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Geophysical surveys in Montserrat for geothermal resources

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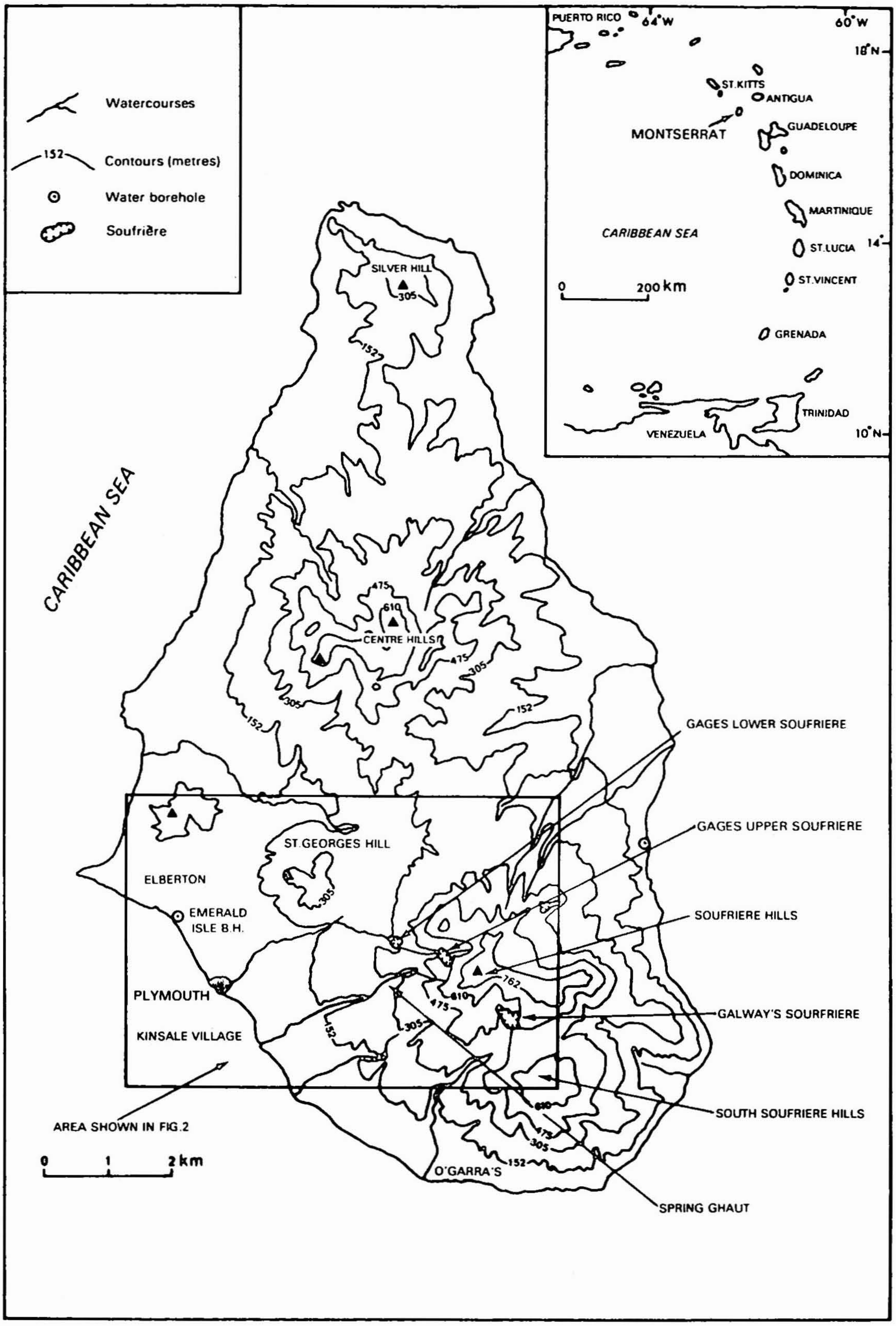

Fig. 1 Montserrat, general

Geophysical surveys in Montserrat for geothermal resources

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1. INTRODUCTION

The Soufrière Hills region of the island of Montserrat in the British West Indies is the island's most recent volcanic centre. An investigation into the area's potential for geothermal energy has been undertaken by the Overseas Development Ministry in London in response to a request from the Montserrat government. As part of this investigation the authors visited Montserrat in April 1975 to conduct an electrical resistivity survey and recommend borehole sites. This report presents the geophysical results and discusses potential drilling sites in the light of them.

2. GEOLOGICAL BACKGROUND AND PREVIOUS WORK

The geology of Montserrat has been described by MacGregor (1938) and by Rea (1974). The Soufrière Hills comprise a central nucleus of four peaks which are considered to be separate volcanic domes, and flanks composed of andesite pyroclastics. The last known volcanic activity is believed to have been a small eruption in A.D. 1646 ± 54 years, but volcano-seismic crises have occurred as recently as 1966-67 (Shepherd, Tomblin and Woo 1971) and 1933-37 (MacGregor 1938). There are several soufrières in the region of which only Galway's and Gage's Upper are believed to be producing boiling water at the present time. Hot springs have been reported at several places; MacGregor describes in detail the soufrieres and hot springs. Robson and Willmore (1955) recorded heat flows of 1.3 x 10^6 cals/sec. and 3 x 10^5 cals/sec. from Gage's Upper and Galway's soufrieres respectively.

A report (Robson 1974) containing a UNO - Canadian offer to develop 360 kW of geothermal power has been submitted to the Montserrat government. We have not seen this report.

Several shallow trial boreholes have been drilled for water supply purposes and are catalogued together with water sample analyses in the engineers' unpublished report (Keith, ?). The water table at most boreholes was only a few feet above sea level. Groundwater was warm or hot in boreholes between Elberton and O'Garra's. There was some steam at the Emerald Isle borehole. The sodium chloride content varied but was often quite high indicating a degree of seawater intrusion.

Fig. 1 shows the area of the geophysical survey together with some of the more important place names and features of interest.

For an account of a similar geothermal problem in St Lucia which includes a full discussion of the application of geophysics to geothermal exploration, see the report by Greenwood and Lee (1975).

3. THE GEOPHYSICAL SURVEY

3.1 Objectives

The primary aim of the survey was to show both horizontal and vertical variations of resistivity in sufficient detail to enable selection of borehole sites. The possibility that geophysics could provide information on the size or nature of the geothermal system was a secondary aim.

3.2 Survey Techniques

The experience of Greenwood and Lee (1975) has shown that over rugged topography use of the colinear dipole-dipole configuration (Appendix), with a "moving" receiver and up to six transmitter dipoles selectable from a fixed transmitter position, was the most productive survey method. Due to the relatively short time available for this survey we used the same technique throughout as logistical problems were similar to those in St Lucia. A dipole length of 200 m was used, with dipole separations of 400 m to 2000 m (n = 2 to 10). Occasionally when the received signal was too small to read the transmitter dipole length was increased to 600 m (this could be done simply by changing connections) giving an effective signal three times greater.

Because of the extremely rugged topography and dense vegetation at elevations over 1000 feet it was impossible to set up a regular pattern of traverse lines. The final distribution of lines is shown in Fig. 2. Lines 1, 2, 3 and 6 were sited to provide broad cover of the area of interest combined with optimum accessibility; lines 4 and 5 were sited to follow up information obtained from previous lines. Lines were cut on a compass bearing and pegged at 200 m intervals. Small local deviations from linearity ($<5°$) were allowed to facilitate crossing difficult topographic features. Some of the lines cross ghauts which are steeply-incised V-shaped valleys where slopes in excess of 60° can cause changes in elevation of several hundred feet over a relatively short horizontal distance. Though in general the "wavelength" of these features was less than 200 m some distortion of the resistivity picture must be expected due to dipole misorientation and shortening caused by a non-horizontal measuring tape. The only correction which has been applied to the data is the modified plotting convention (see Appendix).

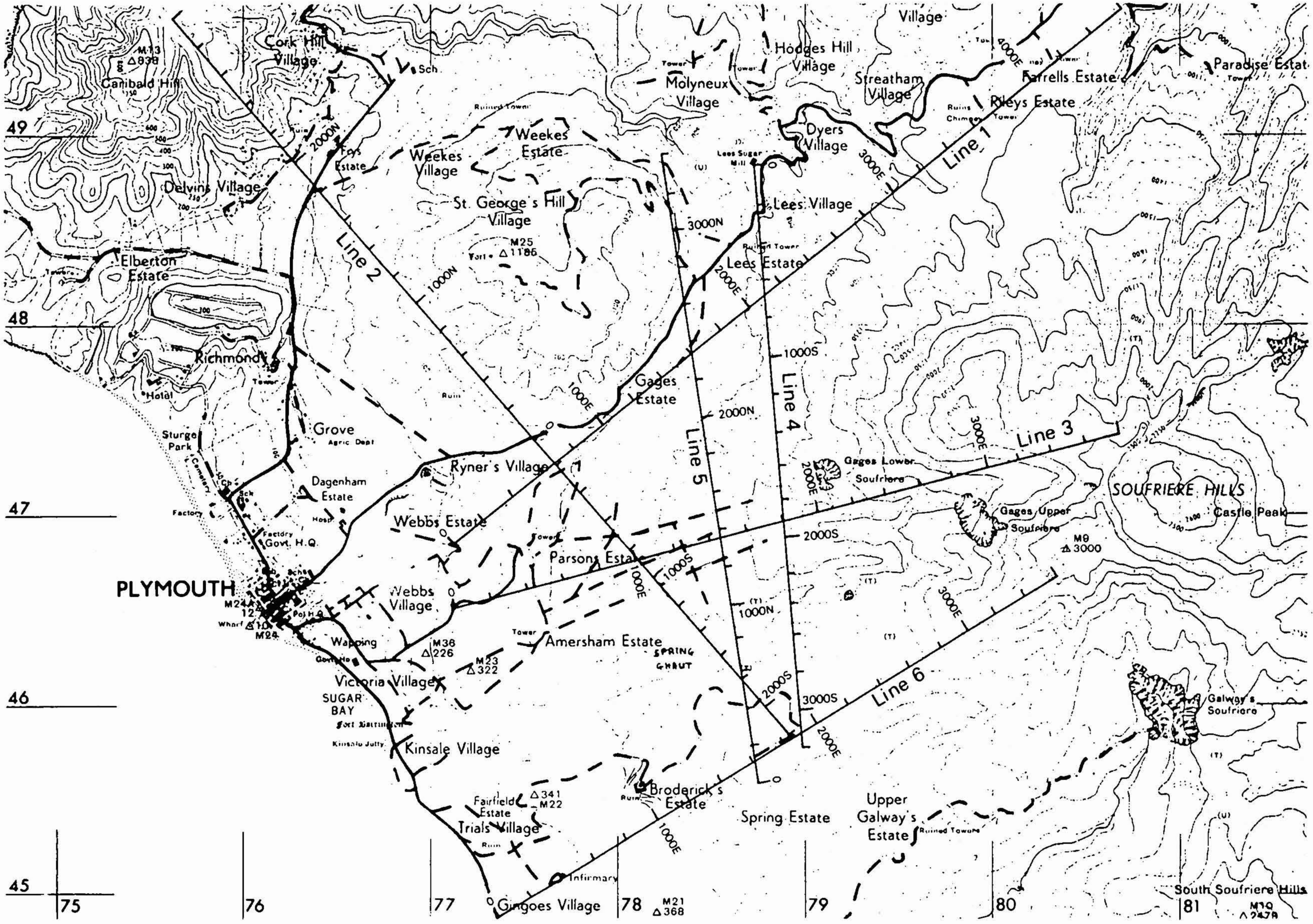


Fig. 2 Plymouth area, Montserrat, showing geophysical survey lines

It is probable that remaining errors are small compared with geologically significant variations in resistivity.

Each transmitter electrode consisted of two stainless steel stakes about 1 m apart, each stake being 1 m long and 2.5 cm thick and hammered well into ground treated with salt water. The electrode resistance was such that currents between 2 and 5 amps were normally obtained. The receiver electrodes were porous pots containing saturated copper sulphate solution: it was found that movements in the wind of the wire to the remote pot were a source of electrical noise and it was often necessary to lay this wire down carefully on the ground.

Communication between transmitter and receiver parties was by means of hand-held VHF transceivers. When direct communication was impeded by topography a third transceiver on a local high point acted as a relay; this was satisfactory in all cases.

3.3 Instrumentation

The equipment used was made by Scintrex Ltd of Toronto, Canada. The transmitter unit (type IPC-7), powered by a petrol generator, produces on and off pulses each of duration t, the polarity of the on pulses reversing alternately. The pulse length t is switchable from 1 to 32 seconds; in practice the shortest cycle time which gives a steady signal at the receiver is used giving effectively a DC measurement. (If electromagnetic coupling is present the received signal rises slowly to an asymptotic value; the long pulse lengths and a provision for manual switching were available in case of this eventuality but were found to be unnecessary in Montserrat.) Output limits are 10A, 1500V, 2500W. The receiver (type RDC-8) is essentially a sensitive high-impedance voltmeter displaying the signal directly on a moving-coil meter, with a provision for manual self-potential cancellation. The range of measurement is from 10 μV to 40V; in practice the sensitivity was limited by SP fluctuations and a signal became unreadable if its amplitude was much less than the noise level. The receiver also had a facility for automatic SP tracking during the off period, but this was not often used.

3.4 Organisation

Line cutting and manual labour were effected by a team averaging 18 men provided by the Montserrat Government Lands and Survey Department under the charge of a surveyor/foreman. Two vehicles provided by the Agriculture Department were used to transport equipment and personnel. The Public Works Department provided petrol, storage space and general maintenance facilities.

The mountain lines (3 and 6) were cut before the authors' arrival. All other line cutting, pegging and geophysical work were carried out during April. Of the 29 days spent by the authors in Montserrat 22 were spent on productive surveying, 4½ unpacking and packing and on general administration, ½ day on vehicle repairs and 2 days were taken as rest days. Additionally one of us (JMCT) spent one day collecting water samples for analysis by the Hydrogeological Department of IGS.

4. RESULTS AND INTERPRETATION

The resistivity pseudo-sections for each line are shown in Figs 3-8 together with a true-scale topographic profile.

Line 1 (Fig 3) shows a relatively undisturbed pattern with little lateral variation. This does not imply horizontal layering of geological units but only that conditions of porosity, salinity and temperature do not change significantly along the length of the line. To interpret this in terms of actual rock conductivities, values of apparent resistivity have been plotted against dipole separation on logarithmic scales (Fig 9) and compared with theoretical curves for a two-layer case (Keller and Frischknecht, 1966). The results indicate a "basement" of resistivity probably less than 1 Ωm at a depth below surface of 240 ± 30 m. If Fig 9 is regarded as a depth sounding about the centre of the line, the elevation of which is approximately 265 m, then the top of the basement approximates very closely to sea level. The most likely interpretation is therefore a water table near sea level; this is broadly in agreement with the borehole results mentioned in section 2 but this conclusion should be checked by a detailed consideration of the hydrogeology. It is possible to draw a very tentative conclusion about the temperature of the groundwater by applying a form of Archie's Law:

$$\frac{Ro}{Rw} \approx \frac{1}{\phi^2}$$

where ϕ = porosity = 0.5, say (e.g. Keller and Frischknecht, 1966, table 7, value for post-Palaeozoic clastic volcanics),

Ro = formation resistivity = 1 Ω m, say

$\therefore$ Rw = groundwater resistivity $\approx$ 0.25 Ωm.

This is a typical value for seawater at normal temperatures. The results are not, therefore, incompatible with "cold" saline intrusion, although the sensitivity to changes in porosity and salinity is high.

The presence of localised areas of wet or dry steam beneath this line is unlikely as there are no anomalous zones. A uniform layer of steam beneath virtually the whole of the line cannot be ruled out by geophysics alone, though other considerations render this unlikely. There is no evidence of a low-resistivity layer near the surface caused by condensed steam.

Line 2 shows a generally similar situation but with rather more disturbance, probably from topography (Fig 4). The apparent zone of very low ($<$2 Ωm) resistivity at depth between dipoles 15 and 20 is discussed later; otherwise the interpretation is similar.

Line 3 (Fig.7) shows an anomalous zone indicating a low-resistivity body which is shallowest near 2200E and whose depth increases slowly towards the west but more quickly towards the east. The ghaut draining Gage's Upper soufriere coincides with the centre of the anomaly. On line 4 (Fig.5) the anomaly suggests a structure which is shallowest in two places, each corresponding roughly to a ghaut. The near-surface contours at the flanks of the anomaly slope away at almost 45° indicating steep sides to the body. The shape of the anomaly is similar to the well-documented case of a horizontal slab of low resistivity (e.g. Coggon, 1974, Fig.6), but the apparent levelling-off of the contours towards both ends of the line, together with the results of other lines, suggests rather a localised upwelling of a conductive "basement" At the two apices of the anomaly the conductive zone probably reaches close to surface. The slight rise in resistivity directly beneath the anomaly is a characteristic feature of dipole-dipole anomalies and is probably not due to dry steam as may be supposed.

To test the above interpretation a two-dimensional model of the resistivity variations beneath line 4 (Fig.10) was submitted to computer program RESCAL (Geotronics Corporation). This program calculates the apparent resistivity pseudo-section due to a two-dimensional model made up of blocks of various resistivities. The minimum block size allowed is one-third of the dipole length (66 m in this case) and the maximum separation between dipole centres is six times the dipole length. Variations in topography are not allowed.

The pseudo-section due to the model is shown in Fig.11. Although not correct in detail the general shape of the artificial section is very similar to that measured in the field. This supports the theory that the anomaly could be caused by a localised upwelling of a conductive 'basement', the top of this conductive body being less than 200 m below the surface between 1600 and 2200S on line 4. The model shown in Fig 10 should not be taken as an exact representation of the structure. Changes in resistivity shown in the model do not necessarily coincide with changes in rock type. It should also be remembered that the model is only two dimensional and does not include topography.

Fig.6 shows that beneath line 5 the anomalous structure lies at somewhat greater depth; the shape of the 5Ωm contour suggests that the flanks of the causative body may be more conductive than the centre.

Assuming that the anomalies on lines 3, 4 and 5 are due to the same structure, the strike of the body is approximately E-W. The "low" on line 2 already mentioned is then seen to lie on the same line.

We consider that the anomalies are caused by saline or mineralised water. The coincidence with ghauts suggests a false anomaly due to distortion of the electrode geometry, but this is discounted for the following reasons:

(1) even a considerable distortion should not give rise to changes approaching two orders of magnitude such as are observed here. The slightly disturbed readings from dipole 12 on line 4 show the sort of effect that one would expect;

(2) similar ghauts elsewhere (e.g. at 750N on line 2) do not give rise to such an effect.

A tentative explanation of the anomalies follows, but again these conclusions should be examined in the light of consideration of the hydrogeology. Water rises from a heat source located beneath the Soufriere Hills; some of it reaches surface in the form of hot springs at Gage's Upper soufriere. Away from the heat source the water spreads downwards and outwards towards the west to reappear as warm "soufriere water" in the boreholes near the coast (section 2). The courses of Spring Ghaut and Gage's Soufriere Ghaut may have been determined by lines of fissuring or crustal weakness (see e.g. MacGregor, p. 40). Groundwater would flow preferentially along these lines causing the observed correlation of anomaly centres with the ghauts. Some support is lent to this concept by the observation in the field that groundwater emerging as hot springs at Gage's Upper disappears into the ground again a short distance down the ghaut towards Gage's Lower.

The pseudo-section for line 6 (Fig. 8) shows a strong, localised anomaly which seems to be related to dipoles 8 and 9. In the field various non-linear responses were noted: different response to positive and negative pulses, reciprocity failure etc. Metal water pipes are present in this area but probably not near enough to cause such a large effect. The cause remains uncertain but is probably not of geothermal significance. The area of low resistivity near the west end of the line is probably caused by seawater intrusion.

5. SYNTHESIS AND BOREHOLE RECOMMENDATIONS

The only area where geophysics has indicated an anomalous structure probably due to warm or hot water is in the zone extending west from 2200E on line 3. A borehole is recommended in this area to test the geothermal potential. We do not recommend a specific site as the anomaly is sufficiently large for the decision to be made on access and other grounds, but it should lie within the triangle formed by Spring Ghaut, Gage's Soufrière Ghaut and the 785 Easting grid line, preferably as far to the east as possible where the source is considered to be shallowest. The borehole should not be terminated before 200 m unless positive results are obtained earlier.

There is no geophysical evidence to support a site between Lee's and Gage's estates as suggested in the report by Merz and McLellan (1974). This area shows no geophysical anomalies.

The Emerald Isle area merits re-examination on the basis of the water borehole results. This area would be difficult to test by geophysics because of its proximity to Plymouth and because extensive saline intrusion could cause very low resistivity throughout.

Geophysical work was not attempted in the

Galway's soufrière area because of major difficulties in siting a long enough line combined with insufficient time. Therefore we cannot comment on the potential of a borehole in this area.

6. CONCLUSIONS

The geophysical survey has defined one area where a borehole should be sited. The probability is that hot water, with or without steam, exists at relatively shallow depth below this area.

If the "geothermal system" is defined as the area of convective circulation of groundwater, then the triangle of section 5 may define the minimum size of the system. Possible extensions of this area, or other areas, have not been found due mainly to the difficulties of systematic resistivity mapping in the rugged topography of Montserrat.

We repeat that the geophysical data should not be considered in isolation, but in association with investigations of the hydrogeology and geochemistry. The best conclusions can only be drawn from a synthesis of all available data.

7. ACKNOWLEDGEMENTS

We wish to record our thanks to Mr D.K. Buckley of IGS, for organising line-cutting and making arrangements in advance of our visit; to Mr K.A. Cassell, Permanent Secretary to the Chief Minister, for providing very effective liaison and arranging local support facilities; to Mr George Edwards, Public Relations Officer, for solving day-to-day organisation problems; and to our driver Mr Archie Chambers who consistently worked very long hours for us and succeeded against all expectations in keeping our vehicles on the road, both literally and figuratively, almost without interruption.

APPENDIX

The dipole-dipole configuration

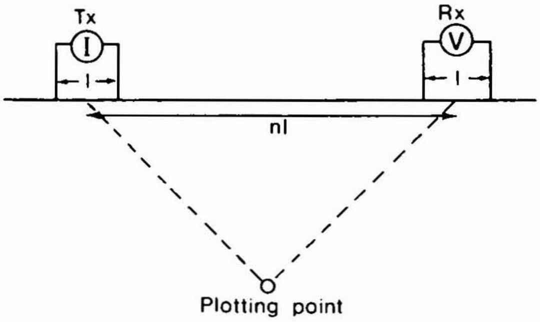
A known electrical current I is passed into the ground at a transmitter dipole consisting of two electrodes a distance l apart. Voltage (V) is measured at a similar receiver dipole, positioned so that the distance between dipole centres is nl where n is normally an integer greater than 1 . For the colinear dipole array used in this survey all four electrodes are in a straight line. The apparent resistivity is given by the formula

$$\rho a = \frac{\pi l n (n^2 - 1) V}{I}$$

Values of ρa are normally plotted as an electrical "pseudo-section" in which the plotting points are the intersections of lines at 45° to the horizontal in a vertical plane through the dipole centres (see diagram). Such a section represents the true resistivity distribution in a very distorted way, but can be used as a basis for qualitative interpretation or comparison with computer-derived models.

In Montserrat because of the irregular topography the plotting convention was modified somewhat in that the plotting point was taken as the intersection of lines at 45° to the line joining the dipole centres.

The dipole-dipole array gives good depth penetration, relative freedom from electro-magnetic coupling and operational convenience. For more details see, e.g. Coggon (1974).



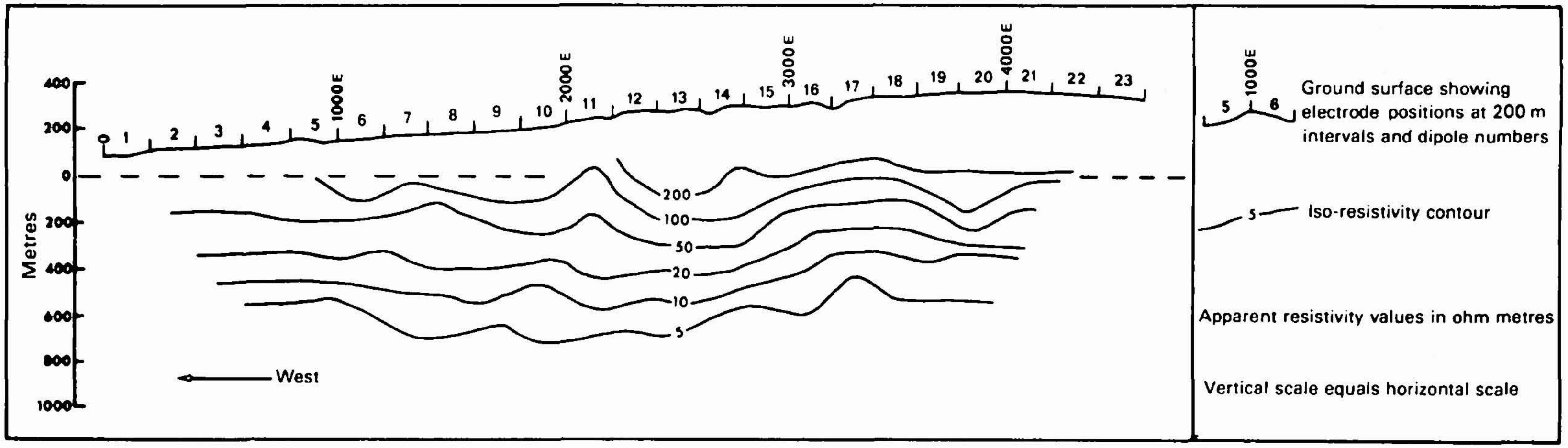


Fig. 3 Line 1 Apparent resistivity cross section

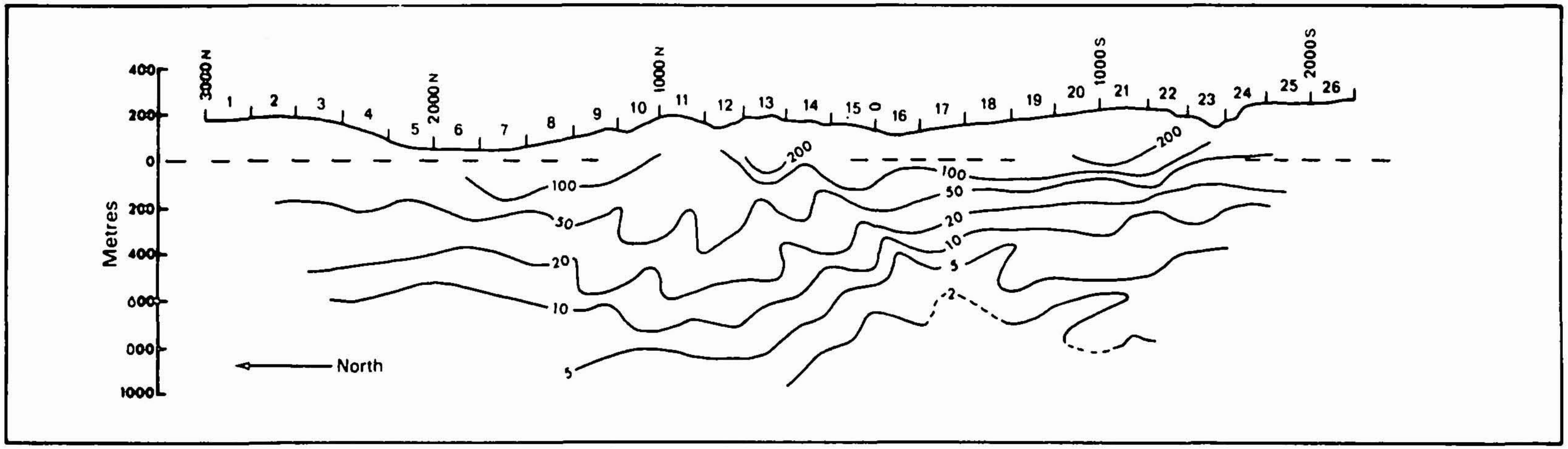


Fig. 4 Line 2 Apparent resistivity cross section

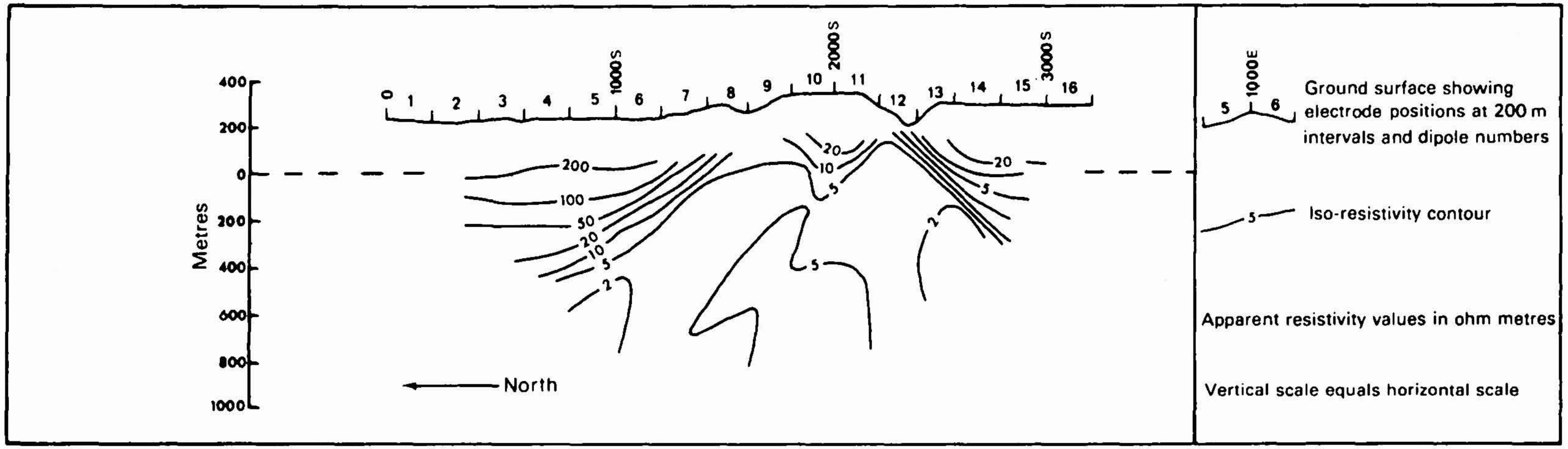


Fig. 5 Line 4 Apparent resistivity cross section

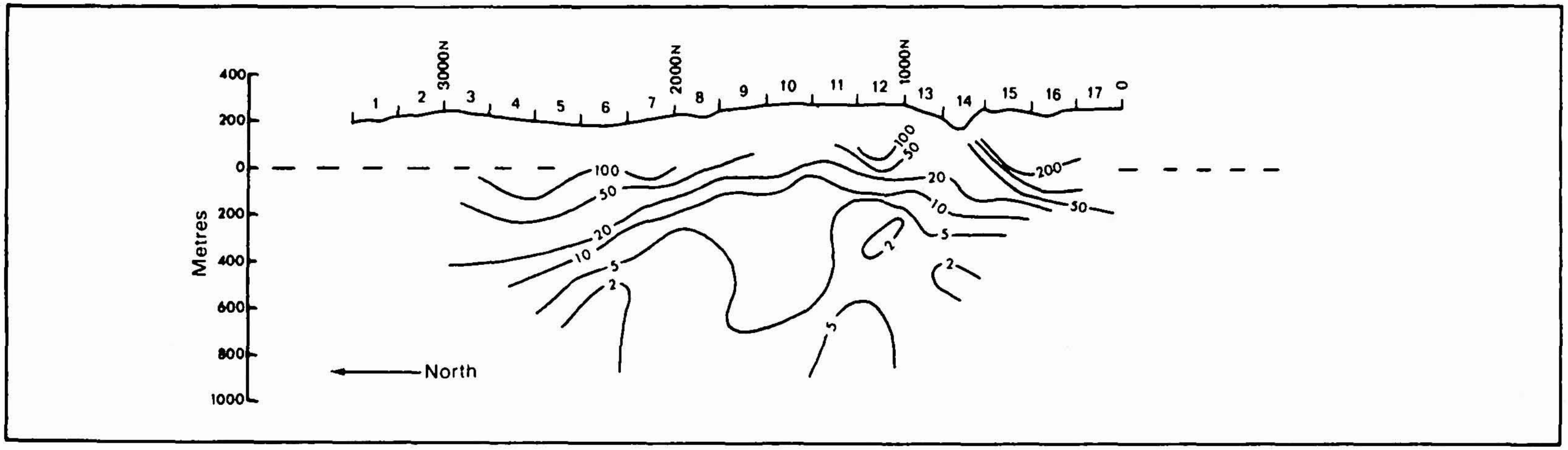


Fig. 6 Line 5 Apparent resistivity cross section

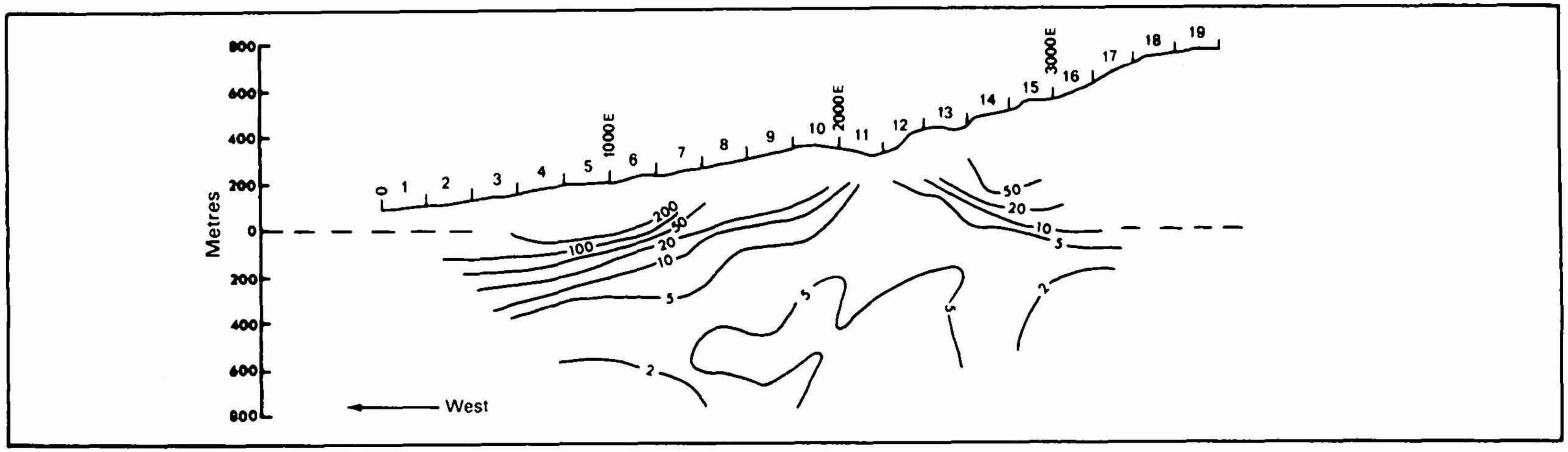


Fig. 7 Line 3 Apparent resistivity cross section

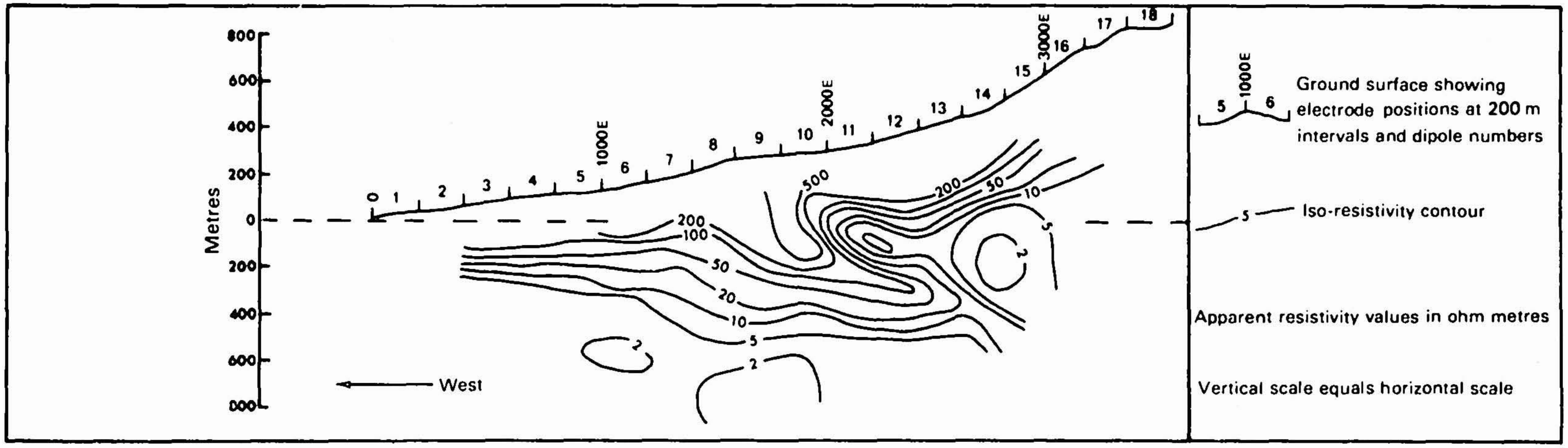


Fig. 8 Line 6 Apparent resistivity cross section

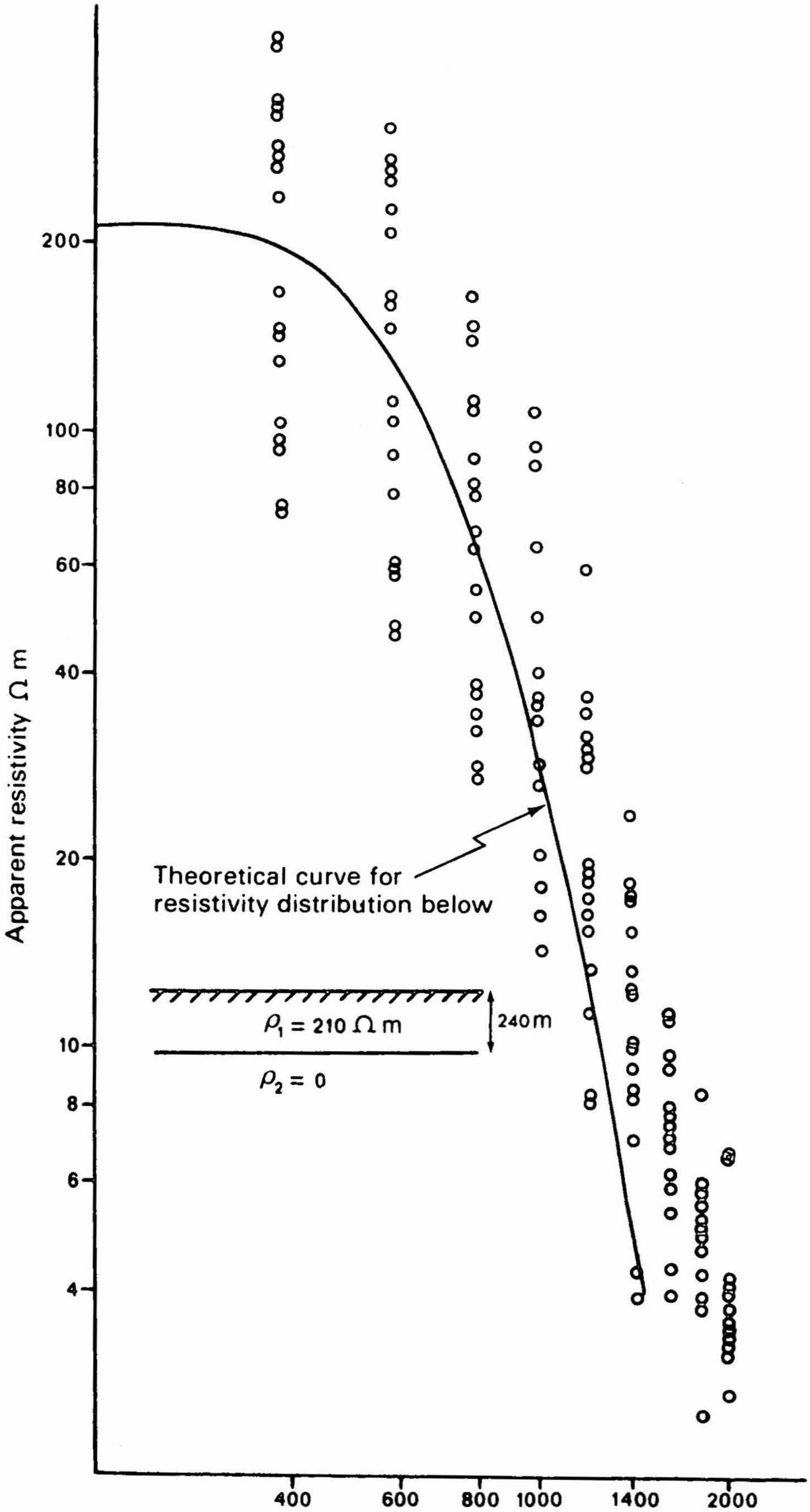


Fig. 9 Line 1 depth-sounding

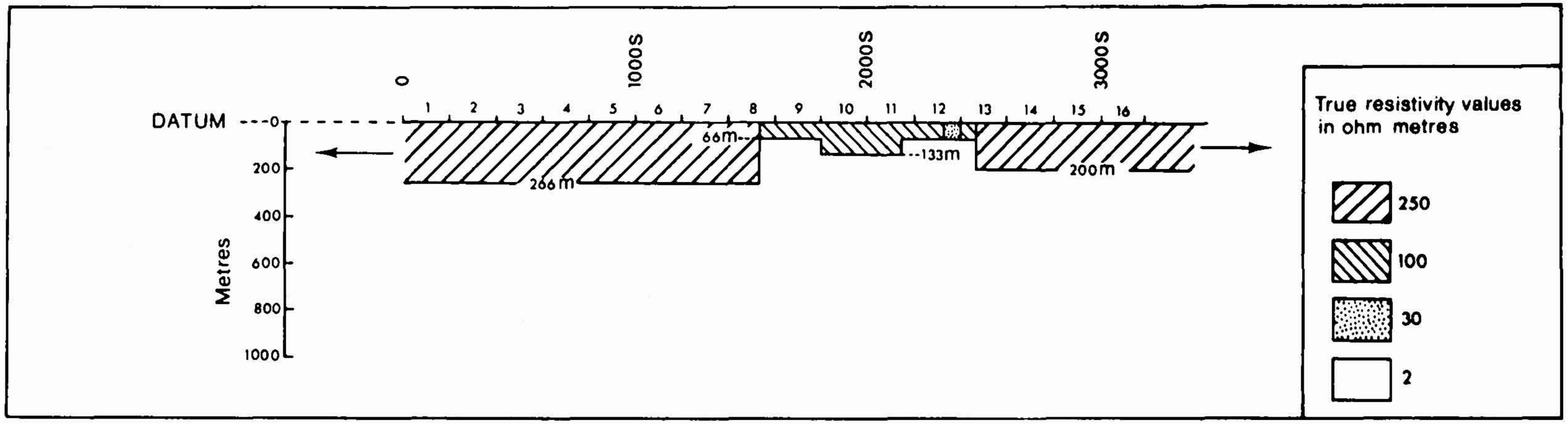


Fig. 10 Line 4 Two dimensional model of true resistivities

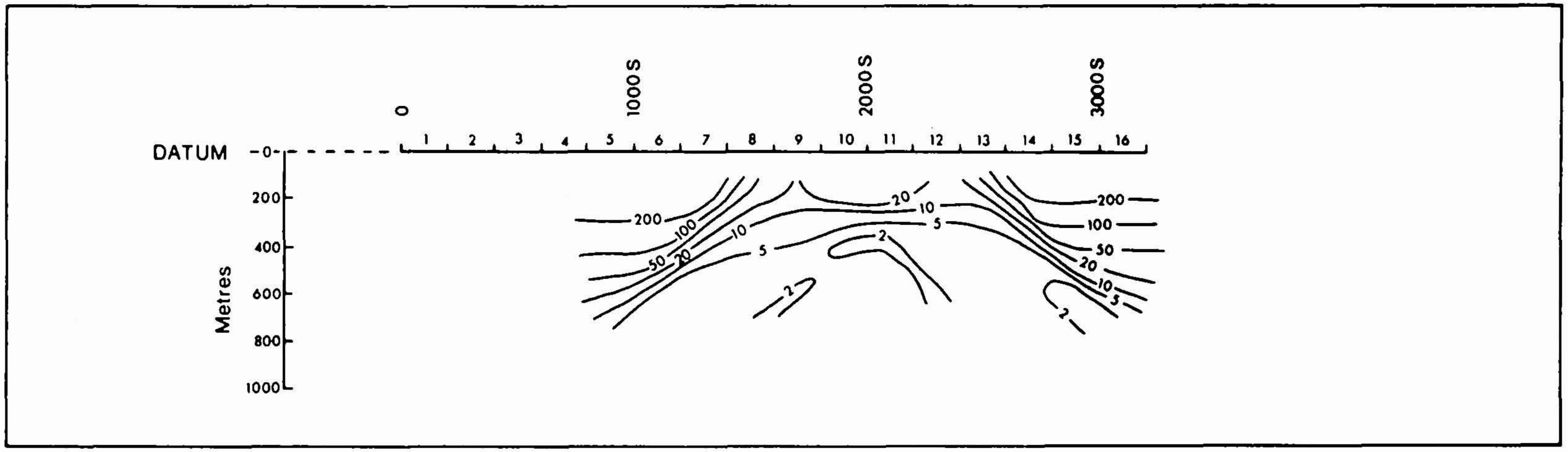


Fig. 11 Line 4 Computer generated apparent resistivity cross section

REFERENCES

COGGON, J.H. 1974. A comparison of IP electrode arrays. Geophysics, Vol. 38 No. 4, pp. 737-761.

GEOTRONICS CORPORATION. RESCAL, Two-Dimensional Resistivity and IP Modelling for the Explorationist Published by Geotronics Corporation.

GREENWOOD, P.G. and LEE, M.K. 1975. Geophysical surveys in St Lucia for geothermal resources. Geophysical Report No. 26, Inst. Geol. Sci. [unpublished].

KEITH CONSULTING ENGINEERS LTD. Montserrat surface and groundwater development program: log of test holes [unpublished]. Copy at Public Works Department, Montserrat.

KELLER, G.V. and FRISCHKNECHT, F.C. 1966. Electrical methods in geophysical prospecting. (London: Pergamon Press.)

MACGREGOR, A.G. 1938. The Royal Society expedition to Montserrat, B.W.I.: The volcanic history and petrology of Montserrat, with observations on Mt. Pele in Martinique. Philos. Trans. R. Soc. Lond. B Vol. 229, pp. 1-90.

MERZ and McLELLAN, 1974. Notes on geothermal prospects on Montserrat, Dominica and St Vincent. Submitted to ODA [unpublished].

REA, W.J. 1974. The volcanic geology and petrology of Montserrat, West Indies. J. Geol. Soc. London, Vol. 130, pp. 341-366.

ROBSON, G.R. 1974. Report submitted to Montserrat government [unpublished].

ROBSON, G.R. and WILLMORE, P.L. 1955. Some heat measurements in West Indian soufrieres. Bull. Volcanol., II, Vol. 17, pp. 13-39.

SHEPHERD, TOMBLIN and WOO, 1971. Volcano-seismic crisis in Montserrat, West Indies, 1966-67. Bull. Volcanol. Vol. 35, pp. 143-163.