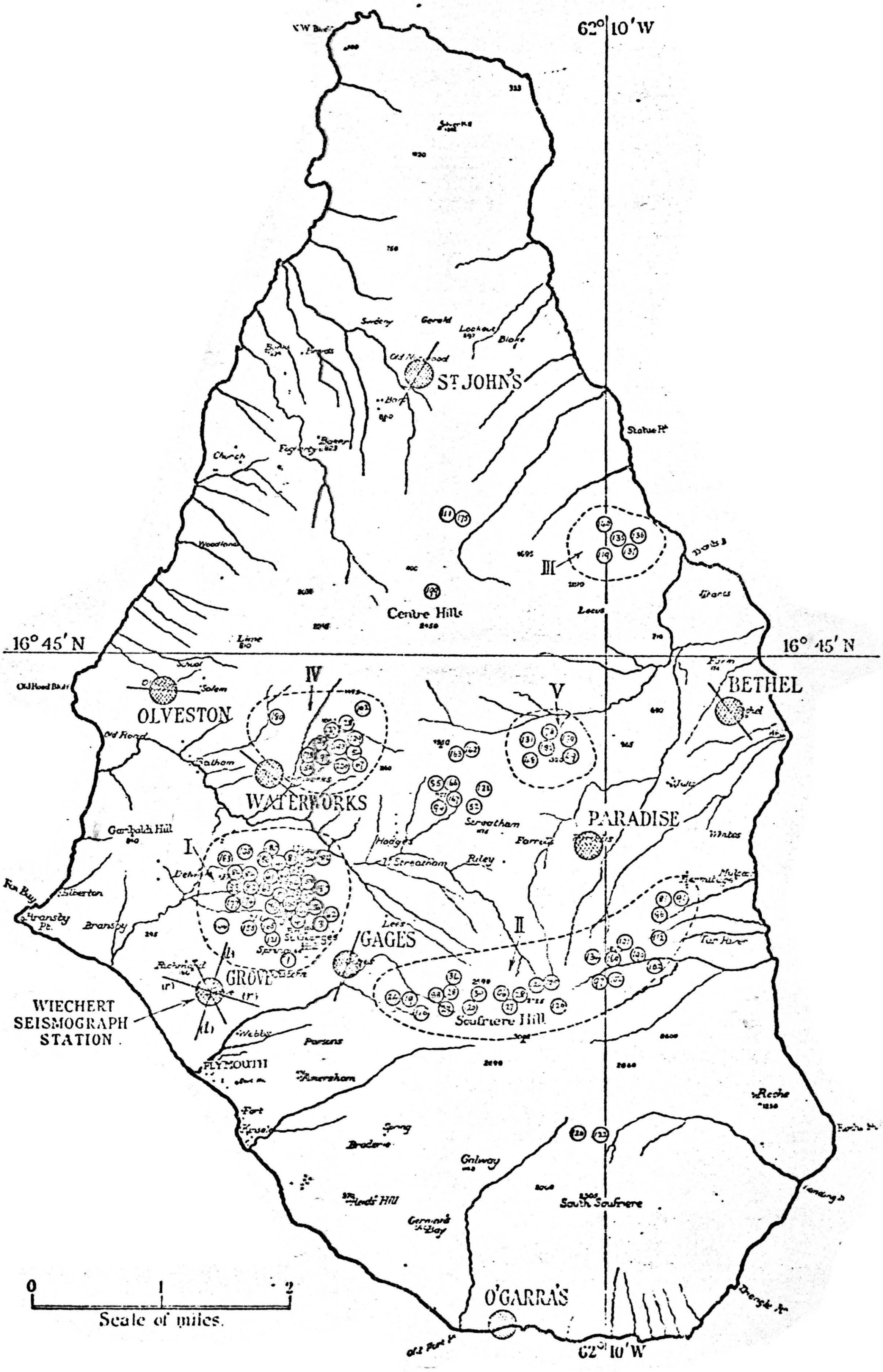


FIGURE 7 (from Powell, 1936). Location of epicentres in 1936 seismic crisis.

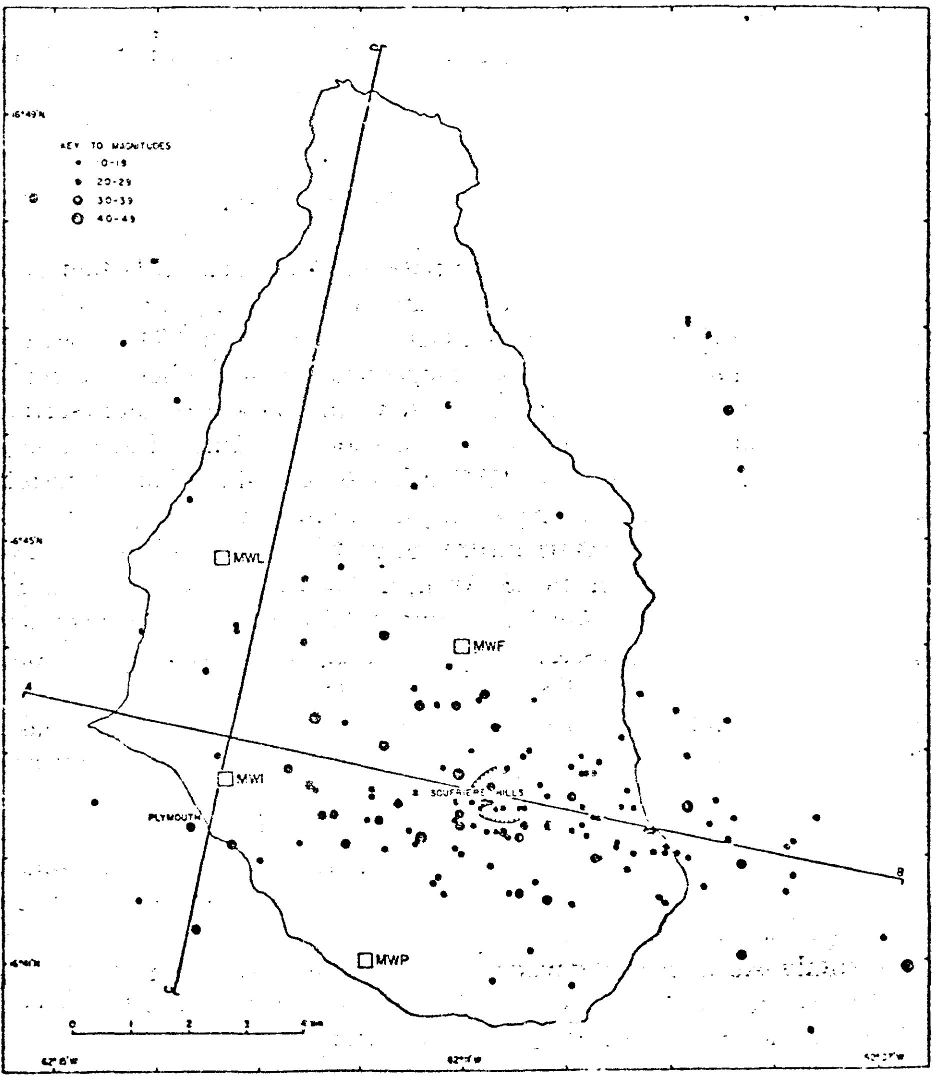


FIG. 8 - Map showing distribution of epicentres in Montserrat during the 1966-67 crisis. Solid circles represent the epicentres. Squares indicate seismograph stations: MWI = Grove; MWL = Salem; MWF = Farrells; MWP = St. Patrick's.
(from Shepherd et al, 1969).

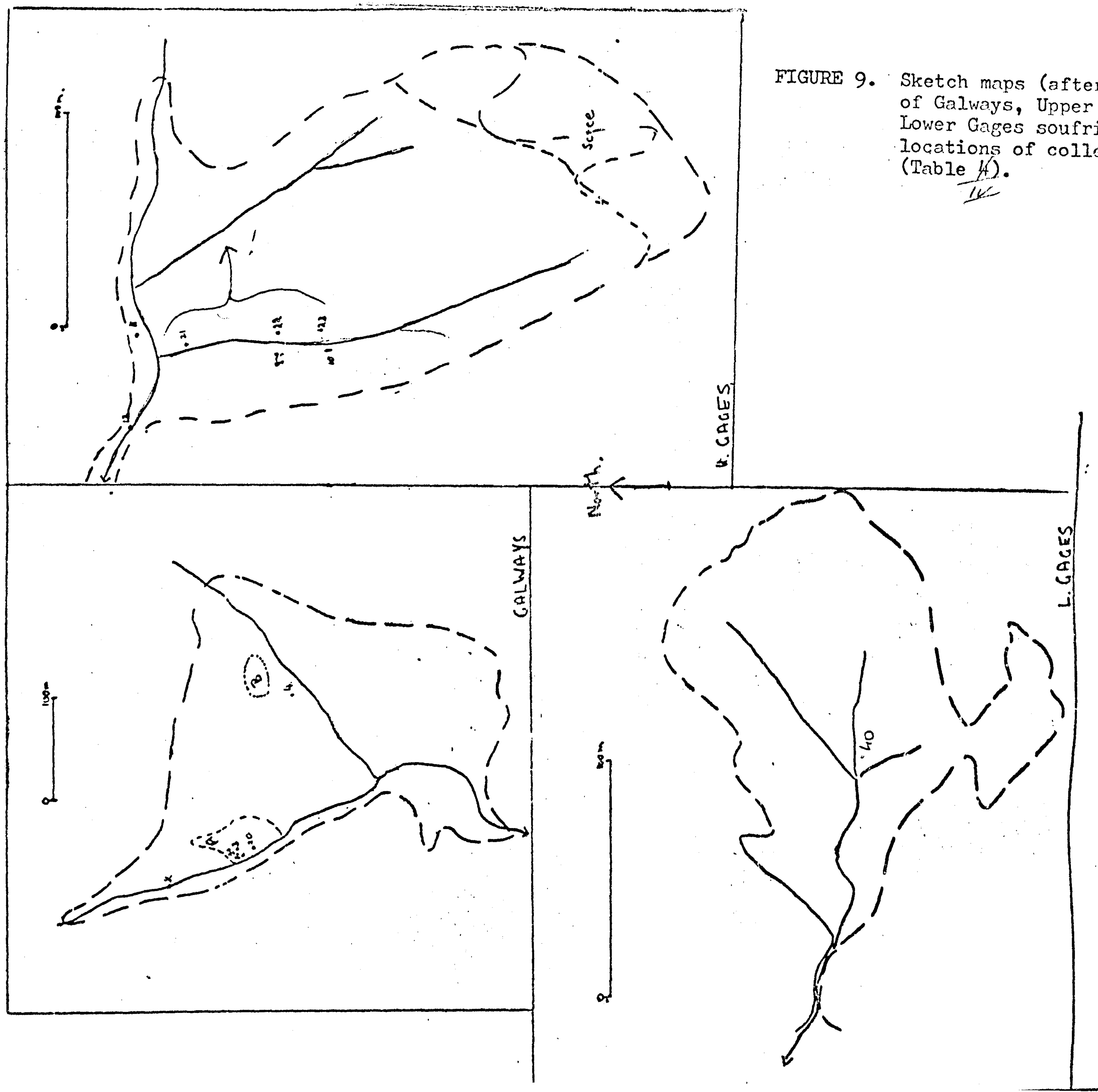


FIGURE 9. Sketch maps (after Martin-Kaye) of Galways, Upper Gages and Lower Gages soufrieres showing locations of collected samples (Table ~~4~~). IV

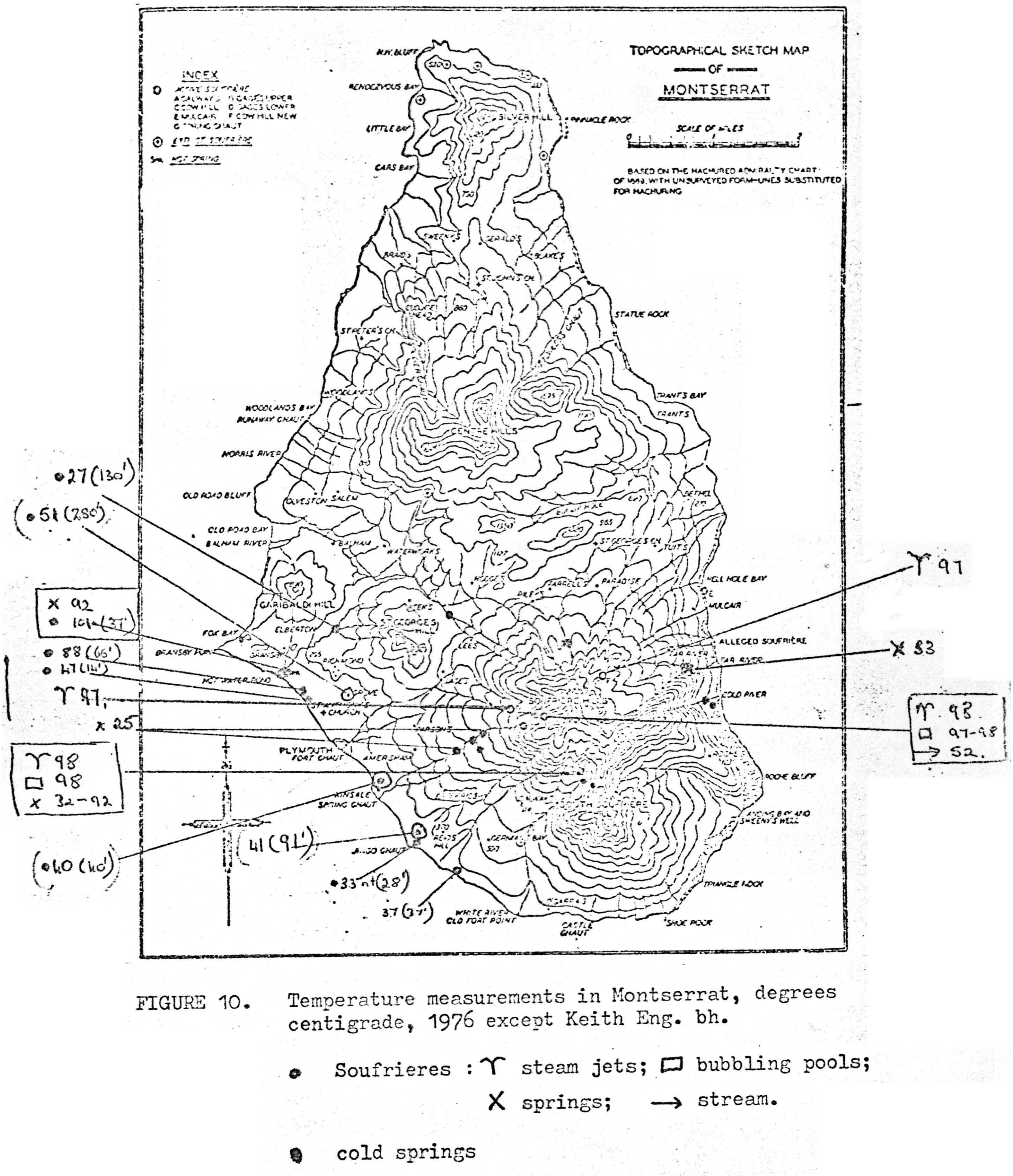


FIGURE 10. Temperature measurements in Montserrat, degrees centigrade, 1976 except Keith Eng. bh.

● Soufrieres : Υ steam jets; □ bubbling pools;

X springs; → stream.

● cold springs

● hot springs

● boreholes (depths in feet)

⊙ boreholes - Keith Engineers (depths in feet)

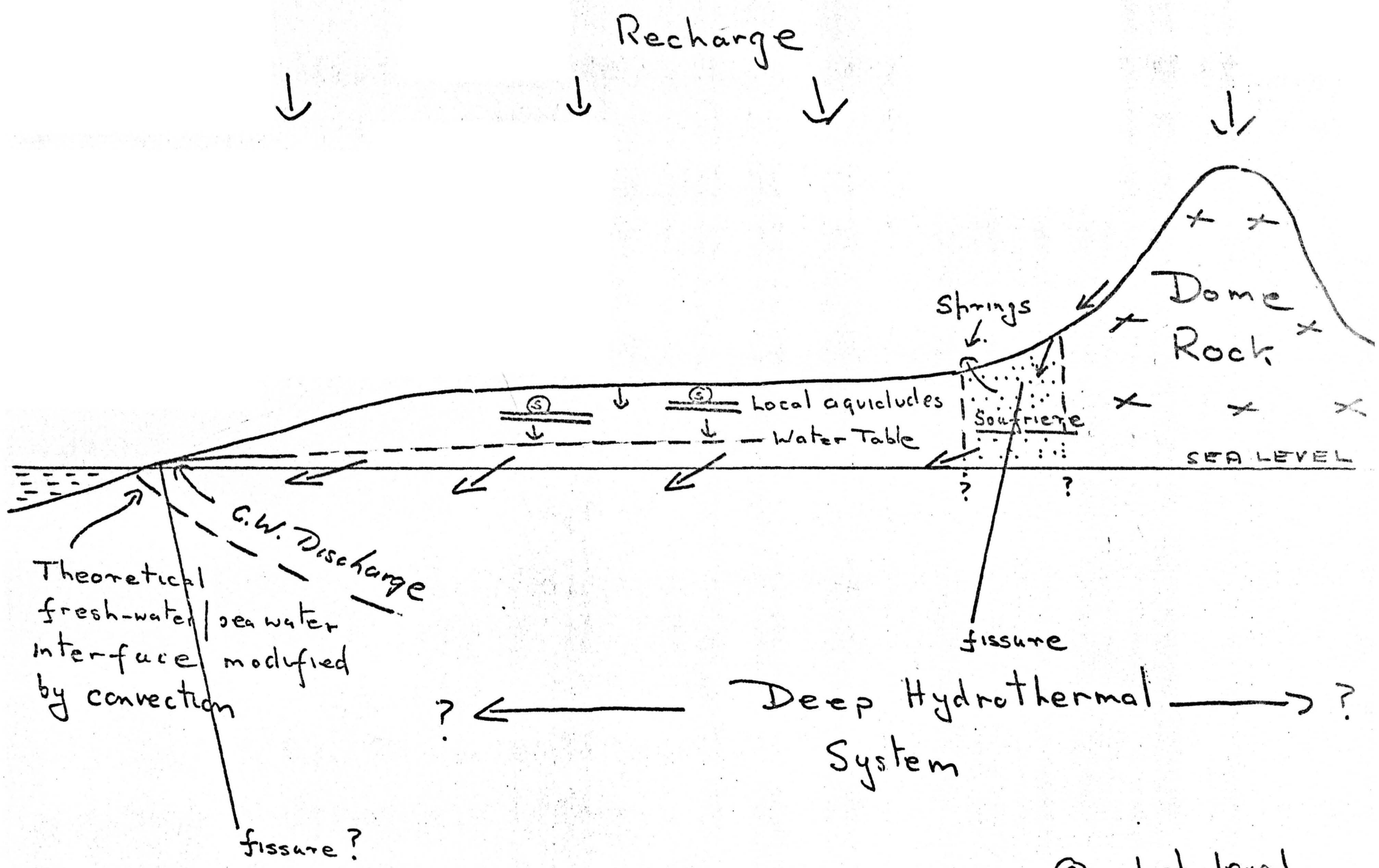


Figure 11 Schematic Cross-Section from Interior To West Coast, Montserrat.

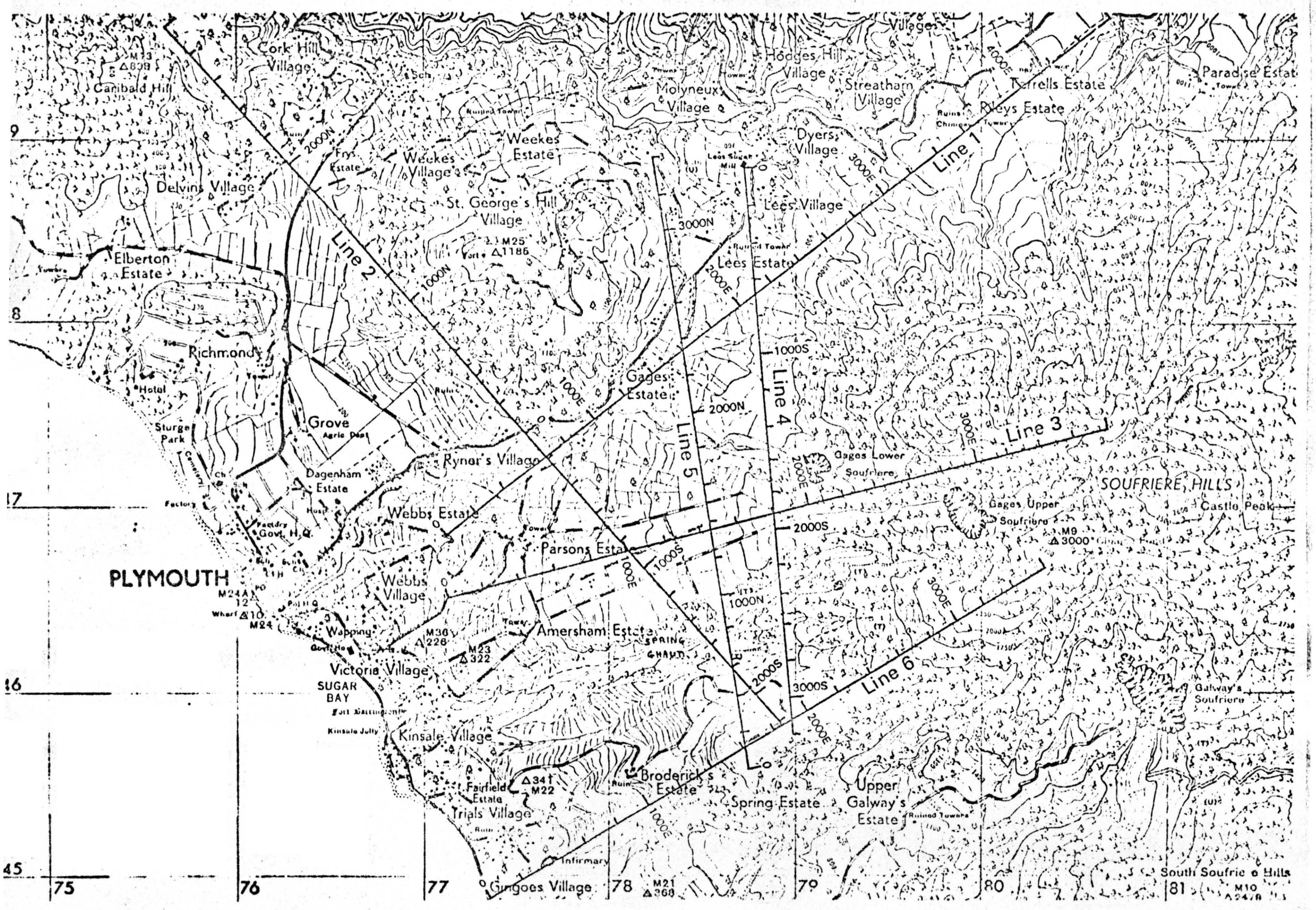


FIGURE 12 (from Tombs and Lee, 1975). Plymouth Area, Montserrat, showing geophysical survey lines.

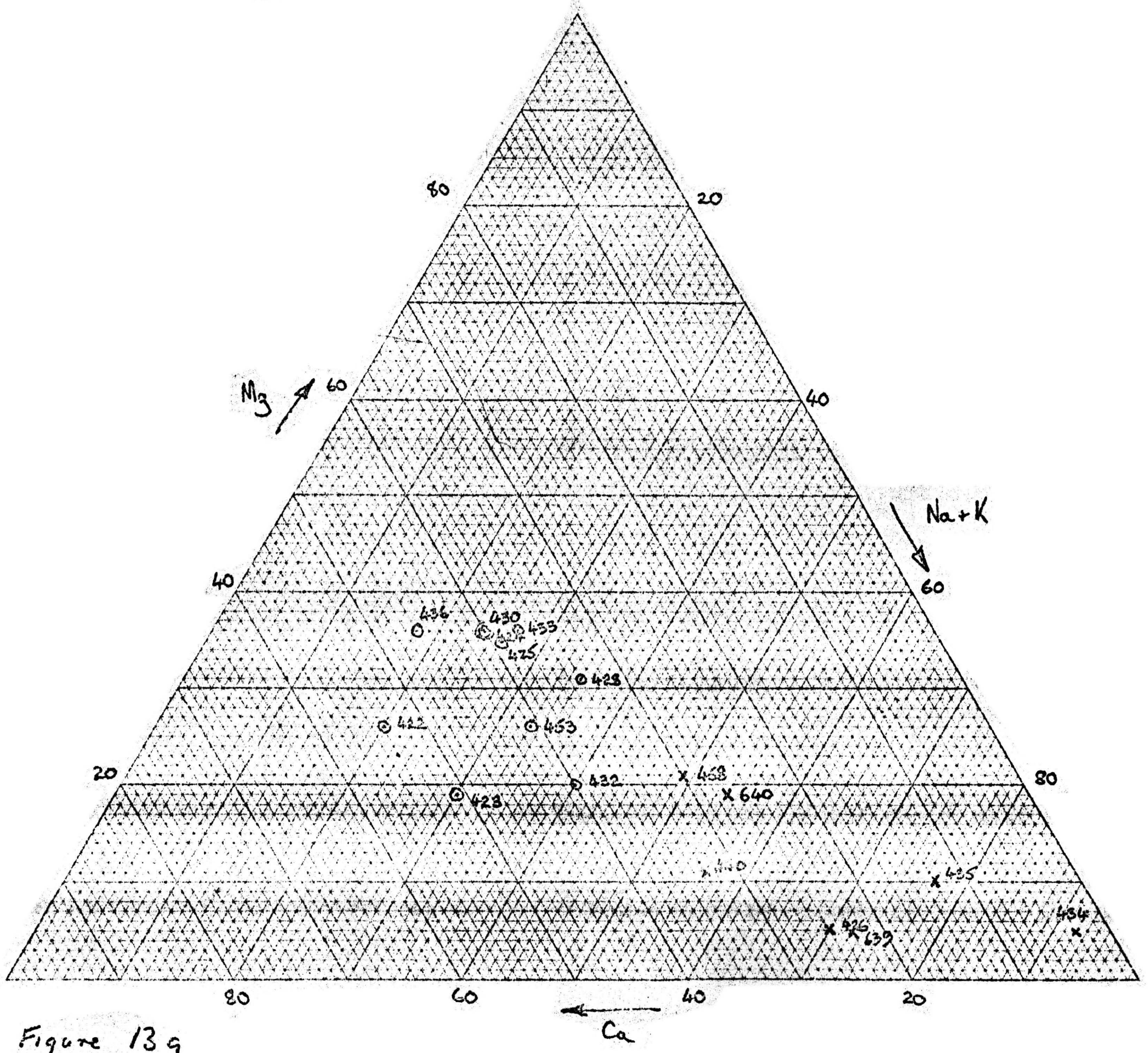

80
20
Mg
60
40
Na+K
40
60
436
430
427
433
425
428
422
453
20
80
432
458
423
640
440
435
434
426
639
80
60
40
20
Ca

Figure 13a

WELLS Graph Data Ref. 5590 Triangular Co-ordinate

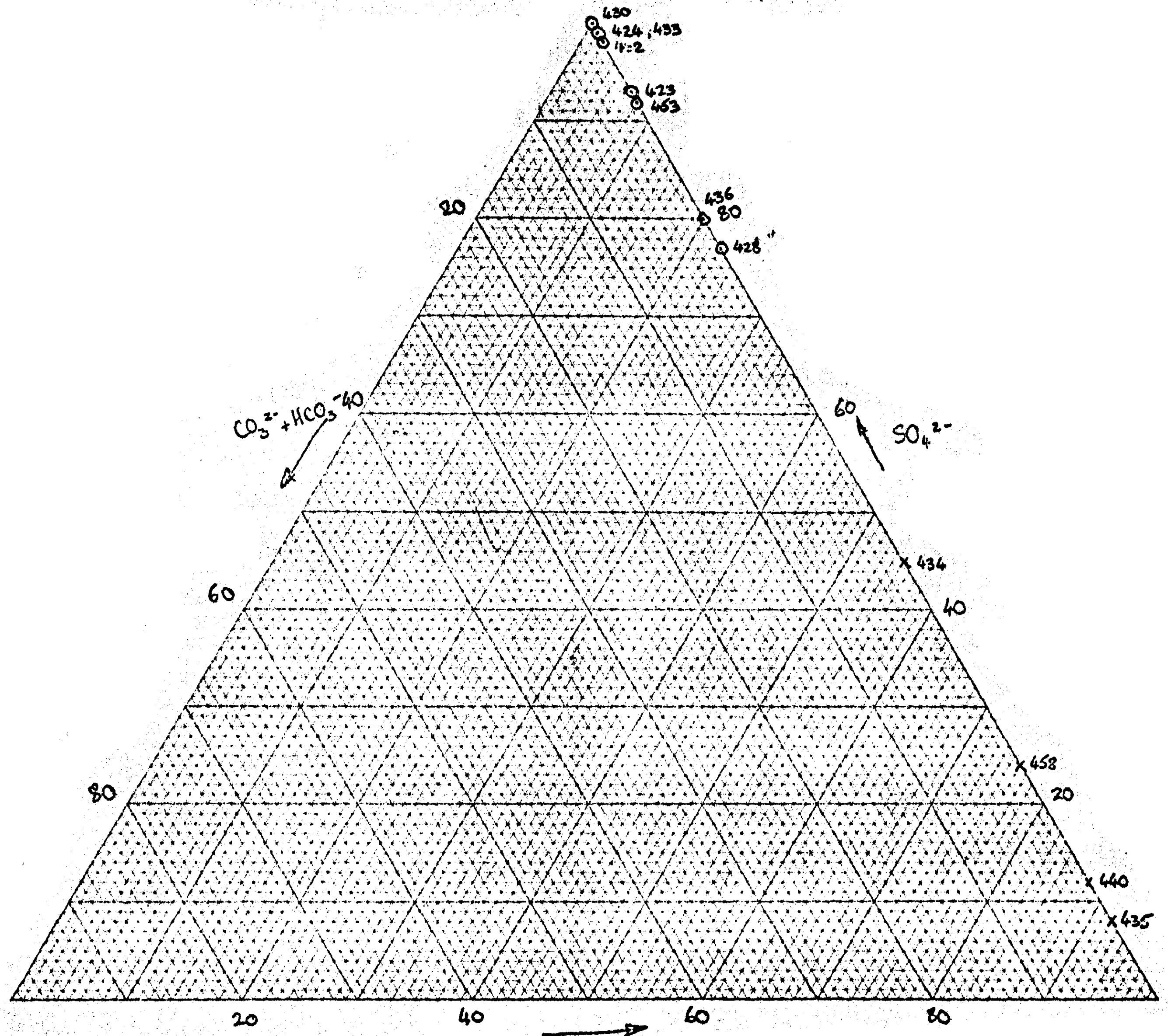


Figure 13 b.

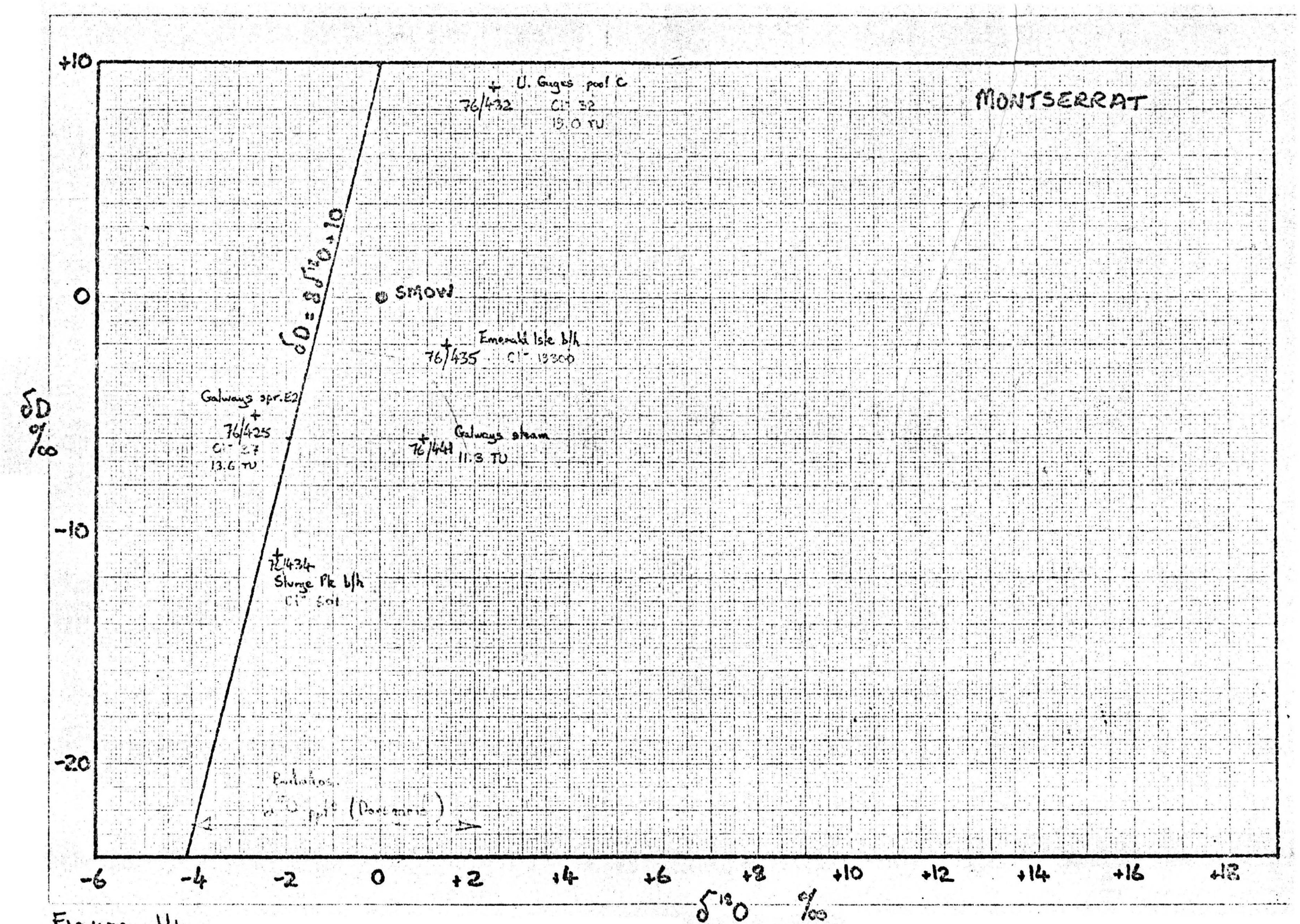

MONTSERRAT
δD ‰
$\delta^{18}O$ ‰
+10
0
-10
-20
-6
-4
-2
0
+2
+4
+6
+8
+10
+12
+14
+16
+18
$\delta D = 8\delta^{18}O + 10$
SMOW
U. Gages pool C
76/432
Cl⁻ 32
15.0 TU
Emerald Isle b/h
76/435
Cl⁻ 13300
Galways spr. E2
76/425
Cl⁻ 27
13.6 TU
Galways steam
76/441
11.3 TU
76/434
Slunge Pk b/h
Cl⁻ 601
Barbados.
$\delta^{18}O$ ppt

Figure 14.

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UFRIERE HILLS

GEORGE'S HILL

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TABLE I: *Summary of the volcanic history of Montserrat* (from Rea, 1974)

Main centre of activity	Parasitic Centre	Description of event	Date	Main rock types involved
Soufrière Hills		Solfataric and seismic activity	Continuous in historic time	Hornblende-hypserthene andesite
		including seismic crises	1966–67[1] 1933–36[2] 1897–98[2]	
		Small pyroclast flow	A.D. 1646 ± 54 YR.[3]	
		Formation of Castle Peak Dome and? breaching of English's Crater		
		Formation of English's Crater and associated pumice flows	18 390 ± 360 YR. B.P.[4]	
		Formation of Chance's and Galway's Domes and associated pyroclast flows and mud-flows.	23 568 ± 786 YR. B.P.[5]	
	St George's Hill →	Eruption of pyroclast falls		
		Formation of Gage's and Perche's Domes and associated pyroclast flow and mudflows		Two-pyroxene andesite
South Soufrière Hill	Roche's →	Intrusion	? Younger than 40 000 YR.[6]	
		Extrusion of Raspberry Hill Dome		Basaltic andesite
		Eruption of White River Pyroclast Fall series and associated lava flows.		Basalt to two-pyroxene andesite.
	Landing Bay →	Extrusion of lava	0·96 ± 0·25 m.y.[7]	Hornblende-hypersthene andesite.
Centre Hills	Carabald Hill →	Extrusion of lavas and pyroclastics		Hornblende-hypersthene andesite and two-pyroxene andesite.
		? Period of high sea level		
South Soufrière Hill		Extrusion of lava flows	1·6 ± 0·34 m.y.[7]	Basalt
Silver Hill		Extrusion of lavas and pyroclastics	1·55 ± 0·21 m.y.[8]	Two-pyroxene andesite
Harris-Bugby		Extrusion of lavas and pyroclastics	4·31 ± 0·22 m.y.[7]	Two-pyroxene andesite

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1. Shepherd *et al.* 1971. 2. *E.g.* Robson & Tomblin 1966. 3. ^{14}C date on charcoal from the pyroclast flow (J. F. Tomblin, pers. comm.). 4. ^{14}C date on charcoal from pumice flow (Shotton *et al.* 1970). 5. ^{14}C date on charcoal from pyroclast flow (Shotton *et al.* 1968). 6. Tuffaceous limestone disturbed by the intrusion dated at about 40 000 YR on palaeontological evidence (Westermann & Kiel 1961). 7. K-Ar age (J. C. Briden pers. comm.). 8. K-Ar age on late stage? intrusive lava (D. C. Rex pers. comm.).

TABLE II : Active Soufrieres of Montserrat
(from MacGregor, 1939)

Name of soufrière	Date of origin and record of activity	Location referred to summit of Chance's mountain	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	⅝ 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
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	Quite extensive area in south bank affected by gases. Temperature of hot springs some way down main ghaut 53–58° C.
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 ⅝ 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 thermograph; 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	2¼ 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	¾ 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

TABLE III. Active Soufrieres of Montserrat : Temperature Details

Name of soufriere	Area of devastation in acres	Elevation range in feet asl	Temperature(1) of steam jets in degrees Celsius	Temperature of bubbling water	Year
Galways Records: 1903 Sapper 1936 MacGregor 1937-52 Quoted in Martin-Kaye as degrees Farenheit but between 1937-46, figures probably Celsius. Records maintained by Montserrat Agricultural Department 1966 Shepherd et al (1969) 1976 Current investigation	13	1200 - 1400	93	-	1903
			98 - 120	72 - 92	1936
			100 - 120	72 - 82	1937
			98 - 126	79 - 86	1938
			100 - 120	85 - 90	1939
			99 - 120	81 - 89	1940
			102 - 110	75 - 91	1941
			104	80 - 92	1942
			102 - 103	72 - 79	1943
			98 - 99	80 - 82	1944
			80 - 100	82 - 98	1945
			98 - 99	97 - 98	1946
			88 - 93	88 - 93	1947
			88 - 98	88 - 99	1948
			93 - 96	88 - 98	1949
			- - -	85 - 96	1950
			- - -	88 - 96	1951
			- - -	88 - 96	1952
			98 - 114	- - -	1966
			98	98	1976
Gages Upper Records: 1903 Sapper 1936 MacGregor 1966 Shepherd et al	8	1300 - 1750	97	- - -	1903
			93 - 95	Cool owing to water in main ghaut	1936
			99		
			97 - 99.5	- - -	1966
			98	97 - 98	1976
Cow Hill	3/4	1500 - 1850	96	- - -	1936
			97	- - -	1976
Gages Lower	4	850 - 1050	90 - 97	- - -	1903
			112 - 115 thermograph (Perret)	82	1936
			95 by max. thermograph		
			88 - 94	- - -	1952 (Martin-Kaye)
			98	- - -	1976

(1) Temperatures measured mainly by ha held mercur thermometer and main je measured

Number	Location and Occurrence	Ground elevation ft asl.	Flow Rate gpm	Temperature degrees Centigrade	pH	S.E.C. micromhos	Remarks
1	Galways Spring	c. 1300	10	92	-	3990	See map Figure for sites
2	Galways Spring	c. 1300	10	68	-	1700	
3	Galways Boiling Pool	c. 1300	-	98	-	12400	
4	Galways Spring East	c. 1300	200	42/55	-	3100	
5	Hot Pond Spring	c. 5	5	92	-	38500	
6	Amershams A Spring	512	-	25	-	500	
7	Amershams B Spring	735	30	21	-	260	
8	Amershams CII Spring	830	-	25	-	570	
9	Upper Gages Boiling Pool	c. 1600	-	97/98	-	15000	See map Figure for sites
10	Upper Gages Boiling Pool	c. 1600	-	97/98	-	17500	
11	Upper Gages Boiling Pool	c. 1600	-	97/98	-	3800	
12	Upper Gages Stream	c. 1600	-	52	-	7000	White Waterfall
13	Sturge Park B.H.	c. 5	-	47	-	2200	Depth sample at 4.5 mbgl
14	Emerald Isle B.H.	c. 5	-	87	-	48000	Depth sample at 20.5 mbgl; Temp. range 41-87°C.
15	Tar River Spring	640	15	32.5	-	1340	Travertine
16	Ryan Spring	1640	0/15	20.5	-	290	
17	Dowdies Spring	1770	1	20.5	-	320	
18	White Ghaut Spring	c. 1200	1	-	-	340	
19	Elberton Borehole	125	-	26.5	5.9	290	Depth sample at 28m
20	Galways Steam Condensate	c. 1300	-	98	5.3	55	
21	Upper Gages Condensate	c. 1000	-	98	3.4	120	
22	Upper Gages Condensate	c. 1000	-	98	3.2	220	
23	Upper Gages Condensate	c. 1000	-	98	5.3	130	
24	Galways	c. 1300	-	97	3.8	150	
25.	Galways Spring	c. 1300	-	32	6.0	790	
26.	Bath Spring	555	20	25	7.5	330	
27.	Craelius 1. (Hot Pond bh.)	c. 5	c'flow c.5	Boiling and flushing			
28.	Craelius 1. bh				6.0	45000	Depth sample at 4.5m
29.	Craelius 1. bh				6.0	45000	Depth sample at 8.0m
30.	73.4 bh	?		29	6.3	750	Sort. Montserrat Numbers. Pumping.
31.	73.10 bh	??		29.5	6.8	740	
32.	Lindsay Spring	?	50	23	6.5	440	Spring Ghaut above Amershams C II
33.	Irrigation Well MWA	?		31	6.3	2200	
34.	73-5 bh	?	28	28.5	6.3	1060	
35.	Amershams Spring CI	c. 1400	10	23	6.5	200	
36.	Amershams Spring D	c. 1400	20	23	6.5	210	
37.	O Garra's Estate House Well	c. 15	-	28.9	6.6	3400	Depth Sample.
38.	Charlie's Pond			26	6.2	250	
39.	New Spring	1650		25		425	
40.	Lower Gages Condensate						
41.	Craelius 1. overflow	5					
42.	Craelius 1. D.S. at 4.2m	5					
43.	Craelius 1. D.S. at 11.5m	5					
44.	Craelius 4. Depth Sample Gingoes at 8.5m	21		33.6	6.0	2900	

TABLE V. Analyses of Water Samples from Montserrat, mg/l

Field Sample Number	Lab Sample Number	Locality	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	Li^+	SiO_2	B	pH	Conduct'y μmhos	Temp. C
1	76/422	Galways' Spring 1	53	1.9	134	39	24		0.030	308			3900	92
2	76/423	Galways Spring 2	137	6.8	211	48	60	1060	0.029	207			1700	63
3	76/424	Galways Pool 3	172	5.6	250	136	46	6850	0.178	293			12400	98
4	76/425	Galways Spring E2	62	6.6	87	48	37		0.018	139	3.4		3100	55
5	76/426	Hot Pond Spring	6300	790	2100	252	14600		7.8		35		38500	92
7	76/428	Amersham Spring B	17	3.0	16	8.8	22	98	0.007	86			260	21
9	76/430	Gages Upper Pool A	111	8.3	171	94	7	7000	0.068	349			15000	98
11	76/432	Gages Upper Pool C	240	16	214	64	32	1920	0.085	227	4.3		3800	98
12	76/433	Gages Upper Steam	144	11	184	108	33	400	0.056	257	3.6		7000	52
13	76/434	Sturge Park b/h	400	375	41	18	601	670	0.295	133	1.2		2200	47
14	76/435	Emerald Isle b/h	9700	790	1490	700	19300	2200	6.7	278	14		48000	87
15	76/436	Tar River Spring	56	7.5	133	64	67	370	0.05	120			1340	32.5
19	76/440	Elberton B/h	27	2.7	15	2.8	64	23	0.003	0.9		5.9	290	26.5
32	76/453	Lindsay Spring	28	4.9	33	12.7	22	325	0.003	77		6.5	440	23
37	76/458	O'Garras Est. Well	385	3.8	205	86	727	318	0.212	122			3400	29
41	76/639	Hot Pond Craelius 1	8400	1080	2550	316	20000		10.1	9.4				
44	76/640	Gingoes Craelius 4	228	23	108	46	356		0.148	111		6.0	2900	33.5
						Steam Condensate Samples								
20	76/441	Galways Vent 2	1.1	0.9	0.4	0.3	3.0	53	<0.002			5.3	55	98
21	76/442	Gages Upper Lwr. Vent					<2		<0.002			3.4	120	98
22	76/443	Gages Upper Mid. Vent					18		<0.002			3.2	220	98
23	76/444	Gages Upper Upp. Vent					22		<0.002			5.3	130	98
24	76/445	Galways Vent 1					43		<0.002			3.8	150	97
40	76/636	Gages Lwr. Vent					10		0.003					

TABLE VI. Tritium and Stable Isotope Analyses

Field Sample Number*	Lab. Sample Number	Locality	^{3}H	^{18}O	D
			TU	vs. SMOW ‰, per mil	
1	76/422	Galways Spring 1	6.4	nd	nd
4	76/425	Galways Spring E2	13.6	-2.7	-5
5	76/426	Hot Pond Spring	31.8		
7	76/428	Amershams Spring B	nd		
11	76/432	Gages Upper Pool C	19.0	+2.4	+9
12	76/433	Gages Upper Stream	11.0	nd	nd
13	76/434	Sturge Park b/h		-2.2	-11
14	76/435	Emerald Isle b/h		+1.4	-2
15	76/436	Tar River Spring	nd		
19	76/440	Elberton b/h			
32	76/453	Lindsay Spring	nd		
44	76/640	Gingoes Craelius 4			
	76/641	Rainwater	nd		
<u>Steam Condensates</u>					
20	76/441	Galways Vent 2	11.3	+0.9	-6
21	76/442	Gages Upper Lwr. Vent	nd		
22	76/443	Gages Upper Mid. Vent	nd		
23	76/444	Gages Upper Upp. Vent	nd		
24	76/445	Galways Vent 1.	nd		
40	76/636	Gages Lwr. Vent	nd		

* See Table IV

TABLE VII - MOLAR ELEMENTAL RATIOS

Sample no.	Na/Cl	Na/Li	Cl/B	K/Cl	Ca/Cl	Li/Cl x10-3
76/422	3.41	534		0.11	4.94	6.39
76/423	3.53	1426		0.10	3.11	2.48
76/424	5.77	292		0.11	4.81	19.8
76/425	2.59	1042	3.31	0.16	2.08	2.49
76/426	0.67	244	127	0.05	0.13	2.74
76/428	1.19	732		0.12	0.65	1.63
76/430	24.5	493		1.08	21.7	49.7
76/432	11.5	852	2.25	0.45	5.93	13.5
76/433	6.73	776	2.79	0.30	4.94	8.67
76/434	1.03	409	153	0.57	0.06	2.52
76/435	0.78	437	420	0.04	0.07	1.78
76/436	1.29	338		0.10	1.76	3.82
76/440	0.65	2730		0.04	0.21	0.24
76/453	1.96	2833		0.20	1.32	0.69
76/458	0.82	548		0.005	0.25	1.50
76/639	0.65	251		0.05	0.11	2.59
76/640	0.99	465		0.06	0.27	2.13

TABLE VIII - SILICA AND K/Na/Ca GEOTHERMOMETRY CALCULATIONS, °C

Sample no	K/Na/Ca = 4/3	K/Na/Ca = 1/3	Silica Qz	Silica Amorphous
76/422	21		194*	87
76/423	42		182	59
76/424	36		190*	83
76/425	50		156	34
76/426		(220)		
76/428	48		129	9.6
76/430	49		221	97
76/432	72		175*	65
76/433	59		198	73
76/434		(363)	154	32
76/435		(204)	204	79
76/436	45		148	26
76/440	50		-23	
76/453	47		123	4.4
76/458	36		149	27
76/639		(225)	37	-67
76/640	(99)	(171)	143	22

*Indicates Qz temp assumes adiabatic cooling, otherwise assumes conductive cooling.

APPENDIX A

Details of selected boreholes drilled by Keith Engineers in Montserrat. Numbers as in the Engineers Report.

1. Number 23
2. Location Elbertons
3. Ground Elevation + 125'
4. Total Depth 250'
5. Diameter
6. Casing 5" to 136'
7. Temperature
8. Static water level 87' bgl = +38'
9. Specific Capacity 0.3 gpm/ft
10. Quality Hardness 115; Cl 150; Fe 0.5
11. Lithology etc.

0 - 30	sandy clay
30 - 120	hard sand
120 - 140	loose sand
140 - 155	coarse sand
155 - 250	hard sand/rock

Measurements in May 1976

Casing 0.82' agl
RWL 89.9' bgl = +35.1'
TD 130'
Temperature 98' - 27°C
114 - 26.5°C
130 - 26.5°C

Depth sample from 92'

1. Number 25

2. Location Emerald Isle

3. Ground Elevation + 8.8'

4. Total Depth 112'

5. Diameter

6. Casing 65' (4") on completion

7. Temperature 71°C when casing at 70' - discharge
43°C " " " 90' - discharge

8. Static water level 3' bgl ≡ + 5.8'

9. Specific Capacity 50 gpm test - production rate

10. Quality -

11. Lithology etc.

0 - 18'	fine black sand/volcanic ash
18 - 45	brown sand/rock
45 - 70	rock/some blue clay
70 - 112	rock/sand

May 1976

Casing top - 0.49' agl .
RWL = 3.35' bgl = +5.45'
TD = 67'

Temperatures
(-6.71) 16' - 41.5°C below casing top
(-23.71) 33' - 50°C
(-39.7) 49' - 68.5°C
(-56.7) 66' - 87.5°C

Sampled at 66'

1.	Number	34(1)	34(2)	35(3)
2.	Location		Gingoes	
3.	Ground Elevation	64.7	65.	45.26'
4.	Total Depth	92	118.	90
5.	Diameter	-	-	-
6.	Casing	None	91'(4")	88'(2")
7.	Temperature	?	40.6°C (of discharge)	?
8.	Static water level	+ 4'	?	+ 2.6' (42.7' bgl)
9.	Specific Capacity	4 gpm / high D.D. on 35(3)		
10.	Quality	Analysis. Table I	Chlorides 300/325	
11.	Lithology etc.			

1		2	
0 - 60	sand/boulders	same	
60 - 70	sand	"	
70 - 90	rocky	"	
90 - 92	sand	90 - 101	sand
		101 - 118	rock

May 1976

Well sites visted but casings apparently pulled.

1. Number 37

2. Location Grove

3. Ground Elevation 122.4'

4. Total Depth 280' (i.e. 170' below sea level)

5. Diameter

6. Casing 275' (now removed) screen 5'

7. Temperature 50.6°C / Cl of 6200 end of test
47.8°C / CL of 4850 beginning of test

8. Static water level + 12

9. Specific Capacity 8 gpm/?

10. Quality (Beginning Cl 4850; Hd 770; Fe 6.8
3 hrs test (End Cl 6200; Hd 450; Fe 2.8

11. Lithology etc.

0 - 170 fine sand/rock
170 - 190 sand
190 - 230 sand/rock
230 - 280 sand

1.	Number	38 (1)	38 (2)
2.	Location	Kinsale	
3.	Ground Elevation	96'	97'
4.	Total Depth	135' (43' b.sea level)	165'
5.	Diameter	-	-
6.	Casing	110' (4")	160' (8" - 4")
	Screen	5'	5'
7.	Temperature		40°C (on discharge)
8.	Static water level	+ 4'	-
9.	Specific Capacity	3/5 gpm production rate	7 gpm
10.	Quality	Metals turn blue	Analysis in Table

11. Lithology etc.

	1	2
0 - 20	sandy clay/rock	same
20 - 50	fine sand/boulders	"
50 - 135	sand	"
135 - 165		sand/sandstone

1. Number 55

2. Location Sturge Park

3. Ground Elevation c. +6'

4. Total Depth 20'

5. Diameter -

6. Casing 14' (8")
Screen 10'

7. Temperature 47°C (discharge)

8. Static water level 3.5' bgl = c. +6'

9. Specific Capacity 22 gpm (production rate)
T = 6700 gpd/ft (by date test)

10. Quality Cl 850; Hardness 143; Fe 0.01; pH 7.8

11. Lithology etc.
0 - 8 mf sand
8 - 20 mc sand/gravel. NB Pebbles are old beach gravel.

May 1976

Casing top = 7.38' agl = +13.5' c.
RWL = 8.53" bgl
TD = 151

Temperature - feet bgl
(+4.5) 9' - 46.5°C
(+2.8) 10.7' - 46.5°C
(+1.2') 12.3' - 46.75°C
(-0.5) 14 - 47°

1. Number 60

2. Location Trants # 7.

3. Ground Elevation 58.23

4. Total Depth 147'

5. Diameter

6. Casing 137' (8") and 10' of screen

7. Temperature

8. Static water level + 2.74

9. Specific Capacity P.T. at 350 gpm

10. Quality Analysis (see Table)

11. Lithology etc.

0	-	10	sandy clay
10	-	50	sand/rock
50	-	55	sand
55	-	125	hard sand
125	-	147	gravel

1.	Number	73.4	73.5	73.10
2.	Location		Trants	
3.	Ground Elevation	-	-	68.62
4.	Total Depth	-	193	121
5.	Diameter	-	-	-
6.	Casing	-	174' 20 (screen)	-
7.	Temperature	-	-	-
8.	Static water level	4.7'	75.38	+3.42'
9.	Specific Capacity	4 gpm/ft	3 gpm/ft T = 8,800 gpd/ft	6.5 gpm/ft T = 46,400
10.	Quality			
11.	Lithology etc.			

TABLE I - APPENDIX A

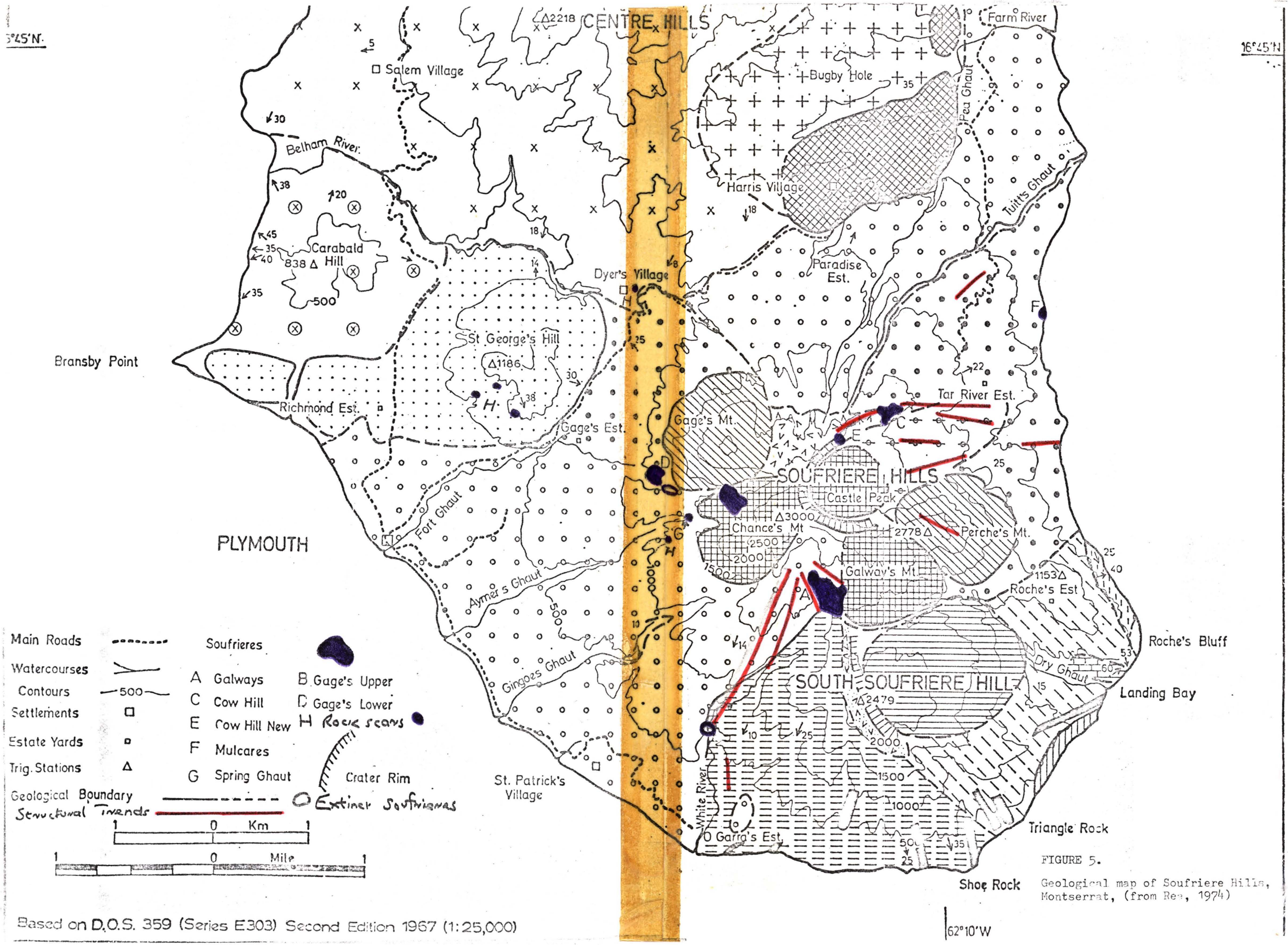
Chemical Analyses : Water Wells Montserrat

	1	2	3
pH	6.2	7.6	6.3
SC (micromhos)	1160	980	1310
CO_2 free	331	13.0	385.0
Alk. to Phenolphtalein (as Ca CO_3)	nil	nil	nil
Alk. to Methylorange (as Ca CO_3)	406	166.5	528.0
Carbonates	nil	nil	nil
Bicarbonate	495.32	203.13	644.16
Total hardness (Ca CO_3)	522.5	181	500
Ca	101.6	36	105.2
Mg	65.2	22.11	57.59
Cl	44.0	156.0	165
F	-	-	nil
Fe	.725	.125	2.6
Sulphate	166.2	43.2	40.74
Chlorides (Na Cl)	75.51	257.1	271.9
S_1O_2	128.0	105.0	145
Phosphate	-	0.3	-
Free Ammonia	.02	0.00165	0.00165
Albuminoid Ammonia	0.0198	0.00165	0.00165
Nitrite	-	0.002	-
Nitrate	0.3	1.31	nil
TDS (180°C)	964	590	865

1. Kinsale Test Well No.38
2. Trants # 7 No.60
3. Gingoes Well No.34

APPENDIX B. Craelius holes : Montserrat, May/June 1976

1.	Number	1	2	3	4	5
2.	Location	Hot Pond	Middle Gages A	Middle Gages B	Gingoes	St. Patrick's
3.	Ground Elevation	+ 4.5 ft	+ 920 ft	+ 914 ft	+ 21 ft	+ 36.5 ft
4.	Total Depth on completion	(37.3 ft)	(33.1 ft)	(21.5 ft)	(28 ft)	(37.2 ft)
5.	Diameter	1.5 in	1.5 in	1.5 in	1.5 in	1.5 in
6.	Casing	0.75 in pipe to total depth from 5.26 ft agl. 2.0 in casing from 5.26 ft. agl to 2.9 ft. bgl.	2.0 in to 23.7 ft. CASING WITHDRAWN	0.75 in pipe from 9.1 to 42 ft.	2.0 in O.D. from gl to 24.6 ft. bgl.	from 0.34 ft. a to 30.5 ft from
7.	Temperature	214°F at 37.3 ft (101°C)	<77°F at T.D. (25°C)	<77°F at T.D. 21.5 ft. (25°C)	92°F at 28 ft. (33°C)	99°F at 37.2 ft (37°C)
8.	Static water level	+ 3.02 ft	+ 906 ft	+ 914 ft	+ 1.1 ft	+ 0.13 ft.
9.	Specific Capacity					
10.	Quality					
11.	Lithology etc.	Grey and pink altered volcanic rocks	Hard altered grey and pink volcanic rock to 16 ft. "rotten" rock to 30 ft. Thereafter grey clay	Grey volcanic boulder sections and brown clay to 15 ft, rock altering to white powder and pale grey clay at 28 ft, blue-grey clay to T.D.	Pebbles and boulders of patchy volcanic agglomerate	Boulders of pat volcanic agglom in sands with r ochre at 28 ft.



Based on D.O.S. 359 (Series E303) Second Edition 1967 (1:25,000)

FIGURE 5.

Geological map of Soufriere Hills, Montserrat, (from Rea, 1974)