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A PRELIMINARY RESISTIVITY INVESTIGATION (VES) OF THE LANGADA HOT SPRINGS AREA IN NORTHERN GREECE

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Abstract—In total 24 direct current resistivity soundings were carried out during the preliminary stages of a geothermal exploration survey of the Langada hot springs area (northern Greece).

The analysis of the data revealed a horst-type morphology striking NW–SE. Correlation between the location of hot springs, successful drill holes and the basement (horst) indicates that the sector of geothermal interest is concentrated along the major axis of the horst mapped.

The horst type geothermal structure fits in very well with the pattern of temperatures measured in the major area, as revealed by the temperature map.

INTRODUCTION AND GEOLOGICAL SETTING

The investigated area is located towards the north-western part of a graben structure (the Mygdonian graben) that belongs to the Serbomacedonian massif, a series of Permian and Jurassic carbonates overlying a metamorphic and igneous basement of upper Carboniferous.

The deep metamorphic basement rocks (Kockel *et al.*, 1972) were affected by the Hercynian orogeny with a NE–SW direction and by a younger orogeny with a NW–SE direction, as revealed by the existing fault zones in the area (Fig. 1).

The NW-striking, NE-dipping faults (Mercier *et al.*, 1976), form a major fault system which separates the Serbomacedonian massif from the Vardar zone. Along some of these faults, reverse movements of Pre-Tertiary age have been observed (Smith and Moorey, 1974). It therefore appears that extension has reactivated old lines of weakness, resulting in the formation of a graben, probably during the early Neogene (Psilovikos, 1977).

Gravity and aeromagnetic surveys in the investigated area (Thanassoulas, 1983) revealed the existence of a tectonic horst in the basement of the Langada rift valley, raising the top of the basement to 120 m and resulting in the formation of two local grabens (profile AA′ in Fig. 1) to the NE and SW of the horst, with depths of 220 m and 470 m respectively (Fig. 1).

THERMAL INVESTIGATIONS

In order to delineate the hot area and its margins more precisely, and thus establish a preliminary network for resistivity soundings, temperature measurements were carried out in all the existing boreholes drilled for irrigation, (Table 1), and in the major springs ($T \approx 41°C$).

Temperatures were measured with a platinum probe in combination with a Wheatstone resistance bridge. The mean geothermal gradient, obtained in each borehole, was used to assess the expected temperature at a depth of 250 m.

The mean geothermal gradients in the area were of the order of 6–8°C/100 m, which are greater than the mean terrestrial geothermal gradient (3°C/100 m). Application of SiO_2

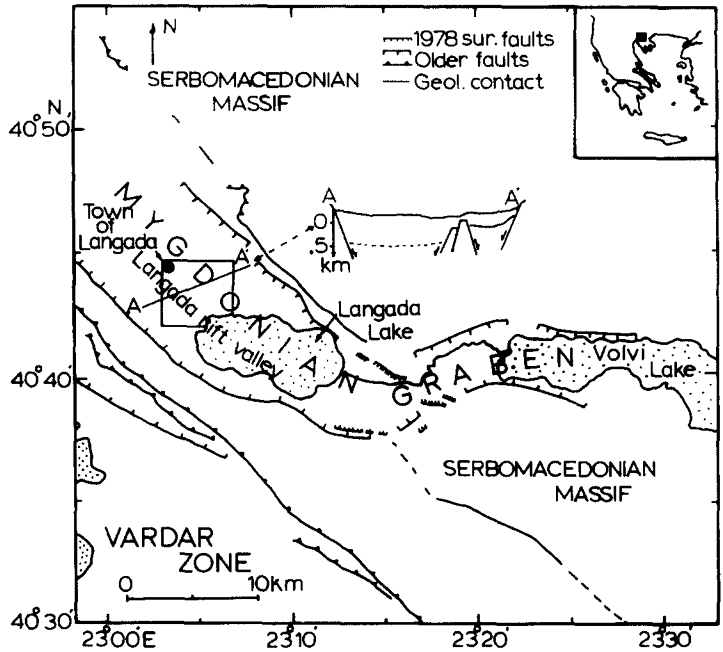


Fig. 1. General tectonics of the investigated area. Faults and major geological contacts are from Kockel *et al.* (1972).

geothermometers, suggested initial water temperatures of around 50–100°C, indicating a low enthalpy geothermal field.

The spatial distribution of temperature is shown in Fig. 2, which indicates a NW–SE orientation of the temperature lines, with the highest values within the area of the hot springs.

This map may include a slight degree of distortion, since the measurement points are not evenly spaced, but it nevertheless gives some idea of the general trend of the temperature field.

Table 1. Boreholes and depths at which temperatures were measured

Borehole No.	Depth (m)	Temperature (°C)
1	10	18
2	40	15.5
3	200	14
4	60	16.5
5	80	19
6	101	18
7	67	27
8	10	33
9	101	23.5
10	40	34
11	120	20
12	92	19
13	115	19
14	73	24.5
15	114	20
16	90	20
17	108	20
18	100	39.5

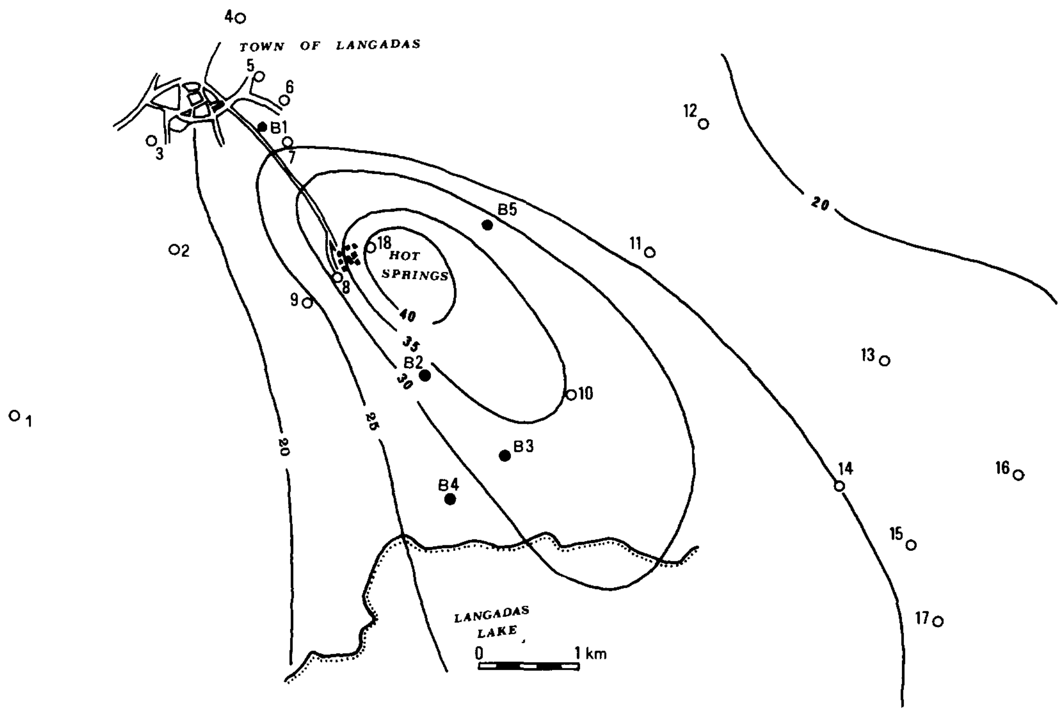


Fig. 2. Temperature contours (°C) at 250 m depth over the investigated area and location of boreholes (B1–5 exploration wells, 1–18 water wells).

GEOPHYSICAL INVESTIGATIONS

The use of electrical resistivity techniques in geothermal exploration is based on the fact that the resistivity of water decreases significantly with an increase of temperature.

During the present investigations, 24 Schlumberger resistivity soundings were performed in an attempt to locate the broad margins of the geothermal field.

Current electrodes were separated up to 1000 m ($AB/2 = 500$ m) and the geoelectric soundings were grouped into four geoelectric traverses (Fig. 3), aligned perpendicular to the main axis of the elliptical temperature anomaly revealed by the thermal investigations (Fig. 2).

The mean distance between the soundings was of the order of 300 m and the separation between traverses was of the order of 1.5 km.

In order to facilitate the interpretation many "mini-electric" measurements were also performed, measuring the resistivities of the various formations at their outcrops.

These measurements were performed by means of the Wenner tripotential technique (Habberjam and Watkins, 1966), taking into account the length of the penetrating electrodes (Krolikowski, 1968; Vandenberghe, 1982).

Vertical variation of apparent resistivities

The shape of the apparent resistivity curves obtained for traverse T_2 is presented in Fig. 4.

The resistivity data were interpreted initially with a program based on Gosh's (1971) method, to invert Schlumberger VES curves into layer thicknesses and resistivities. The number of layers were further reduced by the aid of a DZ chart (Zohdy, 1974). The final models were improved

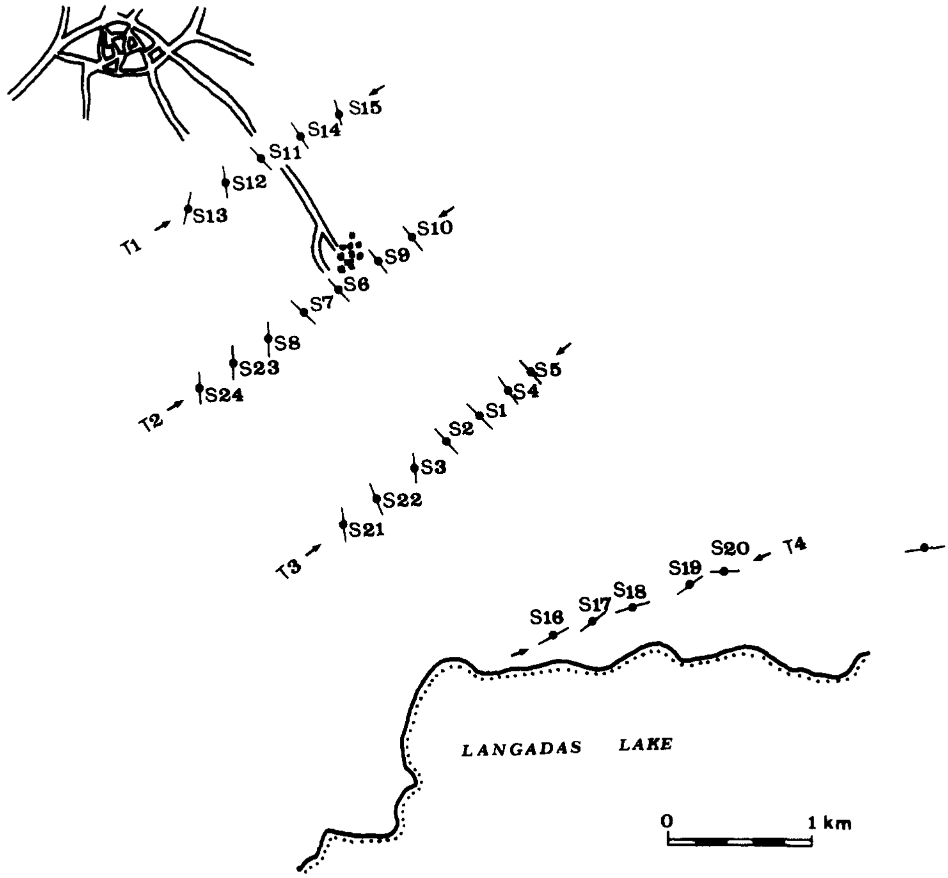


Fig. 3. Location map with soundings.

by the steep descent technique (Koefoed, 1979). The equivalence problem was solved by considering the results of the "mini electric" measurements and the results of a detailed gravity survey in the area (Thanassoulas, 1983).

The possible geoelectric models obtained are presented in Fig. 5(a, b, c, d), together with the corresponding apparent resistivity spaces.

The following geoelectric formations can be identified from these diagrams:

(a) Surface formations, with large lateral variations in apparent resistivity and small thicknesses, which correspond to the Quaternary. These formations have electrical resistivities between 20 and 45 ohm m, depending on their relative concentrations of sand and clay.

(b) The second geoelectric formation located shows resistivity values between 12 and 48 ohm m and can be followed across all the traverses. The three boreholes that penetrated it revealed alternating layers of sand, clay and gravels.

(c) The last geoelectric formation shown in the solutions corresponds to the crystalline basement of the investigated area.

The geoelectric traverses T_1, T_2, T_3 revealed the existence of a horst in the bedrock. The formation overlying the horst typically shows lower resistivity values (16 ohm m) than the mean of the same formation (27 ohm m). This probably indicates a circulation of hot mineralized water.

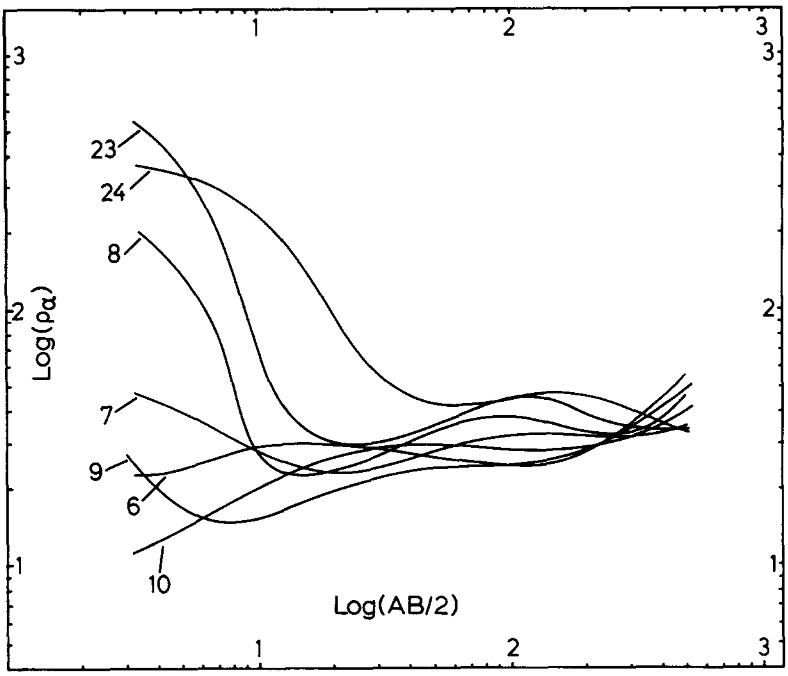


Fig. 4. Resistivity curves obtained for traverse T_2.

Analysis of the geoelectric data also revealed the existence of some faults in the basement, which dips north-westwards to depths greater than 400 m. This is in agreement with the results obtained from other investigations (B.R.G.M., 1972; Psilovikos, 1972; Thanassoulas, 1983).

Spatial variation of the apparent resistivity

The amount of data recorded provides an insight on the three-dimensional geoelectric section of the investigated area.

Qualitative interpretation of the resistivity data was performed by drawing apparent resistivity maps for half current electrode (AB/2) spacings of 100, 250 and 500 m (Fig. 6).

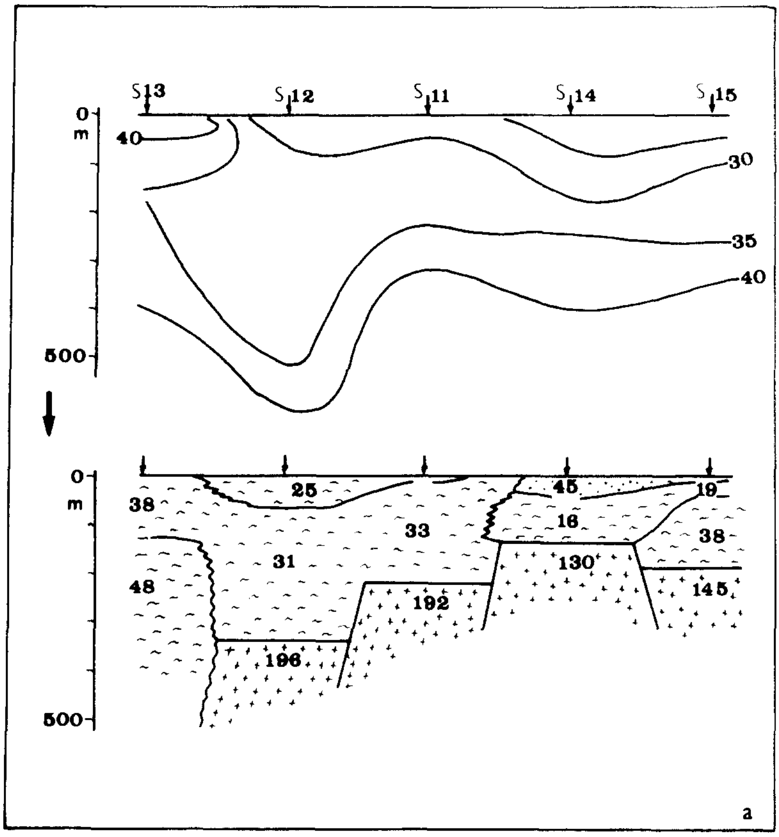
The above figure shows that the apparent resistivity curves for AB/2 = 100 m reach their minimum value towards the Langada hot springs, reflecting the circulation of hot mineralized water in the geologic formations. A similar low, observed towards the southern part of the area, is probably due to water intrusion from the nearby lake.

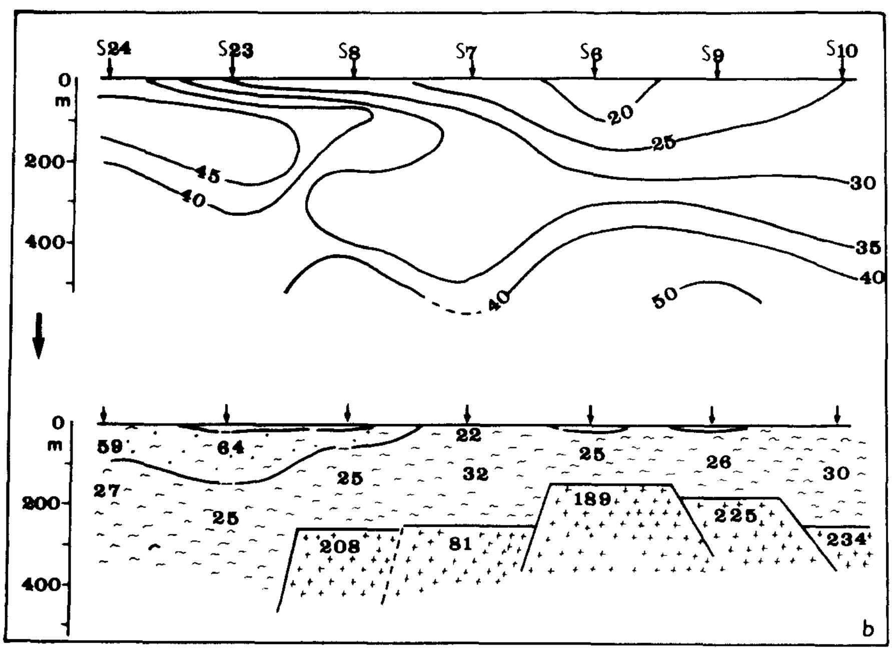
The same general pattern is also shown for AB/2 = 250 m. The low resistivities observed previously within the hot spring area have taken on higher values, reflecting the existence of the horst in the bedrock.

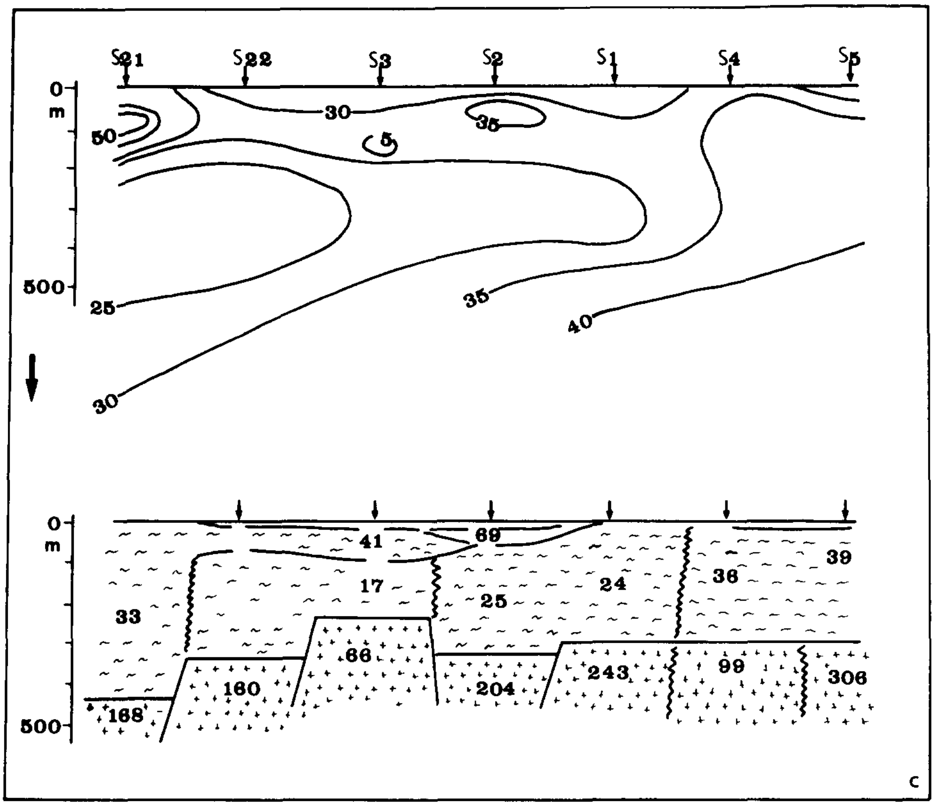
Figure 6c shows the spatial variation of resistivity for AB/2 = 500 m. As one would expect, the low resistivity area has been transformed to a high resistivity one, reflecting the general structure of the horst.

Spatial variation of the bedrock

The results of the geoelectric interpretations, which contained information on the possible depth of the bedrock (crystalline basement), are represented in the map in Fig. 7, which shows the top of the geoelectric resistive bedrock for the whole area investigated.


S13
S12
S11
S14
S15
0
m
500
40
30
35
40
25
45
19
38
16
33
38
31
130
48
145
192
196
a


S24
S23
S8
S7
S6
S9
S10
0
m
200
400
20
25
30
45
40
35
40
50
40
22
59
64
25
26
30
25
32
27
189
25
225
208
81
234
b



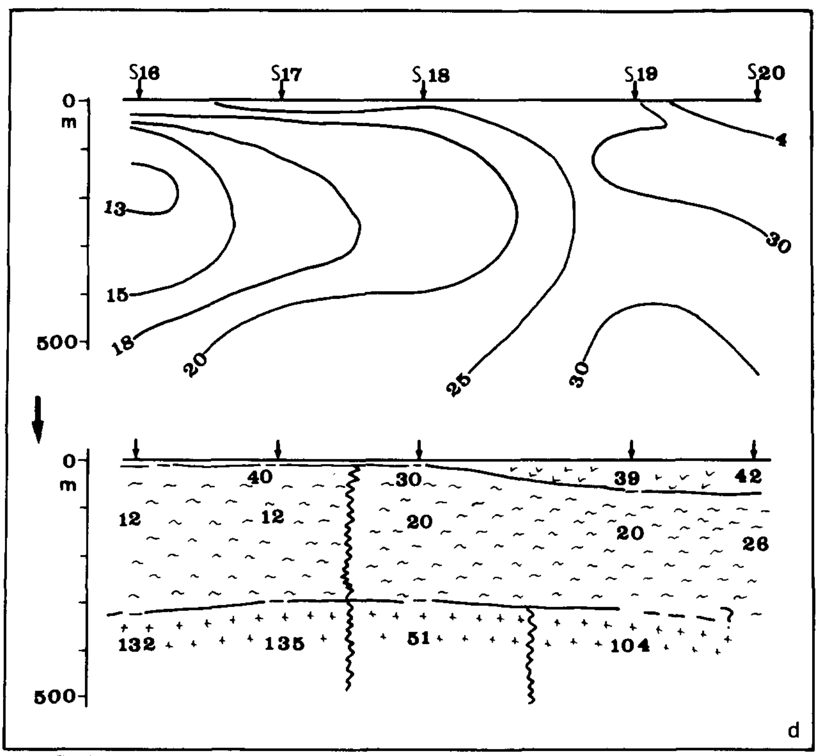
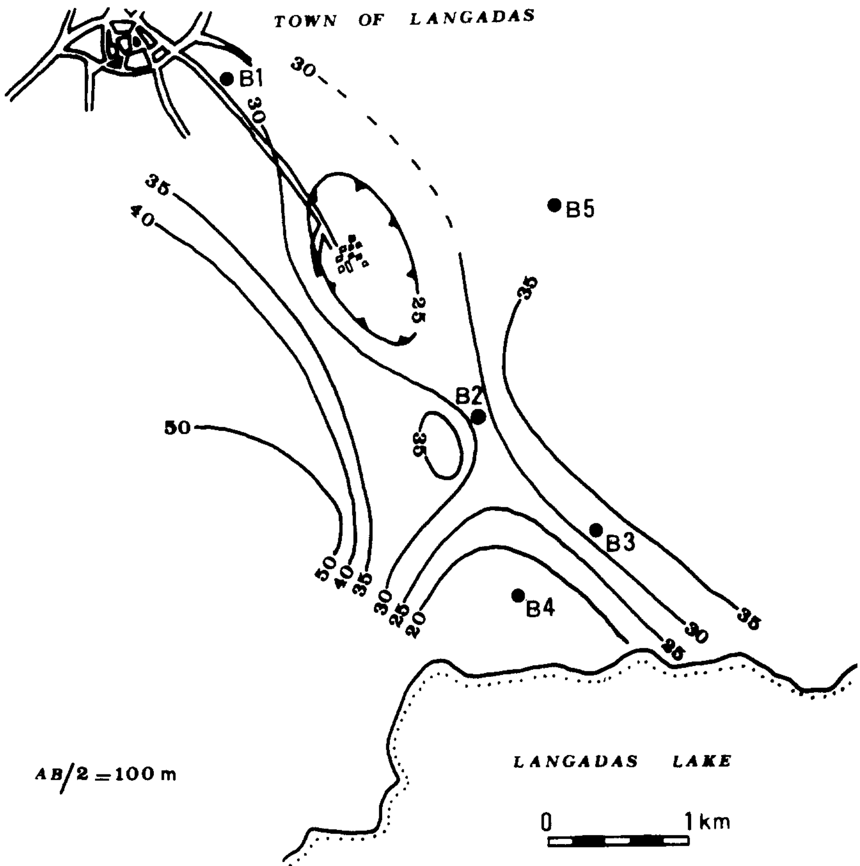
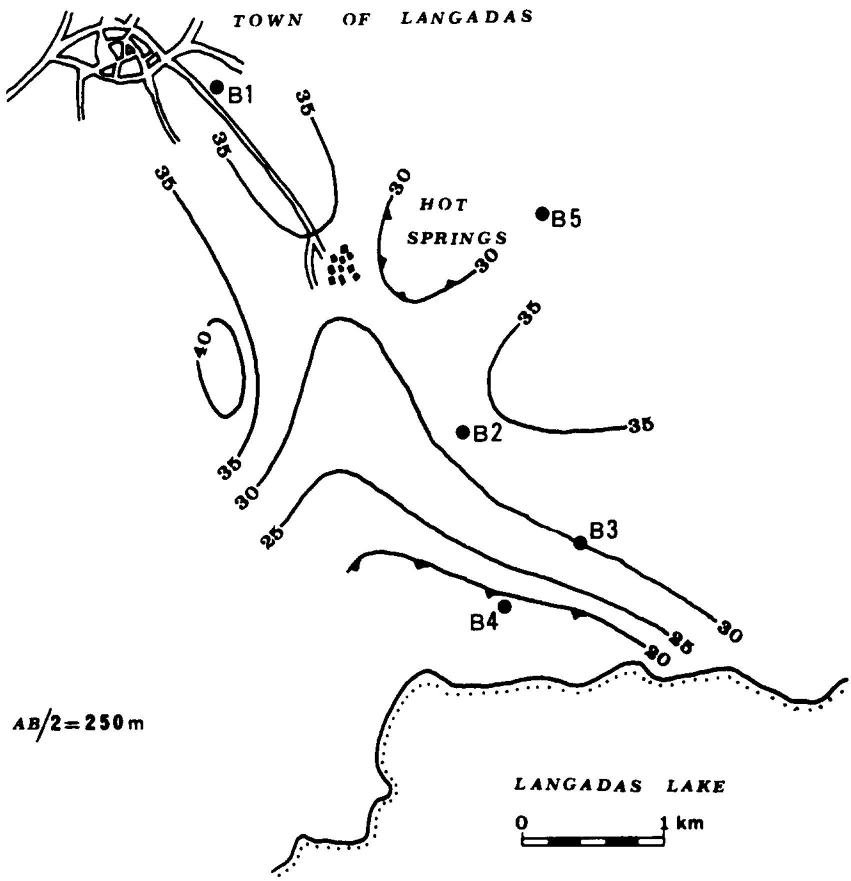


Fig. 5(a–d). Geoelectric models and apparent resistivity for the four measured traverses. (Values in ohm m.)


TOWN OF LANGADAS
B1
B2
B3
B4
B5
30
30
25
35
35
40
50
50
40
35
30
25
20
35
35
30
25
LANGADAS LAKE
AB/2 = 100 m
0
1 km

(a)


TOWN OF LANGADAS
B1
35
35
35
30
HOT
SPRINGS
30
B5
35
40
35
B2
35
30
25
B3
B4
30
25
20
AB/2 = 250 m
LANGADAS LAKE
0
1 km

(b)

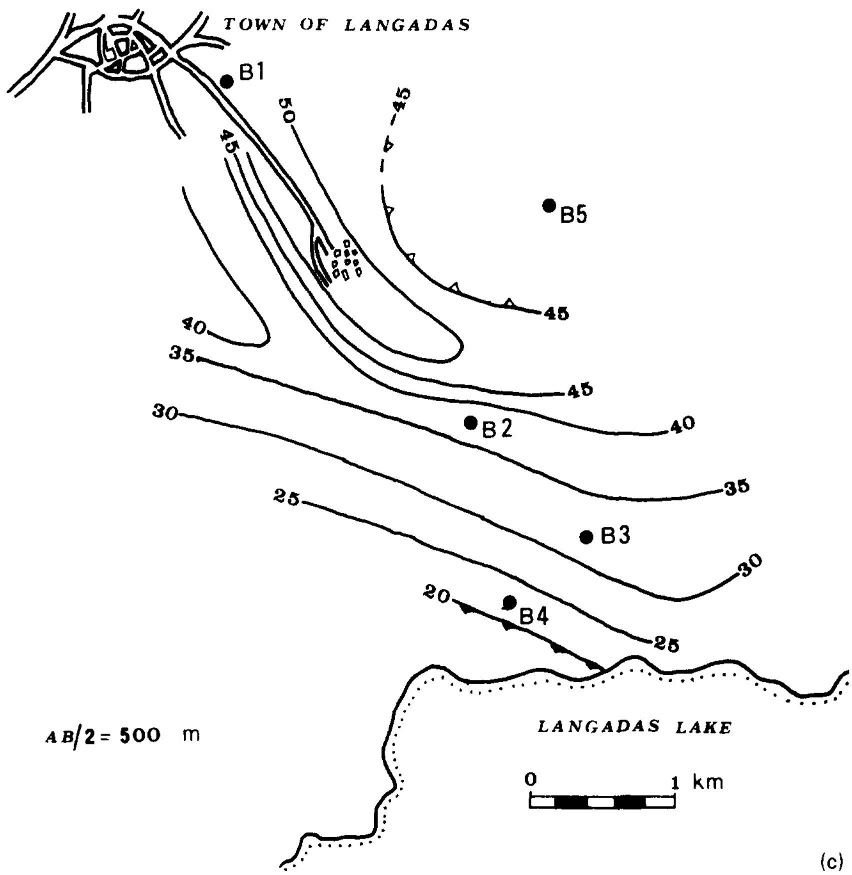


Fig. 6(a–c). Apparent resistivity contours for AB/2 = 100, 250 and 500 m.

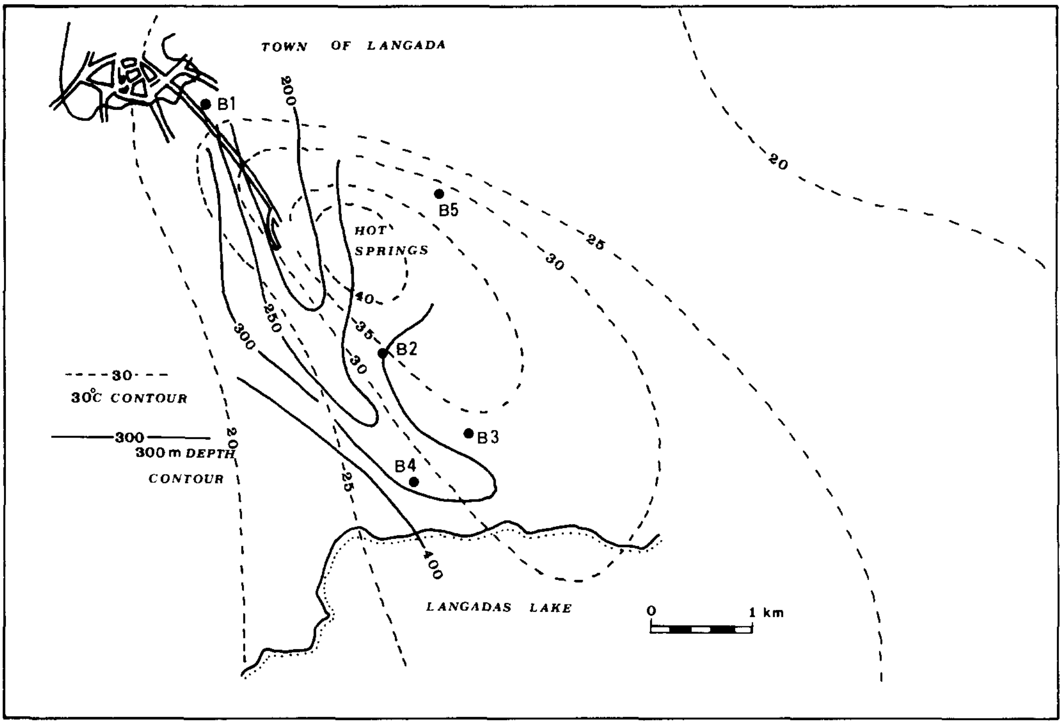


Fig. 7. Comparison between the top of the bedrock and temperatures.

The diagram shows the location and the trend of the horst, which has a NW–SE direction and dips towards the SE.

The same map also presents the observed temperatures. The good correlation between the depth of the top of the bedrock and temperature is obvious, with higher temperatures obtained in regions where the depth of the bedrock becomes minimum, towards the horst.

It is worth noting that the two boreholes (B_2, B_3) located above the horst produced hot water, while three other bores (B_1, B_4, B_5) located far from it (Fig. 6a), did not prove successful.

CONCLUSIONS

The geoelectric investigations revealed the existence of a horst type morphology of the bedrock, striking NW–SE. The spatial distribution of temperature was found to correlate very well with the areal apparent resistivity maps and the area of geothermal interest was found to be concentrated along the major axis of the horst and along a major fault located SE of the area. All the boreholes drilled on the horst proved successful.

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