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AN EC PROJECT ON TESTING GEOPHYSICAL TECHNIQUES FOR THE EXPLORATION OF THE GEOTHERMAL FIELD OF MILOS

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ABSTRACT

The energy R&D Programmes of the Commission of the European Communities deal in particular with the development of thermonuclear fusion and the so-called "non-nuclear energies" including solar energy, biomass, wind power and geothermal energy. In surveying for geothermal reservoirs it appeared that the standard geophysical exploration techniques used in the hydrocarbon industry required modifications of both technique and interpretation if they were to achieve their full potential. Collaborative projects have therefore been established under which geophysical teams drawn from various Member States work together on selected sites. The summarized results of a joint geophysical experiment carried out by eight teams on the island of Milos, Greece, are reported here. Shallow fractured regions forming the reservoir are filled with hot water and vapour, perhaps heated by cooling magma chambers. These fractured and saturated formations were the actual target of the geophysical exploration because they were supposed to be characterized by their very specific physical properties. Emphasis was placed on seismological, magnetotelluric and self-potential experiments. An interpretation of the results from these experiments shows that correlation into a coherent models is possible.

I. Introduction

Research and development of energy technologies is one of the fields in which the Commission of the European Communities is encouraging its 12 western European Member States to work together and to complement ongoing national activities. Research started on coal utilization about 30 years ago and continued in the fields of nuclear fission and fusion. As a consequence of the first oil crisis the Commission initiated in 1975 the Non-nuclear Energy R&D Programme with the aim of developing alternative forms of energy in its Member States. Geothermal energy is part of this programme.

One of the major objectives of the Commission's geothermal research is to improve and to test geophysical explorations methods, since it is known that their application in prospecting for hot water and steam resources requires modification from that used in hydrocarbon exploration. This modification includes the adaptation and recalibration of both instruments and interpretation techniques. As a first step, the Commission established a group project whereby different geophysical teams could test their techniques. The high enthalpy geothermal field of Travale in Tuscany (Italy) was selected as the first test site, and the results of this project were reported in 1985 in a Special Issue of *Geothermics*. Twelve scientific teams from the United Kingdom, France, Italy and the Federal Republic of Germany participated in this project and the experiments demonstrated once more the fact that it is impossible to characterize a geothermal reservoir by one single method. Only by combining several methods can promising results be obtained. The choice of methods depends on the characteristics of the geothermal field to be investigated. In the case of Travale, where the feeding system of the geothermal reservoir consists of deep-reaching hydrothermal convection cells, emphasis was put on geoelectric and electromagnetic techniques. Problems were caused by the complicated geological setting of the reservoir, the high level of cultural noise and the different field logistics and interpretation methods of the different scientific groups. The results obtained did lead to an updated picture of the Travale field but were insufficient to establish a definitive model of the reservoir. However, it was an important first exercise from which the groups involved learned how essential it is to agree on a uniform data processing and interpretation concept and to have compatible instrumentation.

The Commission therefore decided to continue the geophysical experiments in another high enthalpy geothermal field. After considering the logistic possibilities and the geological conditions, the island of Milos in Greece was selected as a second geophysical test site.

This paper gives on overview on the results of the various projects. The details of the individual projects are presented in *Geothermics*, Vol.18, No.4, 1989.

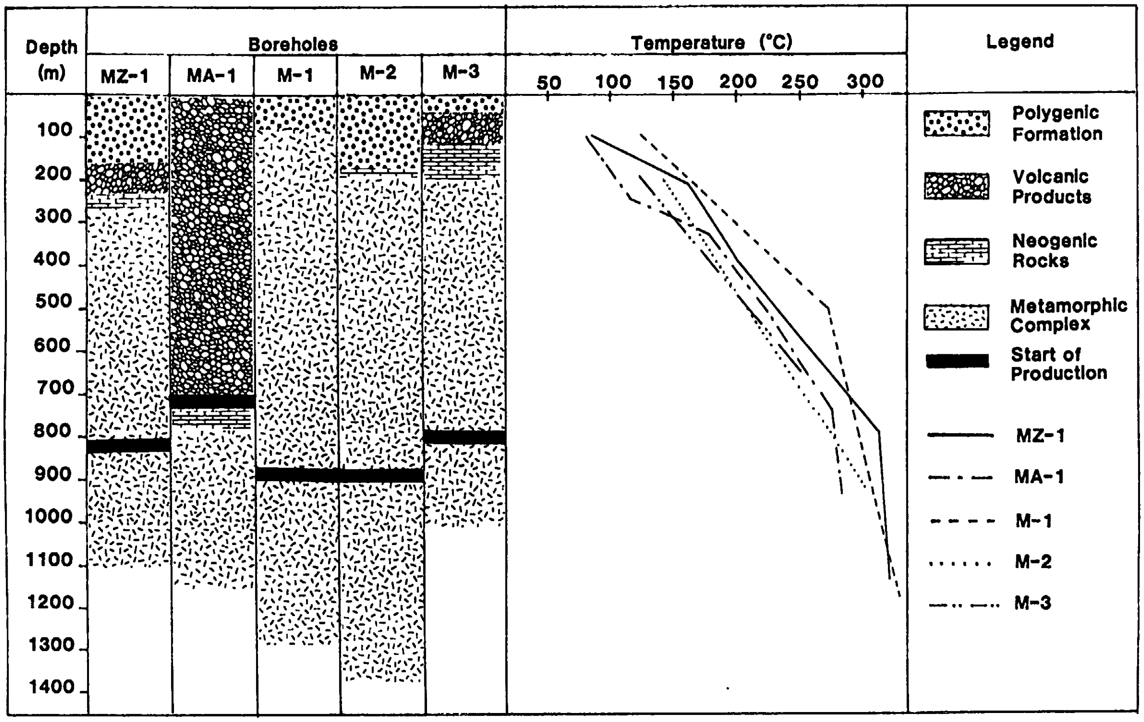


Figure 1. Geological section of the 5 deep boreholes, the corresponding temperature curves and the top of the productive zones

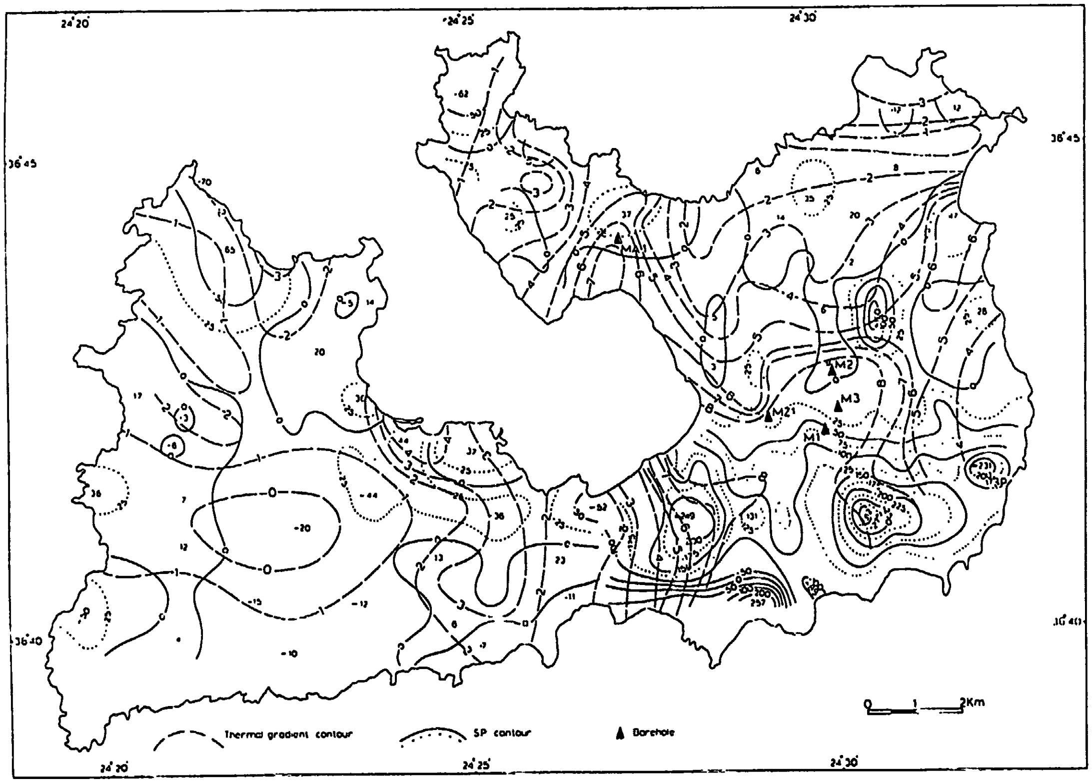


Figure 2. Correlation of SP and thermal gradient measurements (Thanassoulas, 1989)

II. Geology, geodynamics and geothermal situation of Milos

The island of Milos covers an area of 150 km² and is located in the south-southwestern part of the Aegean Sea.

The islands of Milos, Santorini and Nisyros and the area of Methana are situated on the active volcanic arc of the southern Aegean Sea and all these areas are known for having high enthalpy geothermal resources. It was in the Milos area that the most significant volcanic activity took place. It started during Middle to Upper Pliocene as a consequence of the northward subduction of the African plate beneath the Aegean plate (Fytikas et al., 1984). The volcanism is mainly of phreatic type and controls the shape and the morphology of the island. Calc-alkaline volcanic products cover the major part of the island and overlie Neogene sediments and the metamorphic basement.

The island was affected by very intense distinctive tectonic activity during Pliocene and Quaternary times and faults, mainly in NW-SE direction, are still active at present.

Surface hydrothermal activity occurs in a variety of active thermal manifestations such as fumaroles, hot springs, hot grounds and submarine gas escapes. They are mainly located in the central and eastern part of the island and temperatures of the fumaroles up to 100°C were measured.

The hydrothermal alteration of the volcanic rocks produced a good cover by self-sealing above the rather shallow circulating hot geothermal fluids. The results of thermal gradient measurements were reported by Fytikas (1977) and suggested that thermal anomalies of the island are concentrated in the central eastern part, close to Adamas and in the graben of Zephyria. Following thermal gradient, geoelectric and gravimetric measurements, 5 boreholes with depths between 1000 and 1400 m have been drilled in these areas. Figure 1 represents the geological section, the temperature distribution and the top of the productive zone of each borehole. It can be seen that in the graben of Zephyria (boreholes MZ-1, M-1, M-2 and M-3) the production starts within the metamorphic complex and is due to fracturation of the rocks. Only in the borehole close to Adamas (MA-1) the production zone starts some metres above the Neogenic limestones, in a volcanic formation made by lava-breccias, and continues in the limestones and the metamorphic rocks. The temperatures at the reservoirs are between 250 and 320 °C. The boreholes produce a total of 350 t/h steam/water mixture but due to silica scaling problems only a pilot plant of 2 Mwe has been installed so far.

III. The Milos geophysical project

Based on the measured high temperatures of up to 320°C at reservoir level, earlier gravity and geoelectric soundings and volcanological investigations, it was suggested that shallow magma chambers could be responsible for the heat reservoir (Fytikas et al., 1986). It was therefore decided that, in addition to active and passive magnetotellurics and self-potential experiments, seismological techniques should also be applied to investigate the geothermal anomaly. One objective of the project was to test whether these investigations supported or contradicted the hypothesis of shallow magma chambers.

Near surface evidence was provided by self-potential (SP) and audio-frequency MT measurements. SP measurements utilizing the gradient method were performed along profiles totalling 242 km, mainly on the island but also including some sea surface. The sampling interval was 100 m. SP gradient measurements were integrated along the profile, tied to a common zero level, and filtered with a low pass filter to reject high frequency noise. It has been shown (Thanassoulas, 1989) that negative SP-anomalies correlate very well with strongly fractured zones and areas where hydrothermal alteration is evident. A comparison of the SP-map with the thermal gradient map is displayed in Figure 2. There is a strong correlation with areas of steep geothermal gradients. Equally strong correlation is observed between the contour lines of apparent resistivity RHO* at 10 Hz and those of temperature gradient (Haak et al., 1989). Audio-frequency MT-data from all the participating teams demonstrated that low resistivities are concentrated around the established strongly anomalous geothermal areas, probably as a result of high temperatures combined with high salinities of the reservoir fluids in intensely fractured and/or more or less permeable rock formations near surface (30-300m depth).

Information to a depth of about 1000m in the eastern part of Milos came from active-audiomagnetotelluric (AAMT)-experiments in a combined interpretation with the Bouguer-gravity (Drews et al., 1989). AAMT does not use the natural variation of the electromagnetic field but an artificial source. The electromagnetic field is produced by a transmitter feeding alternating currents of up to 20 Ampère into an electric dipole. The frequency ranges from 0.05 to 2500 Hz. At the receiving station the horizontal components of the electric field and all three components of the magnetic field are recorded. A clear vertical separation of low resistivities (0.5 ohm.m) from higher values (10 ohm.m) defined the top of the "electrical basement" as illustrated in Figure 3. A similar interface was also identified by MT measurements carried out in the period range of 0.01 to 10,000 s (Hutton et al., 1989). Depth to the electrical basement varies between some few metres and 300m. This upper interface comes highest in the central-eastern part of Milos, dipping in all other

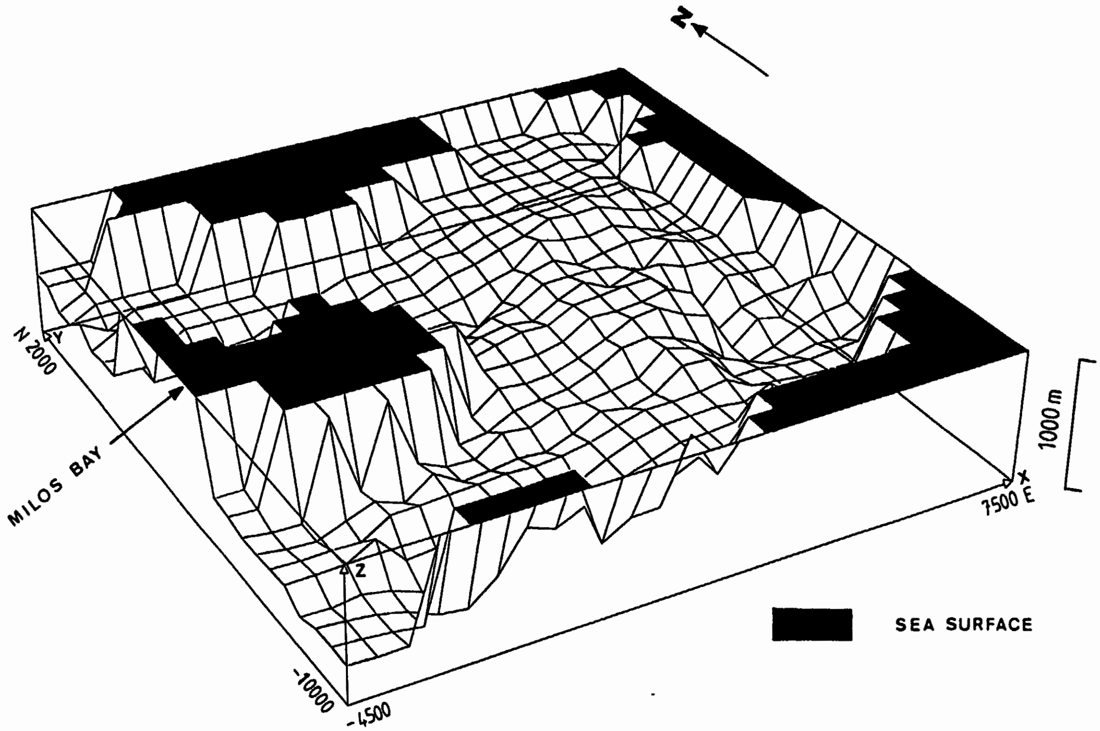


Figure 3. 3-D plot of the top of the electrical basement from AAMT measurements (Drews et al., 1989)

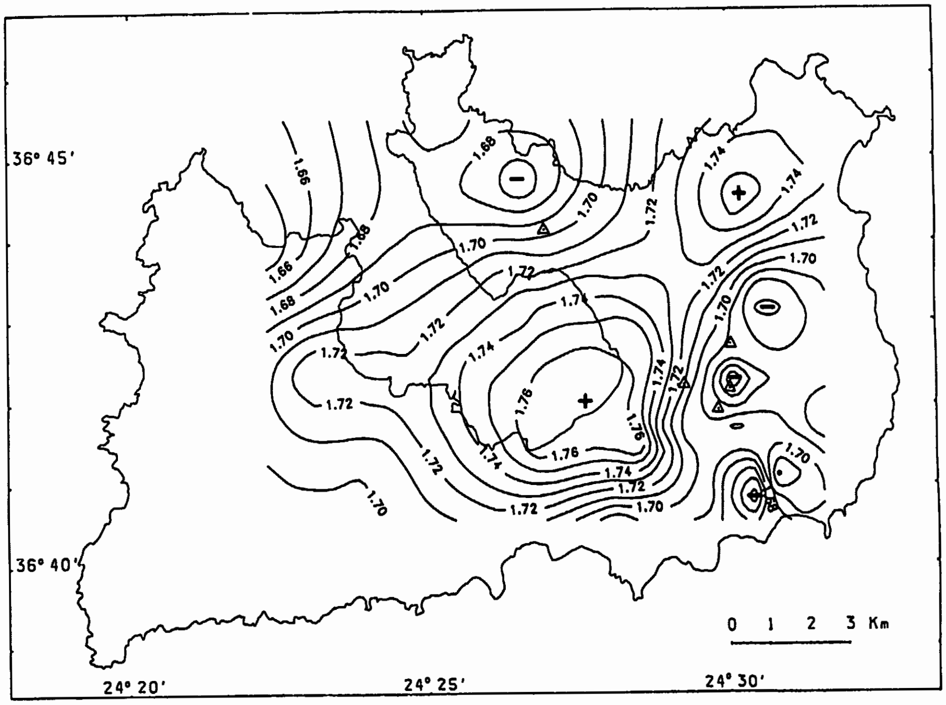


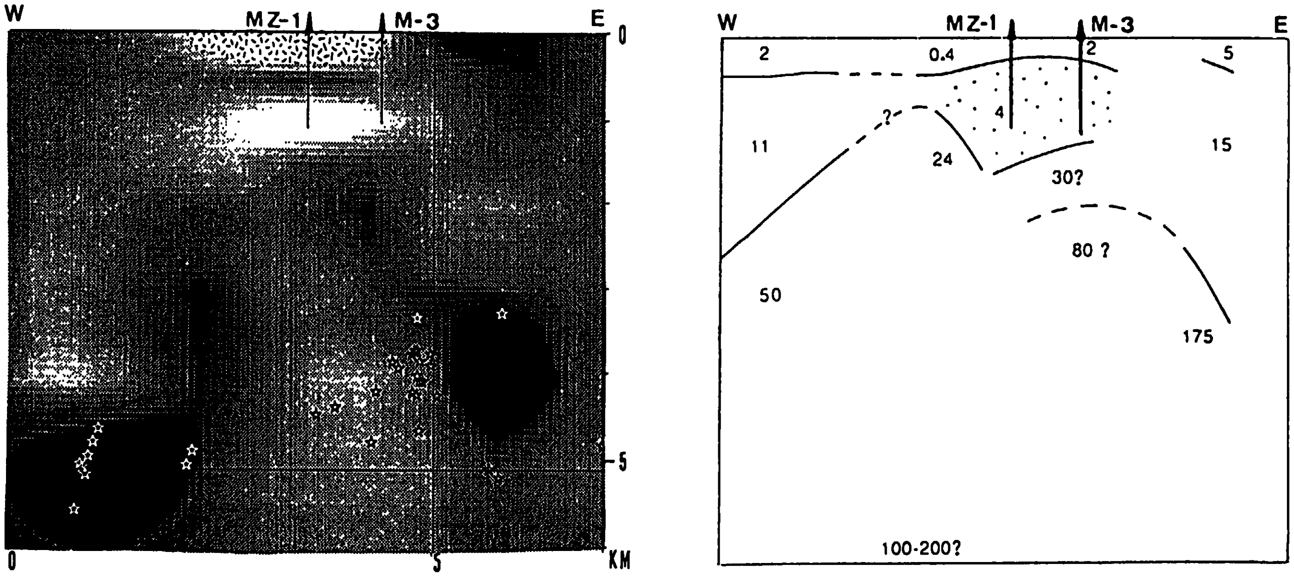
Figure 4. Variation of the V_p/V_s ratio in the central eastern part of the island (Ochmann et al., 1989)

directions. It would appear that this boundary defines the lower limit of penetration of sea water into the sediments; the elevated section perhaps marks the top of the self-sealed cap rock above the geothermal reservoir.

An interesting feature of the uppermost 3 to 4 km within the geothermal anomalous area is revealed from the study of microearthquake data. From velocity studies using traveltime inversion techniques, a reduced V_p/V_s-ratio was observed (Ochmann et al., 1989). Comparable results have been obtained for The Geysers (Majer and McEvilly, 1979). Reasons for the negative anomalies (Figure 4) are structural, petrological, and physical heterogeneities within the reservoir. From these investigations there is also evidence for a minor geothermal anomaly in the central-northern part of the island which agrees well with the ideas of Fytikas (1977) derived from temperature gradient studies and which has been proven by the deep borehole at Adamas.

The vertical structure of the reservoir was also investigated in three dimensions through seismic tomography by Hirn et al. (1989). By using a large number of three-component seismographs with a spacing of sometimes only a few hundred metres a very high resolution was obtained. It resulted in a detailed analysis of the position and geometry of the geothermal reservoir. In Figure 5,the seismic results, presented as a contoured plot of V_p/V_s ratio, are compared with the results from MT-soundings (Hutton et al., 1989) along a W-E profile across the geothermal anomaly. The unshaded zone in the seismic plot between approximately 700 and 1400 m depth corresponds to a high V_p/V_s ratio which is regarded as typical for fluid-filled fractures. The position and depth of the production wells MZ-1 and M-3 is indicated in this Figure 5 and shows that both wells are exactly drilled into the anomaly.

In the same Figure low resistivities of approximately 4 ohm.m identified by MT-soundings correspond to the depth of the highest V_p/V_s ratio from the seismic plot. The location of the section presented in Figure 5 as well as those of Figures 7 and 8 are shown in Figure 6. It also gives an overview of the geology of the island and the position of the 5 boreholes.



(a)

(b)

Figure 5. Comparision between seismic velocity and resistivity data across a W-E profile (location see Figure 6)

(a) V_p/V_s ratio (Hirn et al., 1989).
The lighter the shading, the higher the ratio; the stippled area at the top denotes a zone where data were not interpreted; stars show the locations of earthquakes

(b) Resistivity from audio MT measurements (Hutton et al., 1989)

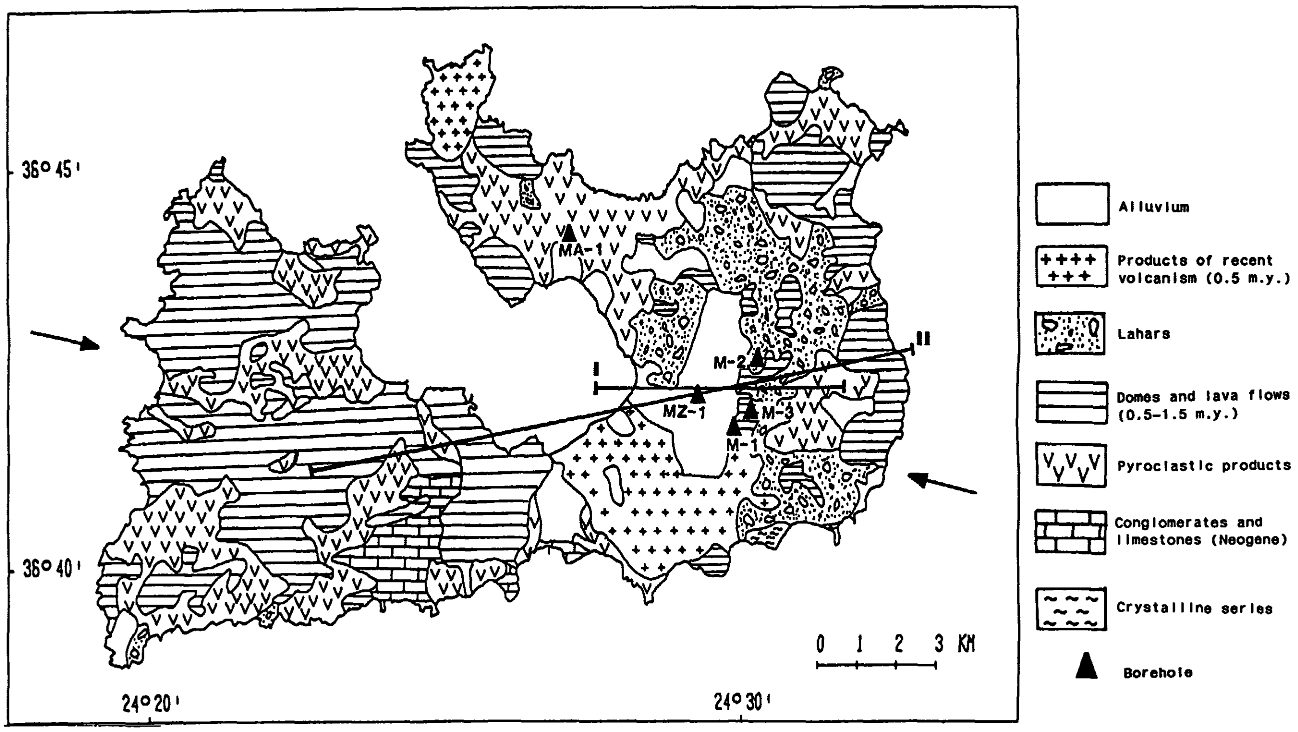


Figure 6. Location of sections. Section I corresponds to the W-E profile of Figure 5; the arrows indicate the generalised vertical section along the NW-SE profile of Figure 7 and section II corresponds to the WSW-ENE profile of Figure 8.

Figure 7 shows that evidence of the deeper geological structures is also given by combining seismological and MT-data. The resistivities from MT-experiments and the hypocentres from the earthquake studies are projected onto a generalised vertical section along a NW-SE profile across the central-eastern part of the island. The Figure also shows the position of three production drillholes. All the mapped seismic events occurred in a zone of higher resistivities. The focal depths are between 4 to 7 km beneath the known reservoir and increase towards the NW to values between 7 and 10 km.

It may be noted that, although location of the natural seismic events per se gave no information about the geothermal reservoir, the analysis of the seismic coda and the seismic tomography which was then possible provided a striking correlation with the other data.

The resistivity structures reveal different characters in the northwestern part and the southeastern part of the profile. The actual reservoir is characterized by low resistivities of about 4 ohm.m. While the uppermost layers along the whole section have resistivities in the range from 0.5 to 5 ohm.m, the dominant feature of much of the NW part is an extended underlying zone with resistivities from 10 to 15 ohm.m. This zone is clearly separated from areas of resistivities between approximately 50 ohm.m under the reservoir and 100-200 ohm.m elsewhere. This higher resistivity zone comes closer to the surface beneath the geothermal reservoir.

The low resistivity at the extreme NW of the section suggests that another reservoir may exist in this region.

All the electrical studies suggest a general increase in resistivity at greater depth. This argues against the earlier hypothesis of a large shallow magma chamber, though it does not rule out the existence of a number of very small chambers of molten magma. The discrimination of such small molten bodies would require more refined 3-D modelling than has been possible in this exercise.

The origin of the seismicity is another aspect that has not been completely clarified. One group considers its results as indicating a tectonic origin (Ochmann et al., 1989), while another suggests a magmatic origin or sudden changes in fluid pore pressure (Hirn et al., 1989). Both groups, however, agree that the seismicity is related to the stress field. In the shallower zones fractures appeared to be more isotropically distributed while at depth there is a dominant fracture and impedance direction.

IV. Conclusions

The results of the geophysical experiments can be summarized as shown in Figure 7:

- in the upper 500 m a layer of low resistivity exists; this could be identified as the top of the metamorphic basement;
- in the SE of the section a well-defined zone of 4 ohm.m coincides with the reservoir proven by three production wells;
- a resistivity interface dips from SE to NW;
- the earthquake activity is concentrated in the higher resistivity zone and dips in the same direction as the resistivity interface;
- no earthquake activity occurs below 7 km beneath the reservoir region.

On the basis of these results and including earlier studies a schematic geological profile has been drawn up (Figure 8) crossing the reservoir region of Zephyria in a WSW-ENE direction. It indicates the dipping resistivity interface as dividing the metamorphic basement from the deeper undefined basement. The metamorphic basement is characterized by multidirectional heavy faulting. These fault clusters are assumed to provide an effective transport system for fluids descending from the surface towards the heat source and convecting upwards towards the reservoir. Though there is no evidence for molten magma chambers at depth, Figure 8 also proposes the presence of cooling magma chambers beneath the reservoir as the most probable sources of heat. That they were not detected by the electrical methods suggests that a large body of molten rock is no longer present, though smaller or solidified but still-cooling bodies could exist. No seismic activity was recorded at these depths, which could be explained by the still sufficiently hot and therefore ductile rock material.

It can be stressed that the geophysical experiments at Milos have been successful. Most important for this success was the high degree of co-operation which was established between all involved groups from the beginning. This included the selection of common measuring sites and the calibration of instruments for a better comparison of results, as well as common data processing and interpretation. Both seismic and electrical data were essential for understanding the fault system which is feeding the reservoir. The SP, MT and temperature gradient data have contributed to a description of the areal extent of the reservoir, while modelling of MT and seismic data gave information on the shape of the anomalies at depth.

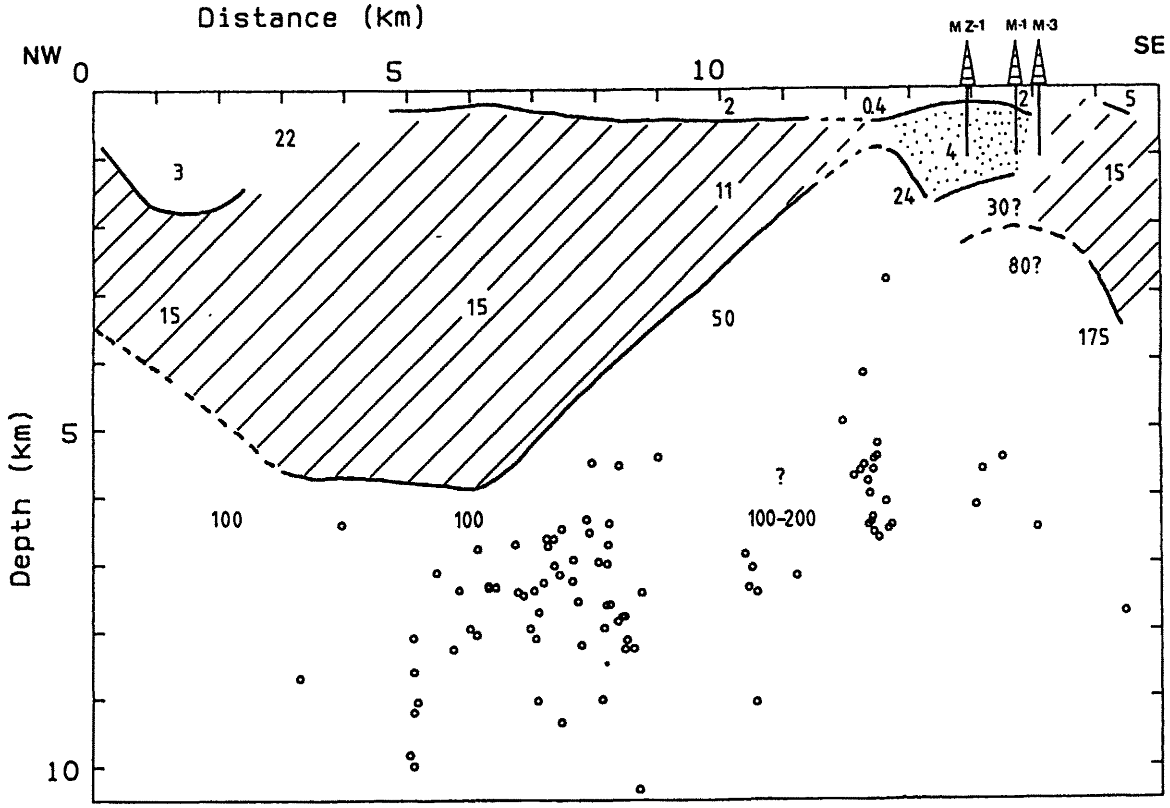


Figure 7. Generalised composite profile in NW-SE direction across central eastern Milos (location see Figure 6), combining seismic and MT interpretations. The dotted area indicates the low resistivity zone coinciding with the proven reservoir, and circles denote earthquake hypocentres

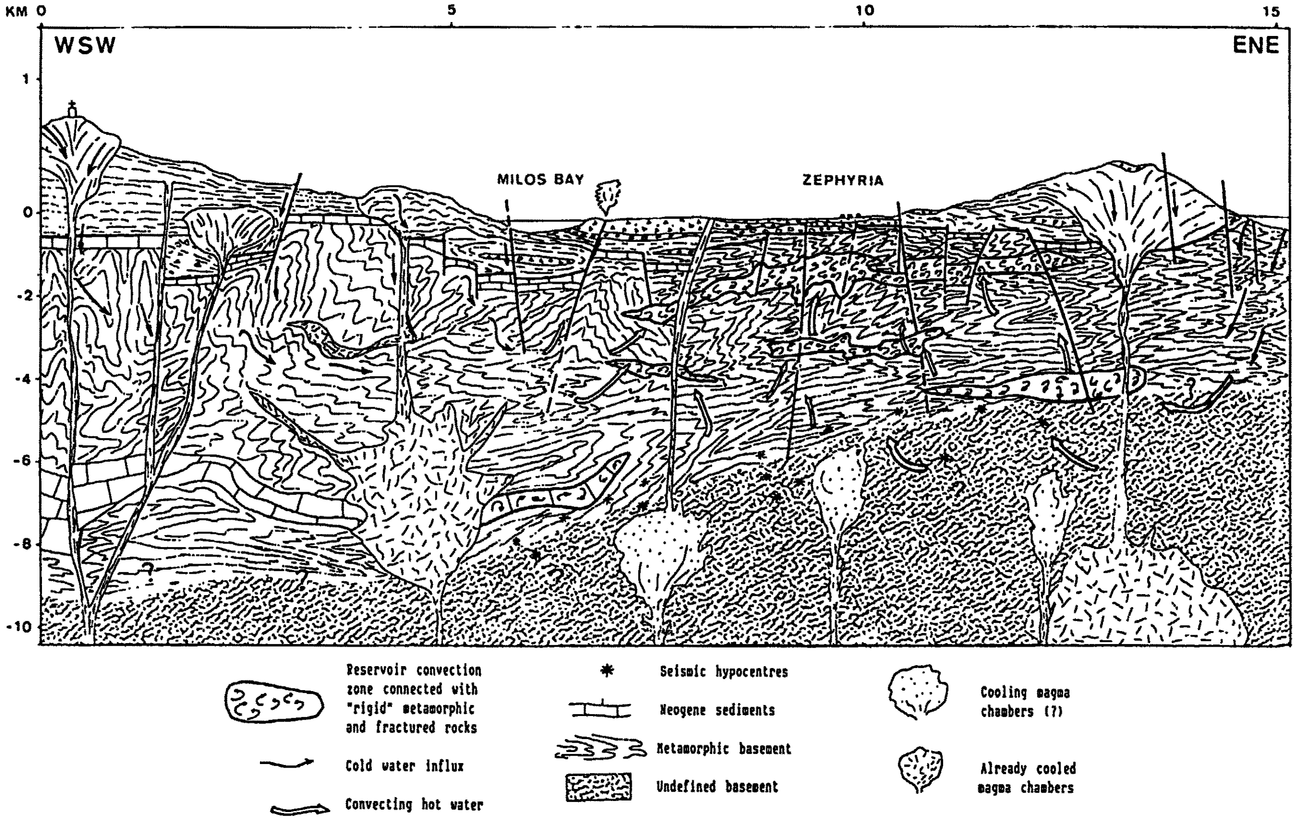


Figure 8. Schematic geological profile crossing the geothermal area of Zephyria in WSW-ENE direction (location see Figure 6)

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