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GEOLOGY AND GEOTHERMICS OF THE ISLAND OF MILOS (GREECE)

by

M. Fytikas* and G. Marinelli**

Abstract - The geothermal research at Milos is reviewed and the geology of the island is discussed in the framework of the geodynamics of Eastern Mediterranean.
The various formations outcropping at Milos are described: crystalline basement, Neogene transgressive conglomerate and limestones, Quaternary volcanic and volcano-sedimentary series. The very recent disjunctive tectonics affecting Milos and the neighbouring islands is discussed together with the volcano-tectonics. The thermal manifestations and the wide and important alterations and mineralizations related to the near surface circulation of hydrothermal fluids are also described.
The geophysical methods utilized in the geothermal exploration to locate exploratory and production wells are briefly illustrated. They include 55 thermometric wells and an electric resistivity survey. Preliminary data from the two Milos wells, both productive, with bottom-hole temperature higher than 300°C are reported.

INTRODUCTION

In the fall of 1970 one of the authors spent two weeks in Greece in the capacity of consulting expert to the Organization for Economic Co-operation and Development (OECD). The aim of this mission was to

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establish whether there were any areas presenting favorable conditions for finding goethermal energy which could be economically exploited.

In the report presenting the results of this preliminary reconnaissance (Marinelli, 1971) the author concluded that numerous areas of Greece evidence favorable conditions for detailed exploration for geothermal energy. The island of Milos was considered to be by far the most important of these areas. On this island in fact it was obvious, even on the basis of a rapid reconnaissance study, that several of the geological conditions basic to the formation of geothermal fields were present.

The conditions found were the following:

1) The presence of a rigid crystalline basement, fractured by very recent disjunctive tectonics. This would tend to facilitate the convective circulation of fluids and hence the rising of isotherms.
2) The presence in this metamorphic complex of marble lenses and calc-schists and, in certain areas, also of an overlying transgressive series composed of conglomerates, limestone and gypsum lenses. These formations might possibly represent the objective of the drillings, i.e. a highly permeable reservoir.
3) A cover consisting of volcanic or volcano-sedimentary products, deeply transformed into bentonite and kaolin by hydrothermal phenomena. This alteration guarantees a high impermeability in the series.
4) The presence of numerous thermal manifestations,

including several small fumaroles with temperatures up to 102°C.

However, the geological feature which led the author to the conviction that Milos was the most promising geothermal region in Greece was the large number of spectacular craters caused by phreatic explosions. (1)

These phreatic craters have very limited diameter (less than 20 m) and are very frequent in those areas where the impervious cover is thin; in the areas where the cover is thicker they are less numerous but much larger (up to 600 m in diameter). The perfect condition of the rims of these craters indicates that they are very recent.

The other author was charged by the Greek Institute of Geology and Subsurface Research (presently the Institute for Geology and Mining Research) with all field and laboratory research aimed at the geothermal exploration of Milos. This work led to a doctoral thesis (Fytikas, 1976a) and to a

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(1) The term "phreatic explosion" was first introduced at the beginning of the century by E. Suess in his famous work "Das Antlitz der Erde". It refers to those eruptions in which no material derived from new magma is ejected and which may be attributed to the steam conversion of water of superficial and not magmatic origin. The term has since been used by the majority of volcanologists (Van Bemmelen, Rittmann, Cotton, MacDonald, etc.) and also by J. Goguel (1975) and it would thus appear unnecessary to introduce a new term, "hydrothermal explosion" (Muffler et al., 1971) which, besides being inexact for a steam explosion, tends further to complicate the already complex geological terminology.

detailed (1:25.000) geological map (Fytikas, 1976b). These two documents have been largely utilized in the present paper.

The field and laboratory work was begun in the summer of 1971 and completed at the end of 1972. During this time the following data were collected:

a) Topographic map (scale 1:20.000) of the entire island.
b) Detailed geological map of the central and eastern regions (approximately 100 Km^2 of the total area of 150 Km^2). The geological map of the western part of the island was finished afterwards.
c) Sampling of all the outcropping formations and of the deeply-seated rocks brought to the surface by volcanic eruptions and phreatic explosions.
d) Petrographic studies; paleontologic and K/Ar datings.
e) 48 thermometric drillings, plus temperature measurements in 15 wells previously drilled for water or mineral exploration. These wells vary in depth from 20 to 80 m, with an average depth of 54 m. The first of these slim holes, at a depth of 72 m, gave a mixture of steam and hot water with a temperature of 138°C.
f) In the spring of 1973 a geoeletrical survey was carried out by the "Compagnie Général de Géophysique". 83 electrical soundings were performed, 14 with an AB line of 2,000 m and 69 with an AB of 3,000 m.

The exploratory work briefly described above was effected over a period of two years, but in fact required only one year of actual field and laboratory work for the geological aspects, and a few months for the topographic mapping and geoelectric survey. The operating cost of this part of the exploratory programme was U.S.$ 84.000. This figure may evoke a sceptical smile in the geothermal exploration community, but in fact it is exact and well-documented.

In May 1973 four sites were selected for deep exploratory drilling and production. (1) No active or fossil thermal manifestations are present in any of them. Since the data available were considered sufficient for these locations, no further exploratory work was performed. Later, some hydrogeochemical data (Dominco and Papastamaki, 1975) confirmed the presence of favorable conditions for geothermal energy on Milos.

The organization and technical direction of the drilling was committed by the Greek Public Power Corporation to the French Company "Eurafrep". The drilling

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(1) Among the partecipants at the meeting for the selection of the Milos drill sites, the authors wish particularly to thank Mr. G. Aportolides, Director of the Institute of Geology and Subsurface Research; Mr. P.E. Gounaris, Director of the Geothermal Service of the Public Power Corporation; Mr. J. Demians d'Archimbaud, Chief Geologist "Eurafrep"; and Mr. A Duprat, Chief of the Subsurface Dept., "Compagnie Général de Géophysique". Their suggestions were extremely useful in the choice of the best possible locations for the exploratory drill sites, and the results of the first geothermal wells demonstrated the accuracy of their indications.

was entrusted to the joint-venture between the Greek "Hydrotechnic" and the French "Foramines".

More than two years later (precisely in July 1975) the first drilling, "Zephyria 1", was begun; it was terminated at 1101 m. Downhole measurements ascertained a pressure of 1375 PSI (over 96 atm) and a temperature of 309°C. Production began on 15 October 1975, but the well was closed after a few hours; a year later it is still closed. Therefore we have no reliable production data available. Our only certainty is that the well is productive and probably has a medium discharge. In 1976 the second drilling,"Adamas 1", was begun about 5 Km NW of the "Zephyria 1" bore. "Adamas 1" was terminated at 1163 m and put into production on 17 May 1976. Again a promising well was closed within a few hours and hence we have no production data; five months later it is still closed. Up to the present time (late September 1976) no decision to execute further geothermal drillings on Milos has been made by the Greek authorities concerned. Considering the remarkable success of the first two wells, the authors sincerely hope that drilling will soon be continued in order to ascertain the geothermal potential of Milos.

GENERAL DESCRIPTION

The island of Milos is located in the south-west region of the Cyclades at 36°44' latitude north and 24°25' longitude east; it is more than 150 Km SSE of Piraeus. Milos is the largest of a small cluster of minor islands whose areas are the following:

Milos - 151 Km^2

Kimolos - 35 Km^2

Polyegos - 17 Km^2

Antimilos - 8 Km^2

There are also some cliffs in the southern zone which will be described below.

The total population of Milos and Kimolos is somewhat under 6.000; the other islands are practically uninhabited.

In the central and eastern regions, where altered volcanic products and volcano-sedimentary products predominate, the morphology of Milos is that of fairly smooth relief. In the western part, an area with many volcanic domes, there are important elevations, the highest of which (Mountain of the Prophet Elijah) rises to 752 m. The island is very irregular in shape and the coastline is quite jagged, typical of a rapidly submerging zone.

The climate of Milos is temperate, of Mediterranean type; the mean annual temperature is slightly under 18°C. The average annual rainfall is 400 mm, three-quarters of which is concentrated in the winter months. The average humidity is rather high, somewhere around 70%.

GEOLOGY

The most recent monograph on the geology of Milos is that of R. Sonder (1924) who, being a volcanologist, did not treat in detail the non-volcanic formations. According to this author the following formations are found on Milos:

1) a Palaeozoic metamorphic series;
2) a transgressive conglomerate followed by a Cretaceous-Eocene limestone series;
3) a volcanic and volcano-sedimentary cover whose age is comprised between the Upper Pliocene and the Holocene;
4) scarce recent alluvial products.

R. Sonder included in his paper a rather imprecise small-scale geological map.

The age of the crystalline basement consisting of weakly-metamorphic schists was thought to be pre-Alpine since the overlying transgressive limestones showed no traces of metamorphism. The limestones were tentatively dated as Cretaceous-Eocene (D'Erasmo, 1924) on the basis of poorly preserved macrofossil molds.

In regard to the volcanic suites, Sonder distinguished five phases of activity. In the first two, dated as Lower Pleistocene, silica-rich products (rhyolites and dacites with a few andesites) were emitted; the age was determined on the basis of Calabrian fossils found in the tuffitic layers (D'Erasmo, 1924). It was supposed that the third phase was also relatively old, but characterized by the emission of more basic rocks, up to basalts. The fourth phase, more recent, according to Sonder produced andesites and andesitic breccias, while the fifth and last phase produced only rhyolites and rhyolitic tuffs.

The aforementicned author was not much concerned with pyroclastic products, and he considered as a terrace a curious formation extremely rich in schist fragments; this formation is often found intercalated in volcano-sedimentary products.

All the authors who have studied Milos more recently have accpted the geological scheme proposed by R. Sonder (1924). Only N. Liatsikas (1955), who described the mineral deposits of Milos, suggested some variations to the succession of volcanic activity established by Sonder. G. Vereadis (1958), who described some deposits, W. Wetzenstein (1969), who studied the genesis of the numerous bentonite deposits, C. Burri and G. Soptrajanova (1967), who dealt with lava petrochemistry, did not discuss the geological data. Even in the "Catalog of Active Volcanoes of Greece" G. Georgalas (1962) reports a description of the thermal manifestations without modifying Sonder' ideas; he also republishes the latter's simplified geological map.

Utilizing the new topographical map (scale 1:20.000) done for geothermal exploration by the I.G.S.R., one of the authors made a detailed geological map of Milos (Fytikas, 1976b). The results of this field work together with the laboratory work, are described in a detailed paper of M. Fytikas (1976a).

Milos and the minor islands are a part of the outer volcanic arc of the Aegean volcanic belt, which has a double-arc structure (Fytikas et al., 1975). This outer volcanic belt comprises the Kromyonia zone in western Attica, the island of Aegina (Pe, 1973), the promontory of Methana in eastern Peloponnesos (Pe, 1974), the islands of Milos and Santorini (Thera) in the Cyclades and the island of Nisyros in the Dodecanese.

All the volcanic activity which has so far been dated is Quaternary (Di Paola, 1974; Fytikas et al., 1975); two volcanic zones, Methana and Santorini, are still active (Georgalos, 1962). The historic activity of Nisyros is limited to powerful phreatic explosions (Keller, 1971; Di Paola, 1975). In the other volcanic areas, including Milos, there has been no true volcanic activity, but only some thermal manifestations.

The Aegean volcanic arc is located about 150 Km north of and is parallel to the so-called Hellenic sedimentary arc. This latter is located on the extensinn of the Hellenides and includes the islands of the Ionian Sea, the Peloponnesos, Kithira, Kriti, Karpathos, Rhodes, up to the southern Anatolian coast. To the south of this arc, at approximately 220 Km from the volcanic arc, there is a rather shallow trough (maximum depth 2270 m), called the Hellenic trench, which separates the arc from the Mediterranean ridge (Ryan et al;, 1971). This trench is assumed to be the present boundary between the converging African plate and Aegean microplate (McKenzie, 1972; Ninkovich and Hays, 1972).

The study of the seismic data of the Aegean region clearly indicates the similarity between the Aegean arc and the circum-Pacific arc-trench systems. It is therefore almost certain that under the Aegean arc there is subducted litosphere, for a maximum length of approximately 280 Km (Comninakis and Papazachos, 1972;

Papazachos, 1973).

The reflection and refraction seismic data (Finetti and Morelli, 1974) indicate that the crust beneath all of the eastern Mediterranean is of continental type. This means that the subduction of oceanic lithosphere at the Aegean arc may be considered almost complete, as a continental collision between the African plate and the Aegean microplate is taking place. The fact that there are still earthquakes along the subduction plane plus the spectacular compressive tectonics recently pointed out by seismic research (Finetti, 1976) however suggest that crustal shortening is still taking place.

This explains the limited volcanic activity of the Aegean arc, as well as the characteristic tectonics of Milos, i.e., a large number of faults with systems of varying orientation; none of these systems, however, is particularly important.

The island of Milos is made up of three main geological complexes: a crystalline basement levelled by erosion, a rather thin neogenic transgressive sedimentary series, and a Quaternary volcanic and volcano-sedimentary suite which covers the island almost entirely. With the exception of some cliffs located to the south of Milos, the other islands of the group are constituted exclusively of volcanic rocks. Small outcrops of volcano-sedimentary products are present only on Kimolos.

The metamorphic basement: - outcrops only in very limited areas on Milos. Many fragments, occasionally up to several tons, have been brought to the surface by phreatic explosions, and to a lesser extent, also by volcanic eruptions.

The almost ubiquitous presence of these xenoliths allows us to determine the homogeneity of the basement underneath the entire island. At the outcrops the metamorphic series appears strongly deformed, with narrow microfoldings; however it is impossible to reconstruct a dominant direction for this foliation. The contact with the overlying series, where it is visible, occurs on a perfectly flat, eroded surface.

The crystalline basement is made up of weakly metamorphosed rocks with greenschist facies, or more rarely blueschist facies. The predominant rocks are schists composed of quartz, muscovite and chlorite, with gradual transition to quartzites, calcischists or to originally arenaceous rocks rich in feldspar debris only partially transformed into albite. Taken as a whole this series, originally made up of a frequent alternances of clays, marnes, silts, cherts and gray-wackes, certainly represents a metamorphosed flysch sequence.

This series of sedimentary origin contains frequent layers which were originally basic volcanites and volcano-sedimentary products. They have now been transformed into prasinite (mainly epidote-albite-chlorite-calcite) chlorite-schist (mainly chlorite, quartz, actinolite, albite) or amphibole-schist (actinolite, chlorite, albite, quartz). The presence of schists composed almost exclusively of chlorite, quartz and a little hematite passing to chlorite-bearing quartzites suggests associations of basaltic hyaloclastites with red cherts, similar to that typical of the ophiolitic associations.

More rarely this volcanic and volcano-sedimentary series is metamorphosed in blueschist facies. Blocks of these rocks ejected from a volcano are mentioned by Vilminot and Robert (1974). The most frequent are glacophane-schist, assemblages of albite, glaucophane, epidote and quartz. Lawsonite and jadeite are commonly found in these schists, but the most characteristic (and often abundant) mineral is gedrite, a usually rare orthorombic amphibole.

There are no serpentinites associated with this series of metamorphosed basalts on Milos. However, on the nearby island of Ios we did find serpentinite lenses intercalated in a metamorphic complex very similar to that of Milos. Abundant and often large marble lenses are found intercalated in the metamorphic series on almost all the Cyclades islands near Milos. We cite Naxos, where there are blueschists as well (Jansen and Schuiling, 1971), Paros, Antiparos, Pholegandros, Sikonos, Ios and Santorini. On Milos there are no outcrops of this marble, but their presence in the metamorphic series is indicated by the occurrence of a few xenoliths brought to the surface by explosive volcanic eruptions.

With respect to the age of this metamorphic suite, the fact that we are dealing with a flysch intercalated with ophiolitic rocks leads us to suggest an Alpine age, probably Cretaceous, by analogy with similar flyschoid series of western Anatolia and continental Greece. Only one relatively significant datum is available. A sample of metamorphic graywacke contains chromite granules. This sandstone must therefore have been formed when the more-or-less serpentinized peridotites of the ophiolitic suite had already been displaced and emerged. On continental Greece this occurred in the Middle Cretaceous (Guernet and Parrot, 1972).

In regard to the age of the marble lenses, they may be of any age, since we are dealing with exotic blocks enclosed during the movement of the flysch nappes. Their age varies from the Carboniferous to the Jurassic. It is extremely likely that the ophiolitic suite enclosed in the flysch are those well-known of Upper Jurassic-Lower Cretaceous age. Older ophiolitic suites are not known with any certainty in the Mediterranean basin, even if several old geological papers dealing with Greece and western Anatolia mention ophiolites connected with Hercynian orogenesis.

Some radiometric dates of metamorphism are available. A K/Ar determination carried out on the glaucophane of the blueschist facies gave 64.2 m.y. while the muscovite of the greenschist facies gave 33.2 m.y.

(Fytikas et al., 1976).

Blueschists belonging to autochtonous or dislocated metamorphic formations have been found, as well as in the western Cyclades, also in Crete (Schubert and Seidel, 1972) and further north in the island of Syros (Dixon, 1972) and in Euboea (Guernet, 1972). This approximately north-south alignment of high-pressure metamorphic rocks suggests a paleosuture parallel in direction to the Hellenides, and hence not corresponding to the present geological situation (Auboin, 1973).

No detailed study has been made either of the distribution of blueschists in the much more abundant mass of greenschists, or of the relationship between these two metamorphic facies. Therefore we are unable to determine whether the infrequent blueschists are fragments of rocks affected by "subduction metamorphism" incorporated into the more superficial crystalline suites, or whether they are residual parts not transformed into greenschists because of the gradual rising of isotherms in the course of the evolution of the plate boundary. This type of study was, in fact, not considered necessary to the geothermal aim of our research.

In any case, the age of the blueschists (65 m.y.) indicates the beginning of the compressive phenomenon, and that of the greenschists (33.2 m.y.) indicates its end. This period of time is generally accepted for Alpine metamorphism, and therefore it is to this orogenesis, and not to the Hercynian one, that one must attribute the southwest Cyclades basement. The Alpine age of the crystalline basement obviously renders unacceptable the Cretaceous-Eocene age of the non-metamorphic transgressive series overlying the basement, as had been tentatively suggested by G. D'Erasmo (1924).

<u>The Neogene Transgressive Series</u> - In the southern and southwestern regions of Milos there are outcrops of the Neogene transgressive series overlying the metamorphic basement. In the southeastern outcrops, more recent volcano-sedimentary products lie directly over the metamorphic complex. The marine transgressive series either was not formed at all in this area because it remained emersed, or was formed but later completely eroded. No definitive evidence has been found to establish either hypothesis; however, the authors believe that the first is more likely, i.e. that the marine Neogenic transgression did not affect the highest parts of the island.

The presence of this sedimentary series below the volcanic cover is certain in the central part of the island, both because there is a small outcrop and because many blocks of Neogenic fossiliferous limestone have been ejected by huge phreatic explosions to the north of the village of Zephyria. This suite was also found at more than 700 m depth in the "Adamas 1" well, but is lacking in the "Zephyria 1", where the volcano-sedimentary suites lie directly over the crystalline basement.

The Neogenic transgressive series is composed of a conglomeratic part whose color ranges from grey to reddish and whose total maximum thickness is about 30 m. The suite is made up of irregular alternations of conglomeratic layers with pebbles having a maximum diameter of 20 cm (average 3-8 cm) and of layers of sandstone with small pebbles. The majority of the pebbles are quartzites from the underlying crystalline basement; schists are less frequent. The cement of the conglomerates is arenaceous and reddish, often impregnated with gypsum. Instead the sandstone layers are grey, rarely calcariferous, sometimes rich in gypsum both in small lenses and in veins. Some small conglomeratic layers are found intercalated in the overlying limestone formation.

The limestone part of the transgressive series, which has a maximum thickness of 150 m, is extremely varied in composition. Most prevalent are grey limestones in layers of 1 to 2 m, full of mollusk molds, mainly of bivalves. Occasionally the fossils are in such abundance as to constitute typical lumachels. These latter have the appearance of travertine due to the dissolving of bivalve shells without subsequently being filled with calcium carbonate during the diagenetic phenomena. Layers rich with coral and calcareous algae are less frequent.

Towards the base of the formation marly and arenaceous yellow limestones are prevalent, in thin layers of 20-80 cm. They also abound with microfossil molds, usually poorly preserved. There are many gypsum lenses and veins, especially in the lower part of the formation.

As stated above, this suite had been tentatively dated as Cretaceous-Eocene (D'Erasmo, 1924) on the basis of lamellibranch molds. However, a preliminary study of the microfossils (E. Patacca, pers. comm.), and particularly the presence of Elphidium crispum (Linné) indicates an age no older than Miocene. Another researcher (E. Mirkou, pers. comm.) has found some Sphaeroidinellopsis sp., microfossils which are typical of the Lower Pliocene.

This series of Neogene age does not contain any volcanic elements; furthermore it was already emersed and eroded when covered by the first volcanic products. This is an indication of the very young age of all the volcanic activity of Milos.

Volcanic Activity and Volcanic Products - Volcanic and volcano-sedimentary products cover the island of Milos almost entirely. Where visible, their thickness is often in excess of 400 m; in the "Zephyria 1"well 250 m were found and in "Adamas 1" more than 700 m.

Volcanic activity began on Milos between the Late-Pliocene and Early Quaternary. This age is certainly anterior to 1.5 m.y. determined by the K/Ar method (Fytikas et al., 1976) on an obsidian from Mt. Bombarda, a lava dome more recent than many tuff and tuffite outcrops on the island. Many indications, however, lead us to believe that it is no older than 3 m.y. We mention for example that the numerous macrofossils found in the oldest tuffites (D'Erasmo, 1924; G. Tavani, pers. comm.) all belong to living species. We also recall that, as previously stated, volcanic activity began after the emersion of the Neogenic suite, and, further, a recent age is in agreement with some general considerations on the age of all the volcanism of the Aegean arc and on subduction rate (Fytikas et al., 1976).

The reconstruction of the volcanic phenomena on Milos is extremely difficult and often impossible. The main reasons for this difficulty are intense disjunctive tectonics, which frequently caused tilting of many blocks, and deep hydrothermal transformations of a considerable part of the volcanic products, in particular the pyroclastics. Moreover it is still not known whether these products are all derived from volcanic activity on Milos itself. At least some of the pyroclastic deposits, in fact, could also derive from the nearby volcanic islands (Kimolos, Poliegos and Antimilos) or from the Anones cliffs (8 miles SSW of Milos). which we recognized as a volcanic center. Furthermore, the very abundant fine products could also derive from the island of Santorini or from even more distant volcanoes. A study of the provenance of such material was not considered essential for geothermal purposes, and in any case would be extremely difficult.

Volcanism began on Milos with important subaerial explosive activity, the products of which conditioned the paleomorphology of the island. These products consist of various types of pyroclastics, deposited both in a subaerial environment and in shallow sea. Among these products we find nice pumice flows, with huge pumices (over 1 m in diameter) and abundant pumice falls with a thickness often in excess of 15 m. The fine products (ash and volcanic sand) are more abundant, especially tuffites rich in macrofossils (mainly lamellibranchs and echinoids), which occasionally alternate with less abundant subaerial tuffs. The large quantity of very fine ash in the marine deposits has often produced characteristic and sometimes spectacular slumpings caused by fluidification under load. These slumpings, however, are always of limited dimensions which do not disturb the general regularity of the volcano-sedimentary deposits.

Above this suite there is a sillar-type ignimbritic episode, limited to the SSW area of the island. The paleosols are numerous, indicating frequent breaks in volcanic activity.

Numerous but rarely large lava domes and less frequent lava flows follow this explosive activity in the central and especially the western parts of the island. Each one of the effusive episodes appears to represent the end of a cycle of activity which began with the ejection of pyroclastic products. Only rarely (eg. the lava dome and the lava flows of Kastro, near the village of Plaka) does the effusive activity appear not to have been preceeded by products of explosive origin. Associated with the lava domes we often find breccias and typical nuée ardente deposits. Mudflows (lahars) are also common, but in general not of great extent. For a detailed description of the products of the explosive and effusive activity in various parts of the island we refer the reader to the paper by M. Fytikas (1976a) and to the geological map (Fytikas, 1976b).

Towards the end of this stage of activity a peculiar product was formed; it forms a layer extending throughout the island and was found in both the deep drillings as well as in several thermometric drillings. Since it is so widespread, this layer, which we have called "green lahar", has permitted us to make stratigraphic correlations which would otherwise have been impossible.

The green lahar forms a layer limited from both above and below by flat surfaces. It lies over volcanic products of various types and also directly over the totally flattened crystalline basement (Cape Spathi area in the southern region of the island). The green lahar is covered only by fairly recent volcanic products and alluvial deposits of the Zephyria plain.

The layer is generally only a few meters thick, but it can be as much as 60 m. The green lahar is made up of a chaotic mixture, without any trace of classation, of fragments of varying dimensions. Almost all of them are angular and show no trace of rounding phenomena; only rarely are they perfectly round. The average size of the fragments is approximately 10 cm, but they are occasionally much larger (up to 70 cm). The smaller fragments become mixed with the clayey-sandy mixture of the non-abundant cement.

Among the fragments, the greenschists of the crystalline basement predominate; blocks of lava and Neogenic limestones are less frequent. The rounded pebbles mentioned above are almost all quartzite and probably were a part of the Neogenic transgressive conglomerate. The components of the cement are, in part, smaller schist fragments and, to a lesser extent, volcanic ash. It is the schists of the cement which give the layer its characteristic green color.

The origin of this peculiar layer intercalated in volcanic formations has been reconstructed as follows. During the volcanic activity of the first period, what is presently the island of Milos extended further south with an elevation formed by a crystalline basement, covered by its surface disgregation products and, here and there, by conglomerates and transgressive Neogenic limestones. A residuum of this metamorphic elevation is represented by two small islands, Prasonis and Ktenia, now located to the south of Milos and both formed of crystalline schists. A violent, explosive volcanic eruption created a thick deposit of ash on this metamorphic relief, perhaps accentuated by an abrupt tectonic uprising. Rains after the eruption caused a mudflow (lahar) in which all the debris (consisting mainly of schist) was carried down the slope and distributed at the bottom over a wide area. This rather uncommon deposit would thus seem also to be an indication of an important tectonic phase of a very recent epoch, a fact which is significant for the convective circulation of fluids heated in depth.

After the formation of the green lahar the last volcanic episodes of Milos occurred. These led to the formation of the big Fyriplaka crater with its huge lava flows in the central-southern part of the island, and of the Trachylas volcanic center, to the northwest of the village of Plaka.

The age of Fyriplaka, determined by a K/Ar dating of the biotite of a rhyolitic lava, is 0.48 m.y. These two gigantic eruptions conclude the volcanic activity on Milos. Both are formed of perlitic products with rhyolitic composition but whereas the Trachylas crater is only minimally preserved, having been destroyed by several large lava flows, the Fyriplaka crater, placed directly on the crystalline basement, is very well preserved. Its internal diameter is 1.700 m while the height of its rim is only 220 m over the base. It is open towards the north where a large flow issued, followed by a gigantic lahar which partially filled the vast Gulf of Milos. The crater is made up of thin layers composed of perlitic lava blocks of varying dimensions (3-15 cm), associated with a much finer mass of small perlitic fragments. Both the shape of the crater and the appearance of the erupted material show a striking analogy with the hyaloclastitic deposits produced by the submarine basaltic volcanism (Tazieff, 1972).

We have no proof that Fyriplaka was formed by a submarine eruption; on the contrary, all the evidence points to a subaerial eruption. Probably this type of perlitic fragment similar to hyaloclastite derives from the intersection between rhyolitic magma and large quantities of water in areas near the surface phreato-magmatic eruption. We therefore consider the Fyriplaka eruption as further proof of high permeability due to fracturing of the crystalline basement of Milos.

From a magmatological point of view, the products of the volcanic activity of Milos fit perfectly into the spectrum of calc-alkaline magmas typical of island arcs. In fact, all the rocks which have been analyzed (Burri and Soptrajanova, 1967) belong to a low-potassium andesitic suite; their composition ranges from low-silica andesite (SiO_2=55.8%) to plagioclase-rich rhyolite (SiO_2=75.1%). No special evolution through time has been noted for the magmas of Milos. The initial pyroclastic products are certainly very silicic (from rhyodacite to rhyolite, as Sonder, 1924, had already observed); but they are followed immediately by materials both rich and poor in silica and the final products are the most silicic of the entire volcanic activity. All the volcanic products are strongly porphyritic. This fact indicates an important heat dissipation during the magma uprising to the surface.

Even though there are no strontium isotope determinations, all the chemical and petrographical data lead to the conclusion that the rocks of Milos belong to a differentiation trend of the same andesitic magma of deep origin.

No abnormal feature, such as the presence of peculiar xenocrysts or xenoliths of deep origin, was observed at Milos indicating significant interaction between the magma and the continental crust, as has been proposed for Santorini, on the basis of strontium isotope ratios (Puchelt and Hoefs, 1971) or, for example, for Kos, on the basis of the occurrence of melted crustal matter (Keller, 1969).

Such phenomena, important for geothermal exploration because they denote an important heat anomaly near the surface, are present on the islands near Milos. On Antimilos, for which there is only brief geological and petrographical description (Marinos, 1960), the authors found numerous lava flows rich in enormous quartz crystals (2 cm), associated with volcanic products of the classic andesitic suite. These rocks have a composition ranging from two pyroxenes low-silica andesite to pyroxene-biotite rhyodacite; they are lacking in K-feldspar and rich in microxenoliths. Petrographical observations strongly suggest that these large quartz megacrysts are xenocrysts. In fact, they do not seem to be in equilibrium with the liquid; in the more basic rocks they are surrounded by a clinopyroxene reaction rim, while in the more silicic rocks they are strongly corroded. Moreover, a very young flow which reaches the sea on the eastern side of Antimilos is constituted by two types of rocks, a low-silica andesite, black and without quartz xenocrysts and a more silicic dacite, light in color and rich in quartz. These two types of rocks are associated in the same flow as the streaks of "schlieren" in anatectic granites.

On the island of Kimolos, separated from Milos only by a few Km of shallow sea, the history of volcanic activity is characterized by a very violent explosive episode. This explosion brought to the surface abundant granite blocks, occasionally weighing several tons. They are very fresh rocks, rich in K-feldspar and with few mafic minerals (biotite and sometimes amphibole). The high-temperature optical character of the K-feldspar, the lack of pleochroic halo around zircons included in the biotite, the thick zoning of the plagioclase and a K/Ar dating attempt all suggest that these ejecta are part of a superficial intrusive massif. This stock seems to be connected to the calc-alkaline magma of the island arc, and hence very young.

The authors consider these two examples of Antimilos and Kimolos as clear indications of the presence of a vast and significant superficial thermal anomaly in the whole group of islands of which Milos is the most important.

<u>Alluvial Deposits</u> - These deposits are scarce and not very widespread on Milos. The most important accumulations are to be found on the Zephyria plain, in other more limited flat areas of the island and on the floor of valleys. With the exception of the Zephyria plain, where the deep drilling crossed some tens of meters of alluvium, these deposits are not very thick. This is due to the recent age of the volcanism, to the morphology of the island, to the scarcity of precipitation and to the permeability of the more superficial volcanic products. One must also recall that the island is in a stage of slow submersion and probably the greater part of the peripherical alluvial deposits are by now below sea level.

These deposits are mainly made up of products of volcanic origin. Fine materials, often converted into clayey minerals and sandy materials predominate over coarser products, permitting limited agriculture here and there. Since these deposits have no significance for geothermal exploration, they were not studied in detail.

<u>Tensional Tectonics</u> - It is clear that the rising of magmas in the volcanic belt of island arcs must be connected with disjunctive tectonics, which seems to contrast with the compressive regime related to converging lithospheric plates which provokes crustal reduction. Actually, at about 200 Km from the trench, where the volcanic belt is formed, large normal faults

with curved surfaces cause a sinking of blocks towards the trench. The rotation of these blocks is favoured by hydrostatic phenomena and may allow enormous quantities of magma to be introduced into the deeper parts of the crust; these decrease progressively towards the surface because of the narrowing of the faults (Marinelli, 1975). These masses may rest for a relatively long time without erupting within "thermal traps", represented by the wedge-shaped fissure of the tilted blocks. These conditions favour crystal fractionation because of heat dissipation and hence the rising of silica-rich and lighter residual liquids. The volcanic activity is connected to fractures transverse to the direction of the arc. In fact, it is reasonable to assume that along these fractures, present in all island arcs, there are no important vertical movements of contiguous blocks due to the lack of significant difference in weight.

The model roughly set forth here also explains the causes of the great possibilities of differentiation of calc-alkaline magmas and which may be observed also on the island of Milos. The stagnation of large masses of magma at a shallow depth, beyond causing local contaminations with the continental crust or even phenomena of contact anatexis, provides an acceptable explanation for the frequent, strong, localized heat flow anomalies of island arcs and cordilleras, and hence for the numerous geothermal fields which (like Milos) are located in the belts of active crustal reduction on the earth.

On the island of Milos one of the most important fault systems is precisely that WNW-ENE which in the north-western part of the island tends to change to E-W and which is parallel to the direction of the Aegean volcanic arc. This system, clearly observable only in the few outcrops of the Neogenic limestone series, controls the breaking of the basement into blocks with formations of horsts and grabens of limited extent. This tectonic trend can also be observed in the volcanic cover, where however more recent fault systems, with different directions, are more evident. Among these, the predominating one runs NNW-SSE practically orthogonal to the first; its fractures probably fed the magmatic activity.

The system parallel to the Aegean arc seems to have caused a tectonic high of the basement all along the southern part of the island. Along this zone, in fact, the crystalline basement outcrops; also the two islets of Prasonisi and Ktenia (which emerge to the south of Milos) are formed of basament rocks.

The deepening of the basement towards the north was confirmed by the geoelectrical survey carried out in the central-eastern part of Milos by the "Compagnie Générale de Géophysique". The two productive drillings also indicate the same phenomenon: "Zephyria 1", located more to the south, reached the basement at -240 m below sea level, while at "Adamas 1", more to the north, the basement was reached at almost -650 m below sea level.

Tectonics normal to the arc are instead responsible for the elevated position of the basement in the central part of the island; this is exactly the opposite of what it would seem to be on superficial observation. The central part is in fact morphologically depressed and, in the northern part, at the center of Milos the beautiful, large Gulf of Adamas opens up. This orthogonal system is very young, and often there are very recent fractures which are imposed on older ones, particularly in the central and eastern parts of the island.

A less important ENE-WSW system of fractures was also revealed by the geoelectrical survey. The NW-SE direction is still less diffuse, and was not revealed by the geoelectrical survey. It is possible that this system is connected to the rejuvenation of old faults of the crystalline basement which are common to the entire Pelagonian zone of which Milos is a part.

These four fault systems determine a breaking-up of the basement and overlying series into fault-blocks which can be very small. Some of them (e.g. that made of crystalline rocks outcropping ENE of the village of Zephyria) are so strongly vertically dislocated as to suggest possible local weight adjustments on underlying lighter viscous masses. A similar phenomenon has been described in the geothermal region of

Larderello in Italy (Marinelli, 1969).

This particular disjunctive tectonic style caused the formation of the Zephyria plain, the only large depression on the island which resembles a graben, with an almost meridian direction. A true small graben is that of the Isthmus of Probatos. No trace of recent folding phenomena was observed on Milos.

The oldest disjunctive tectonics of Milos almost certainly took place in the Lower Pleistocene; it corresponds to the "Walachian phase", known in almost all the Aegean islands. These tectonics must have determined continuous and independent uprising and sinking of individual blocks. Only such movements can explain, in fact, the alternation and horizontal discontinuity of the volcano-sedimentary products deposited in the sea and of the subaerial products. The most recent tectonics, i.e. those successive to the emplacement of the green lahar, must have instead led only to a progressive lowering of the whole island with the sinking below sea level of the southernmost areas. This lowering of the island has continued into historic times, as clearly demonstrated by the discovery in many places, especially within the Gulf of Adamas, of ancient buildings down to 5 m below sea level.

Moreover, direct proof that the island of Milos is located in a region of active tectonics is given by its earthquake activity. Twenty odd important (even if not disastrous) earthquakes have been described from

1738 to the present; but certainly no trace has remained of many others, given the dearth and fitful character of local chronicles. In 1918 an earthquake with magnitude comprised between 2.8 and 4.8 (Drakopoulos and Delibasis, 1975) razed many houses and opened new fumaroles. In 1971 there has been a seismic crisis lasting five days with an average of 13 shocks per hour with a very superficial hypocenter (about 5 Km), a "b" value of 1.2 and M_2=2-3 (Drakopoulos and Delibasis, 1975). The most recent important seismic episode occurred in 1975, apparently of the same type as that of 1971 (N. Delibasis, pers. comm.).

Volcanism mainly connected to isolated eruptive episodes, of both central and fissural type, and the consequent lack of complex large volcanic centers are probably the cause of the lack of important volcano-tectonic events on Milos. No trace either of calderas or of sector-grabens was observed on the island by the authors. The large Gulf of Adamas, considered a caldera by some writers, is actually only the result of the lowering of fault-blocks. The gentle slope of the coast and of the isobaths, the total lack of faults with curved rims and the very irregular shape of the gulf exclude that it may be related to a caldera collapse.

The dense network of fissures and faults in the crystalline basement caused by recent and still active disjunctive tectonics is an extremely important clue for the existence of a geothermal field. These vertical fissures, in fact, permit convective circulation of fluids heated at depth, creating a sharp rising of the isotherms. Furthermore, continuous tectonic activity prevents "self-sealing" phenomena (Facca and Tonani, 1964, 1967) from interrupting this circulation. Tectonic phenomena in fact may either reactivate circulation in sealed fissures and open new fissures.

ACTIVE THERMAL MANIFESTATIONS

Active thermal manifestations are numerous on the island of Milos, but they are all small. They may be divided into fumaroles, hot springs, and hot grounds.

Many of these manifestations were already known, while others were located by the authors through accurate and detailed research. The main subaerial manifestations are shown in the geological sketch included in the appendix and on the geological map of the island (Fytikas, 1976b).

There are many fumarole fields, but they are all small in size and discharge. They are found especially in the central-southern part of the island, where the volcano-sedimentary cover is thin or lacking. In fact, the most important come out of rhyolitic domes (Vunalia, Kalamos, Agrilies) or out of fractures in the crystalline basement, covered by a few meters of pyroclastic products (Aghia Kyriaki, Pyromenes, Palaeochori). In all these places the temperature of the fumaroles ranges from 98°C to 102°C. Other weak emissions in areas where the volcano-sedimentary cover is thicker are found at

Kastanas (86°C) along a fracture on the rim of a phreatic explosion crater, and at Chazou Thiafin (100°C), NE of Adamas. Besides steam, the fumaroles also emit CO_2 and H_2S which oxidizes, depositing acicular sulfur.

The thermal springs are relatively numerous, but with small flow. Almost all of them come out on the coast, slightly above or below the level of the sea. Their temperatures vary from 30°C to 75°C but the measurements are often inexact because of the bad isolation from seawater. Many wells dug on the island contain drinking water at a temperature higher than the average annual temperature of the island.

No hydrogeochemical survey was carried out on Milos. Even though this type of research is almost always extremely significant for geothermal exploration the authors felt it was not necessary for the preliminary exploration of Milos. Old analyses and some recent data indicate that all the thermal waters of Milos are salty, with a salt content always less than that of seawater.

Hot grounds are also frequent on the island of Milos and, unlike the fumaroles and hot springs, were almost unknown. They are to be found inside the large Fyriplaka crater, in the southern part of the island, on the Zephyria plain, along the eastern coast and near Adamas. Many dry mining tunnels have hot walls as well. The maximum temperature measured in these hot grounds (placing the thermometer at a depth of 30-40 cm) is 100°C.

Other thermal manifestations are submarine gas emissions, very widespread around the island. No systematic study was made on them, but it is known that they are very frequent in the Gulf of Adamas and near the southern coast, especially near the Kalamos rhyolitic dome. It has often been ascertained that this gas is hot (or perhaps associated with submarine hot springs), but the authors did not believe it necessary to complete detailed studies on this type of manifestation.

Systematic and accurate search for manifestations, temperature measurements and the study of geological causes which brings them to the surface were considered important for a preliminary evaluation of the geothermal potential of various parts of the island. But different considerations, especially regarding the thickness and impermeability of the cover, determined the choice of the drilling sites. So both "Zephyria 1" and "Adamas 1" were drilled in zones completely lacking active or fossil thermal manifestations.

FOSSIL THERMAL MANIFESTATIONS

On the island of Milos in recent times a very important and widespread hydrothermal activity has developed. This activity has led to the formation of numerous mineral deposits, both by the transformation of already existing products and by the deposition and concentration of new phases.

Hydrothermal action is extremely widespread on the island; its most noticeable effect is the transformation of all volcanic products, but especially the pyroclastic series, into clay minerals. The nature of phyllosilicate which is formed is clearly controlled by the chemical environment, and not by the composition of the magmatic products.

While the intensity of the transformation varies in function of the type of volcanic product (scarse in lava domes, maximum in vitrous ashes), the stable phase of phyllosilicate is a direct function of the pH of the hydrothermal solutions.

In deeper environments the alkaline nature of the solutions is responsible for the "bentonitization" of the volcanic rocks, i.e. the transformation first of glass and groundmass and then of phenocrysts into almost pure montmorillonite (Franzini et al., 1963). In a recent paper W. Wetzenstein (1971) maintains that this transformation into bentonite took place under the sea, and that therefore the phenomenon is connected with an episode of general subsidence of the island. Aside from the fact that the stratigraphic studies carried out by one of the authors (Fytikas, 1976a) tend to exclude the presence of submersion episodes affecting the whole island, there is absolutely no need to go under sea water to obtain bentonite deposits by hydrothermal action on volcanic products belonging to the calc-alkaline suite. In this regard, it is sufficient to recall the occurrence, in the northern part of the island, of numerous tuffitic layers rich in macrofossils which are transformed into kaolin and not into montmorillonite. Moreover, in all the numerous zones of mineral exploitation it is possible to observe a sharp passage between the lower bentonitic zone, light-green in color, and the upper kaolinnic zone, white with red veins (Voreadis, 1958). This passage is clearly linked to a hydrostatic level, which coincides with the mixture of hydrothermal solutions with oxygen-rich ground water. The oxidation of H_2S to H_2SO_4 sharply lowers the pH of the solution stabilizing the kaolin instead of the montmorillonite. The veins and the impregnations of poorly-hydrated (and therefore red) iron hydroxides suggest that the transformation process did not occur under the sea.

Besides kaolin, the oxidation of H_2S determined the formation of abundant alunite and occasionally also small impregnations of sulfur. Sometimes the oxidation of H_2S led to such low pH levels as to remove as sulfates all the metals of the volcanites. The residue, consisting of white silica similar to geyserite, is exploited especially in the western part of the island. The numerous small deposits of barite, resulting from the concentration of the small quantities of barium in the volcanites, probably also owe their origin to the sharp increase in activity of the sulfuric ions which reduced the solubility of barium sulfate. Together with barite small quantities have been found of galena, anglesite and other minerals (Liatsikas, 1955). A rather peculiar deposit is located in the extreme NW of the island. It is a rhythmical hydrothermal deposit of barite and manganese minerals (mainly hollandite, a Ba-bearing MnO_2) in a pyroclastic series sedimented in the sea.

It is difficult to determine at what temperature these equilibria of hydrothermal phases were formed. Probably at the beginning it was somewhere around 100°C. As the hydrothermal transformations reduced by "self-sealing" the high permeability of the volcanic and volcano-sedimentary products, the cover acted more and more as isolation between the deep circulating fluids and the more superficial ones. Thus a slow and progressive rising of the isotherms took place. Of this we have convincing and spectacular proof: phreatic explosions.

PHREATIC EXPLOSIONS

This term refers to all those explosions caused by the pressure of fluids of superficial origin in which there is no intervention of magmatic gases. These explosion craters vary in size (up to 2 x 1.5 Km for the explosion of 1933 in the Pematang Bata Valley in southern Sumatra, Indonesia; Neumann van Padang, 1951) and eject only old material (of volcanic or other origin) without ever expelling fresh magmatic material. In the aforementioned eruption of Pematang Bata besides the gigantic 2 x 1.5 Km crater, another was formed of 1 x 0.75 Km and a hundred odd smaller ones in an area of 5 x 1.5 Km. The volume of the ejected material (mud and stones) was 0.21 Km^3

i.e. much more than that of an effusive volcanic eruption such as that of Kilauea in 1959 (0.15 Km^3). These data are set forth in order to make clear that phreatic explosions, not caused by contact between magma and ground waters (and hence called "hydrothermal explosions" by Muffler et al., 1971), can be very powerful and produced by fluids under high pressure and hence at a very high temperature.

A phreatic explosion takes place when the lithostatic load of an impervious cover becomes lower than the boiling pressure of the hot water of a reservoir. The lowering of the temperature of the fluid during the explosion due to adiabatic expansion is in part restored by the heat of the solid products which are mixed with the steam (Goguel, 1975). An extremely simplified example of this phenomenon is the following. Below an impervious cover 400 m thick (2.5 x 40 = 100 Kg/cm^2 of lithostatic pressure) a reservoir of pure water can reach a temperature of only 309.5°C (boiling pressure: 100 Kg/cm^2). If the temperature is higher, water flashes to steam and the cover explodes, forming a conic crater whose rim is made up of ejected debris. At the bottom of the crater the pressure becomes practically nil, and the deeper parts of the aquifer can explode, forming an irregular cylindrical deepening of the bottom of the conic crater.

These successive explosions often assume the intermittency and aspect of geyser eruptions discharging mud and rocks. After the first explosion the geyser-type explosive activity does not modify the diameter of the crater but increases the rim-deposits and may last for a rather long time. In the above mentioned phreatic activity in southern Sumatra (Pematang Bata) the explosions lasted for 27 days. In the Aegean island of Nisyros, a cycle of phreatic eruptions began in October 1871 and ended in October 1873 without any significant interruptions in the course of these two years (Gorceix, 1874).

This simplified model does not take into account several important factors, such as the cohesion of the cover, the salinity of the water and the quantity of water near the top of the reservoir (this depends on the permeability of the aquifer and controls the possibilities of explosion). Moreover, it does not take into account the fact that a total formational impermeability is unacceptable in region which, like geothermal fields, are all tectonically active. The deep circulation fluids are therefore subject to a hydrostatic pressure which is much lower than the weight of the overlying suites of rocks. The steam phase may thus be present in the reservoir before a phreatic explosion takes place.

The authors believe that there are two ways of arriving at the bottom of the impervious cover, at the fluid temperature necessary to cause a phreatic explosion. The first is related to the transformation previously described for the volcanic and volcano-sedimentary formation of the cover of Milos. We are dealing with progressive phenomena of self-sealing which renders the cover impervious, isolating the convective circulation system and thus creating a gradual uprising of the isotherms. In such conditions phreatic explosions will take place only in a specific period of the geological evolution of the hydrothermal system. Later the system becomes stationary, at least for a geologically brief time (of the order of tens of thousands of years) in which no significant variations will occur in the heat flow of the area.

The second model is instead linked to an already existing impervious cover and to active tectonics. A seismic crisis may suddenly open up an important system of fractures in a reservoir with scarse vertical permeability. A rapid rising of very hot fluids from deeper zones will then take place. If these fluids arrive on the top of the aquifer at a temperature such that the boiling pressure is higher than the lithostatic pressure, then a phreatic explosion will occur.

The authors believe that this second model is much more common than the first. For example, the previously cited phreatic explosions at Pematang Bata on Sumatra and on Nisyros in the Aegean were both preceeded by violent earthquakes.

A third model for phreatic explosions has been proposed by J. Goguel (1953, 1975). The water table of the aquifer can be lowered either because of an overly-intense exploitation of a geothermal field (as is happening at Larderello, Italy) or for natural causes (for example the river erosion which lowers the water table in a plain). The total weight of the cover then diminishes and may cause an explosion. No phreatic explosion of this type is known and the authors feel that it is highly improbable.

A comparative study of many phreatic explosions described in the literature has led the writers to believe that one can roughly correlate the diameter of the crater (not the diameter at the top of the rim) of a phreatic explosion with the depth at which the explosion took place. Once the depth is known, it is easy to calculate the fluid temperature necessary to obtain the explosion pressure.

This utilization of phreatic explosions as thermal indicators in geothermal exploration must be employed with great care and requires very accurate knowledge of local and regional geology.

In the case of the first type of explosion described (self-sealing phreatic explosion) the form of the crater usually approximates that of a reversed equilateral cone (i.e., having an angle of 60° at the vertex). The depth of the explosion should therefore be equal to $\frac{\sqrt{3}}{2}$ d, that is inferior to the diameter by a little more than 10 percent.

For the second type (earthquake phreatic

explosion), the depth depends to a large extent on the network of fractures. If there are many of them, and if the impervious cover is formed of weakly-cohesive rocks, the explosion takes the shape of the trunk of a cone. The crater therefore is flat on the bottom and the depth of the explosion may be less than half the diameter of the crater. If, on the other hand, there is only one fracture and the impervious cover is made up of strongly-cohesive rocks, the crater will tend to have the shape of a pipe, and will have a diameter much smaller than the depth of the explosion.
While in the first model the estimated temperature should correspond to that found at the top of the reservoir, in the second model all we know is that fluids of that temperature are located in depth.
There are no means to evaluate from what depth these fluids have risen. However, if we accept the classical model of convective circulation (Goguel, 1953, 1975), the gradients in the reservoirs must not be very high. Consequently the temperature at the top of the permeable formation will be lower, but not much, than that calculated by studying the craters of phreatic explosions.

Since their age is usually unknown, one might wonder whether these craters represent thermal conditions which existed in the past, but which no longer exist in the present. The authors think that this is highly improbable. The products of phreatic explosions (mainly mud with varying quantities of larger material) are not cemented and must have a very short life, so brief as to be shorter than the time necessary for significant variations in the heat flow anomalies of the area and in the gradient anomaly of the site. In other words, the evidence of phreatic explosions should disappear before the thermal anomaly is attenuated.

Regions which have been desert for long periods of time and where erosive action is hence very limited, perhaps must be excluded from these considerations. We mention in this regard the Danakil Depression in Ethiopia where there is a perfectly preserved phreatic explosion crater whose rim is formed of blocks of salt (Marinelli, 1971).

On Milos phreatic explosions are numerous. The most characteristic group is that found to the east of the Zephyria plain and made up of several tens of small craters having a maximum diameter of 20 - 25 m.

These craters are extremely close to one another and occasionally intersect; seen from the air they have a very characteristic lunar appearance. The ejected products are made up almost exclusively of rocks from the cover series deeply transformed into kaolin and silica. Other small-diameter craters are scattered here and there throughout the island.

The most important group is located to the west and north of the Zephyria plain and includes three large craters having a diameter of several hundreds of meters. The largest of these, Archendimic, apparently represents a group of adjacent craters whose original borders cannot now be reconstructed because the single rims were partially destroyed in successive explosions.

The best preserved of the three is Tyrogalas, which has a diameter of about 600 m; the rim is over 40 m above what was the ground level before the explosion. In the rim we have found not only fragments of lavas and more or less transformed pyroclastics of the impervious cover, but also blocks of Neogenic limestone and of the crystalline basement. Given the huge dimensions of some of these blocks (more than 10 m^3) it is inconceivable that the metamorphic material and that of the Neogenic suite were part of the green lahar and not ejected from their normal stratigraphic positions.

According to our rough estimates, the explosion which formed this crater should have occurred at about 500 m depth and therefore (assuming for the transformed volcanic cover material an average density of 2) under a lithostatic load of approximately 100 Kg/cm^2. According to Mollier's Curve the boiling point of pure water at 100 Kg/cm^2 is approximately 310°C. Astonoshingly close to this are the downhole temperatures measured by extrapolation for the "Zephyria 1" (309°C) and "Adamas 1" (308°C) production wells.

THERMOMETRIC BOREHOLES

On Milos 48 shallow boreholes were drilled, and a further 15 already-existing bores were utilized for temperature measurements. The authors wish to stress their preference for the term "thermometric boreholes" as opposed to "gradient boreholes", because generally in these wells it is not the gradient which is measured but rather the degree of our ignorance regarding superficial circulation of hot or cold water.

To realize this more clearly, one needs only to extrapolate two of the results of the boreholes (see the tables in appendix); no. 58 at 1000 m depth would give 95°C, while no. 63 at the same depth would give an absurd 1400°C. And it seems entirely useless to use a curved extrapolation line. If by using this trick we can make the temperature of no. 63 at 1000 m reasonable, the temperature of no. 58 will automatically become absurd.

Our shallow boreholes had a different goal. The first was located in a "hot ground" near the village of Adamas in hopes of obtaining steam production at a shallow depth. This actually happened (steam and water at 138°C at 72 m depth) and allowed the authors both to receive greater trust from the Greek authorities and to obtain useful information on the composition of the underground fluids. Well no. 1 produced almost equal quantities of steam and water from a casing with 3' of internal diameter. Two months after opening, the discharge of water alone was 760 liters/h, while the pressure at closed well was 3.8 Km/cm^2. The detailed chemical data of this well, completed in different periods, are reported by Dominco and Papastamaki (1974). A preliminary isotopic analysis indicates that this fluid consists in originally meteoric water partly equilibrated with the oxygen of silicate or carbonate rocks (Stahl and Anst, 1973).

Even though this well was very encouraging, it also created some concern. It had only 15 m of non-cemented casing, and it continued to eject fine debris.

After two months the ground around the well began to cave in slightly, fissures opened up and small fumaroles appeared. The probability of formation of a cavern at only 15 m depth was high and, with a pressure of 3.8 Kg/cm^2, a phreatic explosion also became extremely probable. The well was left open and the sinking of the terrain was compensated by many tons of gravel placed in the depressed area around the well. Six months later, as the sinking was still continuing a diagonal well was drilled through which 4 tons of cement were injected, plugging the pioneer borehole almost completely. The amount of cement utilized demonstrated that the hypothesis of an underground cavern was realistic and that a serious risk had unnecessarily been run leaving the hole open for six months.

Naturally in all the other boreholes perforation was stopped when a downhole temperature of 80°C was reached in order to avoid possible dangerous steam leakage. Casings were introduced into the drillings only when necessary for the stability of the walls.

The thermometric measurements were carried out with a thermistor every 10 m. As may be seen on the map (see appendix) these boreholes were not located on a statistical basis. Aside from morphological considerations, those sites were selected which offered the greatest geological interest (thermal control of the cover thickness, presence of hot superficial aquifers, etc.). Moreover, the boreholes were concentrated in the central and eastern parts of the island, which offered geological conditions more favorable for finding geothermal resources.

The petrographic study of the cuttings and of the few cores (taken when circulation loss precluded cuttings) made the thermometric boreholes very useful for a stratigraphic control of the volcano-sedimentary series.

Given the high temperature found in almost all the boreholes, both the dry ones (about two thirds) and those containing water, more sophisticated research was considered unnecessary for geothermal exploration. In several wells the temperature measurements were repeated six months later with almost exactly the same results.

The lack of sharp temperature variations in the boreholes, in particular the lack of irregularity such as the occurrence of a lower temperature at deeper levels compared to upper lelvels, suggests that there is almost no fluid circulation in the cover series. Therefore this series should be considered impervious even in those areas where hydrothermal alteration phenomena are less widespread.

Assuming in first approximation the imperviousness of the cover and rejecting for theoretical reasons the possibility that there may be significant lateral variations of heat flow on such a small island, it would seem logical to assume that the slope of the thermometric curves of the boreholes is controlled by the thickness of the cover. The geoelectrical survey confirmed this hypothesis.

THE GEOELECTRICAL SURVEY

The results of the mainly geological studies carried out as the first stage of the geothermal exploration of Milos gave clear indications for the occurrence in the island of favorable conditions for the presence of geothermal fields. However, detailed information was lacking on the tectonics of the basement and on the thickness of the impervious cover. These data were indispensable for the correct siting of the deep exploration wells and it was impossible to obtain them only from field observations in those areas where the cover is thickest, which are the most interesting for geothermal exploration. Some faults of the basement were in fact undoubtedly hidden by the cover, especially by the green lahar and by the most recent products of volcanic activity.

A geoelectrical survey was then set up as being, in the authors' opinion, the most effective and economical means of obtaining the desired information. A considerable contrast could be expected between the more resistive basement and the volcanic and volcano-sedimentary cover altered and therefore conductive. This geophysical method could also confirm the already known thermal variations within the cover.

The geoelectrical survey was carried out only on the central and western parts of the island (the most promising geothermal prospects) and gave very useful results (Duprat and Fytikas, 1976). We obtained in fact fairly precise indications for the top of the substratum, without however being able to establish if it was made up of the crystalline basement or of the sometimes overlying Neogene limestone series. Good indications were also obtained on the location of faults and this has been very useful for determining the site of the deep exploratory wells.

PRELIMINARY GEOTHERMAL EVALUATION

Before selecting the best possible sites for deep exploratory wells, it was necessary to check whether the geological and economical conditions were favorable to the continuation of the geothermal research.

Geology and economics are closely connected in a small island like Milos. At present, in fact, in spite of numerous mines and mining plants, the required power now is less than 5 MW, that projected for the near future is much less than 10 MW. Hence a certain doubt was justified as to whether it was worthwhile to begin the expensive part of the geothermal exploration program for such a low energy consumption. At the same time, the small size of the island made questionable the possibility of reaching a production which would justify the exploration expenses and above all the risks connected with the uncertainty of the underground research.

Several conditions however led the authors to the conviction that as a whole the conditions were favorable. Milos has a large, well protected gulf which is an excellent natural port. This would facilitate the establishment of an electrochemical industry (e.g. soda-chlorine production, alumina or aluminium factory). The much lower kWh price offered by a geothermal power plant compared with that of a conventional or nuclear power plant should be sufficient to justify a similar installation.

As to the amount of geothermal energy available on Milos, the rainfall (400 mm/year) is sufficient to resupply an important geothermal field, assuming that the recharge takes place where the cover is thin. Even assuming that of the 60,000,000 tons of rain which fall each year on Milos only one sixth penetrates to the subsoil (i.e., one half of the generally accepted estimate) the rainfall would be sufficient to recharge more than 20 wells producing 50 tons/h steam. This estimate of total utilization of water which penetrates to the subsoil is obviously exagerated, but the partial mixing with sea-water would increase the amount of subterranean fluids available. It should be kept in mind, in fact, that the disjunctive tectonics which control the fluid circulation certainly extend to the floor of the sea surrounding Milos. This is particularly important to the south where the crystalline basement probably outcrops on the sea floor. Furthermore, the surface area of Kimolos (35 Km^2) must be added to that of Milos (151 Km^2), since it is very close and also shows favorable conditions for the production of geothermal energy.

Our assessment of the situation was shared by the Greek authorities, and the Public Power Corporation decided to effect some deep exploratory drillings on Milos.

SELECTION OF DRILLING SITES

The results of the exploration stage described in the preceeding sections led to the selection of 4 sites for deep exploratory drilling. Three of them were located in the Zephyria plain and one to the NE of Adamas. The geological reasoning behind these choices is as follows, keeping in mind that the selection was effected by exclusion, i.e. the rejection of those areas which seemed less favorable for the lack of one or more of the prerequisites for a geothermal field.

First of all we considered the volcanic cover. It may lack in some place or it may be present, but not impervious. For this reason we rejected those southern and southwestern areas of the island where the basement or the overlying Neogene limestone series outcrops. These areas are perhaps not entirely negative, due to the scarse formational permeability of the weakly-metamorphosed schists, but they are certainly not among the best.

We then excluded the entire western zone of the island. Here self sealing phenomena in the cover are comparatively less important than in the rest of the island, and moreover there are a great many recent lava domes. These domes are extrusions of very viscous magma which pierce the impervious cover entirely. Since cooling causes a diffuse lava fracturing, the domes represent an important way for percolation at depth of cold surface waters.

We then discarded the areas in which the cover is present and impervious, but too thin. This is the case, for example, of the area to the east of the village of Zephyria in which the largest group of phreatic explosion craters is located. The small diameter of these craters (10 to 20 m) suggests a cover thickness of a few tens of meters. The absence of blocks of deep provenance (schists and Neogene limestones) among the products ejected by these phreatic explosions suggests convective circulation in the aquifer due to scarse fissuring or to self sealing in the fissured zones.

We further rejected all those areas with active superficial manifestations, as this is also an evident indication of a localized lack of imperviousness. Also in the central and eastern parts of the island we discarded all the areas where lava domes outcrop and obviously those areas where we had no information at all (e.g., the northern tip of the island, completely covered by large lava flows of perlitic rhyolite).

This first evaluation left us with a most promising area of only about 30 Km^2. On this we continued the progressive reduction, utilizing other data, especially tectonic ones (importance and recent age of faults determined from photogeological study and ground check and results of the geoelectrical survey). We further utilized data on the top of the substratum, also obtained through the geoelectrical survey, and data from the thermometric boreholes. We thereby reduced the 30 odd Km^2 to about 12 Km^2, 8 on the Zephyria plain and 4 just to the east of Adamas.

The Zephyria plain offers a high of the substratum (top at 250 - 300 m beneath the ground level) and has a cover made exclusively of volcano-sedimentary products without any volcanic centers. The cover is clearly very impervious, as indicated by the lack of superficial manifestations, very low values of the apparent resistivity and the thermometric data with high downhole temperatures and regular thermoemtric curves.

The Adamas zone shows the same characteristics as the Zephyria area, but rather more attenuated by the fact that the cover thickness is greater (500 - 550 m below sea level). Moreover, thermometric holes no. 1 produced water and steam with 138°C at only 72 m.

None of the geological or geophysical techniques used had given any information on the permeability of the reservoir. The best reservoir would undoubtedly be offered by the transgressive Neogene series, but there was no way of knowing whether or not this is present below the cover. Beneath the Zephyria plain we could reasonably hope to find this formation because of its occurrence in the nearby area of powerful phreatic explosions. But there was no information available for Adamas. The deep exploratory drillings actually found this series at Adamas and not at Zephyria.

If the Neogene limestones were not present, one might hope that the drilling would reach some of the marble lens present within the metamorphic basement, or a layer of calc-schist or quartzite. These metamorphic products, being competent rocks within incompetent schistose levels should be greatly fractured and therefore could form a fairly good reservoir.

Since these latter formations are lentiform and hence have no horizontal continuity, it was however deemed more prudent to site the drillings near important faults.

Following these criteria and utilizing the geoelectrical data, three sites in the Zephyria plain were selected, of which only one was drilled. In the Adamas region, however, beyond the aforementioned criteria we also kept the drilling at some distance from the inhabited area, in order to limit to a minimum any possible damage from a drilling accident. An area almost

100 m above sea level was selected to preclude the risk that steam production at shallow depth might spoil the perforation.

DEEP EXPLORATORY DRILLING

Since the Public Power Corporation agreed to effect two deep exploration drillings, it was decided to do one in each of the two promising areas. For the Zephyria plain the most central of the three possible locations was chosen. Here, in order to avoid the risk of steam at shallow depth, a borehole (no. 56) was drilled; at 80 m depth 93°C were found. The hole is located about 1 Km NNW of the village of Zephyria near a N-S fault. After about 260 m of cover, the drilling reached the crystalline basement, unfortunately without finding the transgressive Neogene limestone series. Down to about 800 m the metamorphic series was found almost everywhere to be poorly permeable; at lower depth circulation losses occurred in calc-schist and quartzite layers (Fytikas et al., 1976; Gounaris et al., 1976). This well, called "Zephyria 1" was stopped at 1101 m and was put into production on 15 October 1975. After about 12 hours of discharge the well was closed. It was opened again for a few hours some days later, and then closed up to the present time (30 September 1976).

The second well was drilled in the Adamas area. The selected site is located about 5 Km from "Zephyria 1". It crossed about 720 m of the cover series before reaching the Neogene limestones. At 750 m the circulation loss was complete, hence data are not available. Only at about

1000 m depth were fragments of the crystalline basement observed. The drilling was terminated at 1.163 m (Fytikas et al., 1976; Gounaris et al., 1976). This well, called "Adamas 1", was put into production on 17 May 1976. After about 12 hours it was closed and up to now (30 September 1976) has not been reopened. Even though specific data are not available, it is likely that this well, having found a good reservoir, is far superior to the first.

CONCLUSIONS

The geothermal exploration of the island of Milos cost the Greek authorities a few drachmas and the authors of this paper a great deal of work. The geological studies have been explained in detail also to try to show their great utility in geothermal exploration, as they provide important information at a low cost.

Unfortunately this type of preliminary study is often neglected in geothermal exploratory programs, perhaps because it is believed that they take too long for dynamic times such as ours. In Greece geothermal research began correctly, even if not without some difficulty, and the authors hope that it will be continued both on Milos and in other areas of the country showing similar favorable conditions.

A great many people in Athens, Milos and Pisa helped us with this research; we gratefully thank them all without being able to name them individually. We wish however to express our special thanks to P.E. Gounaris,

former Director of the Geothermal Department of the Public Power Corporation; his enthusiasm, his "savoir faire" and his perhaps somewhat less-than-methodical activism were determining factors in the success of the geothermal exploration of Milos.

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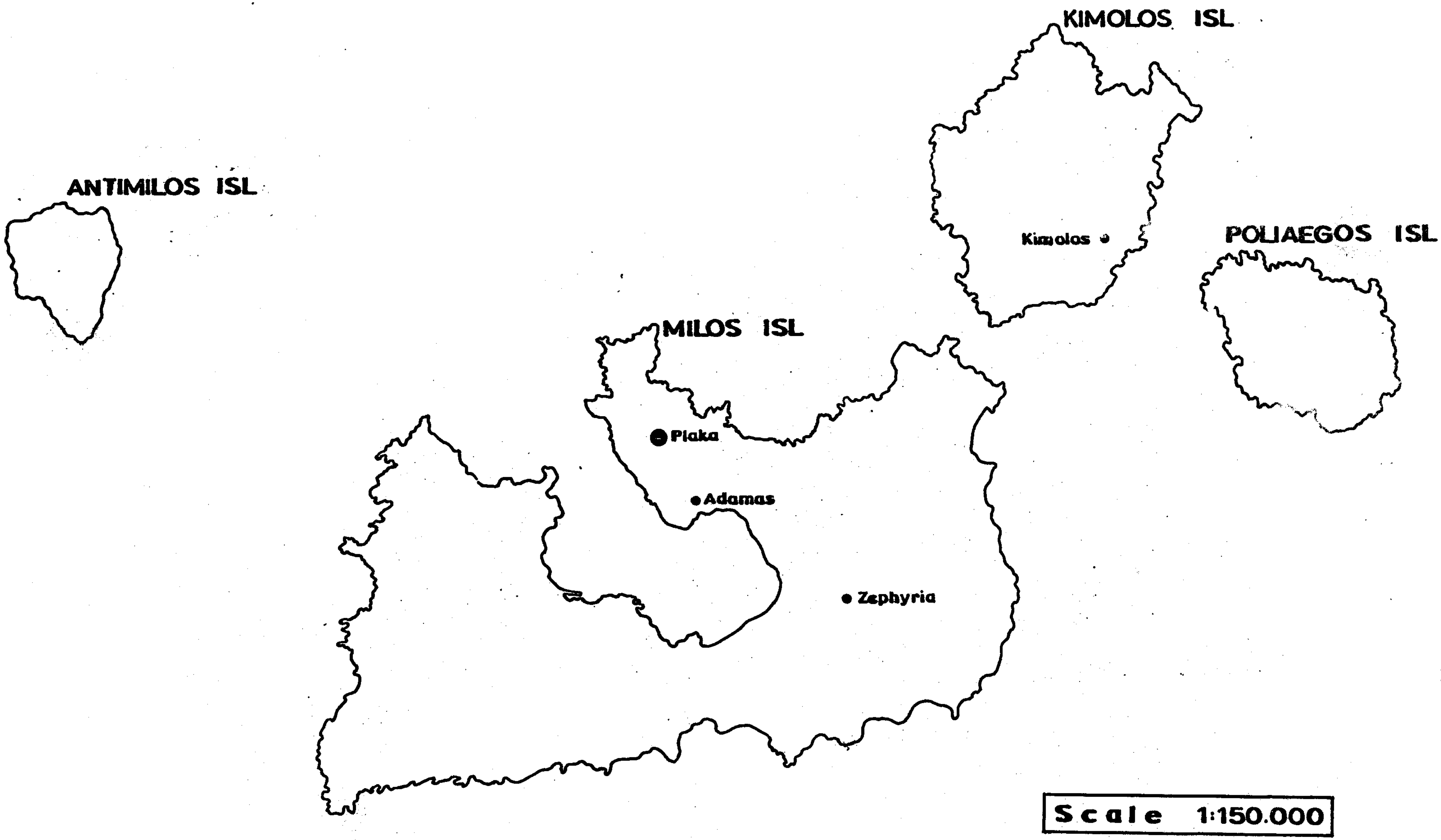
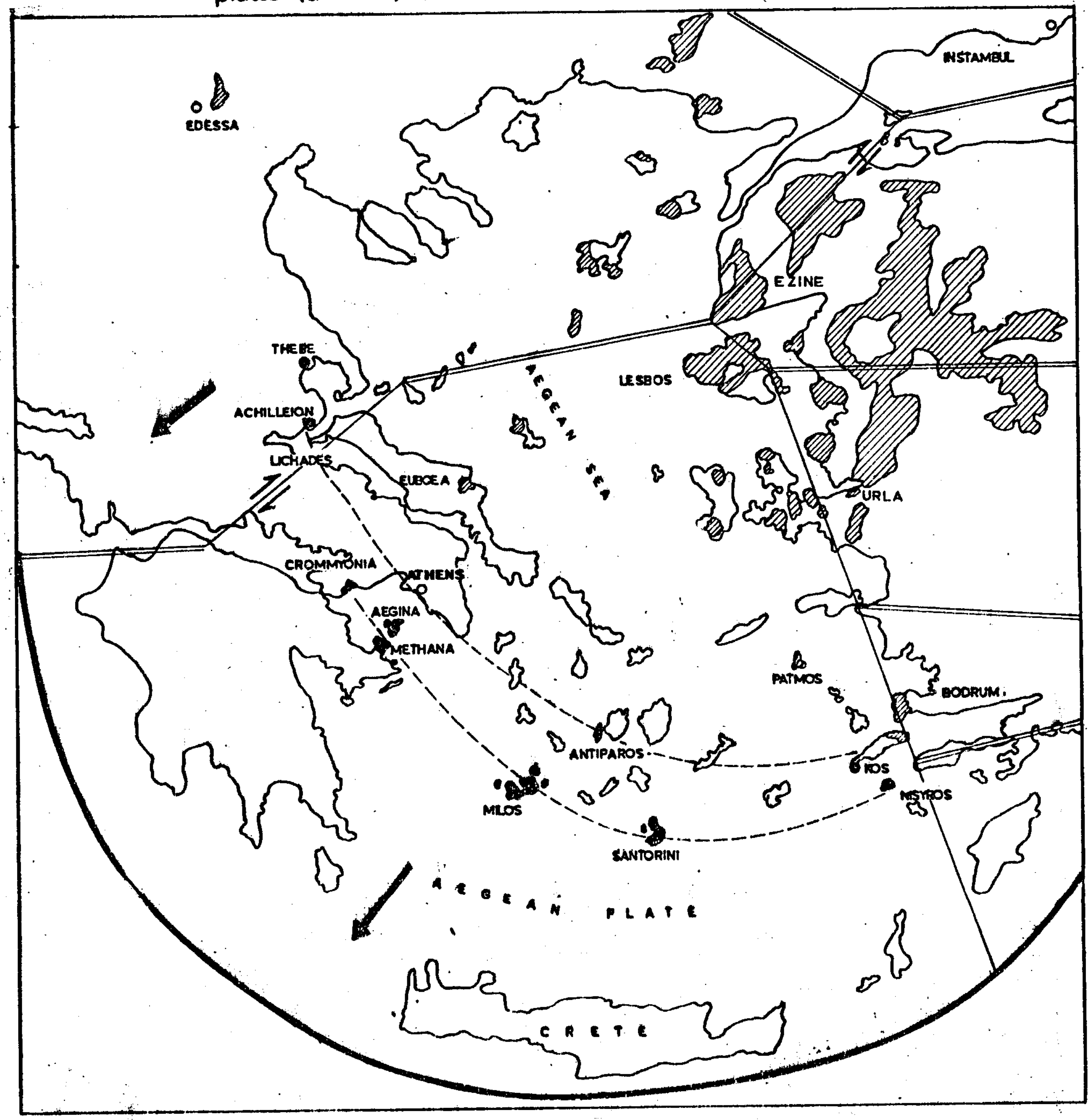
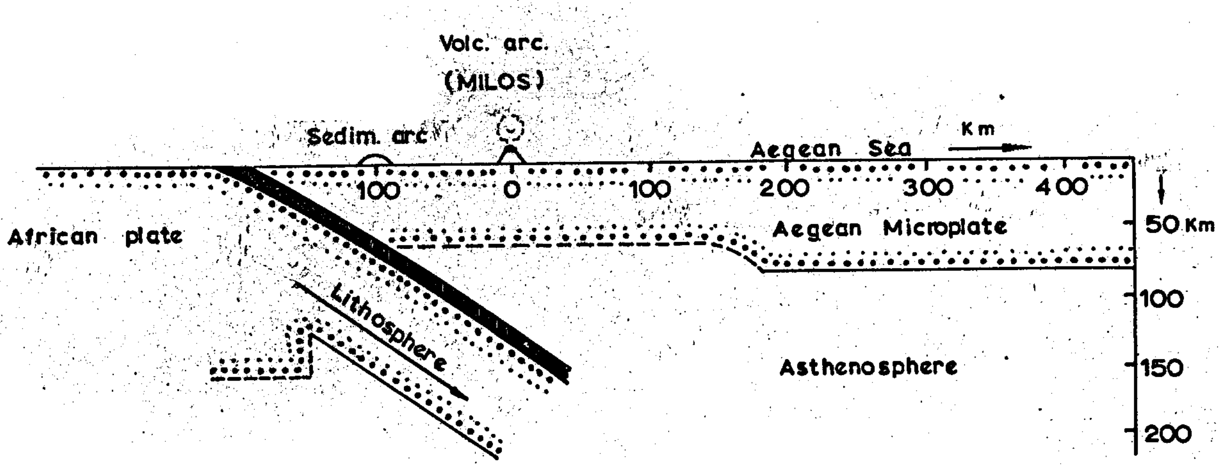

KIMOLOS ISL
ANTIMILOS ISL
Kimolos
POLIAEGOS ISL
MILOS ISL
Plaka
Adamas
Zephyria
Scale 1:150.000

Distibution of volcanic rocks of Tertiary and Quarternary age in the Aegean region. Plate boundaries and relative motion of the plates (arrows) after Mckenzie (1972)

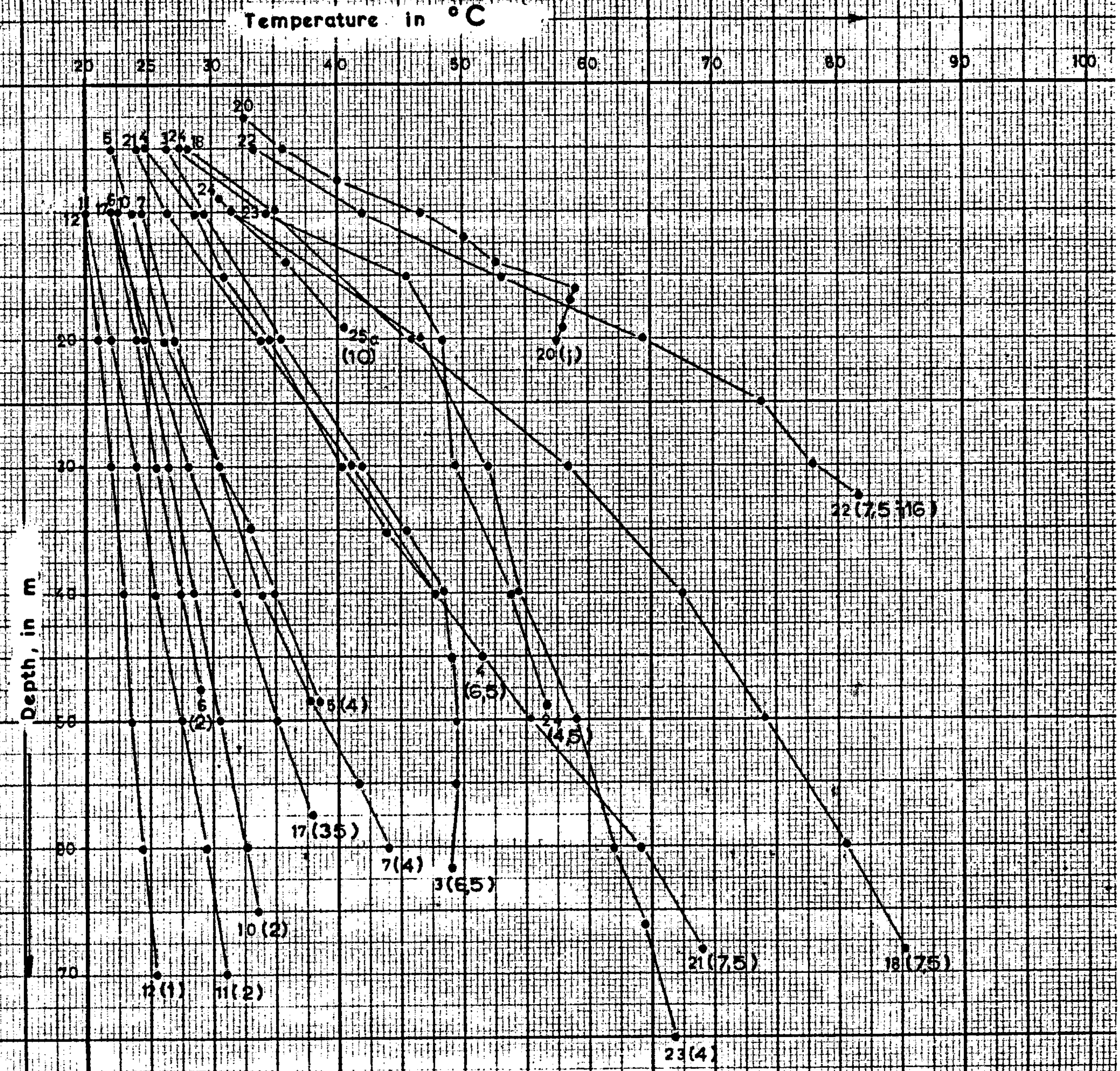


LEGEND

- Calc - alkaline, shoshonitic and alkali - basaltic volcanics of Tertiary age.
- Calc - alkaline volcanics of active volcanic arc.
- Distension fractures.
- Trancurrent lines.
- The double arc of active volcanoes.

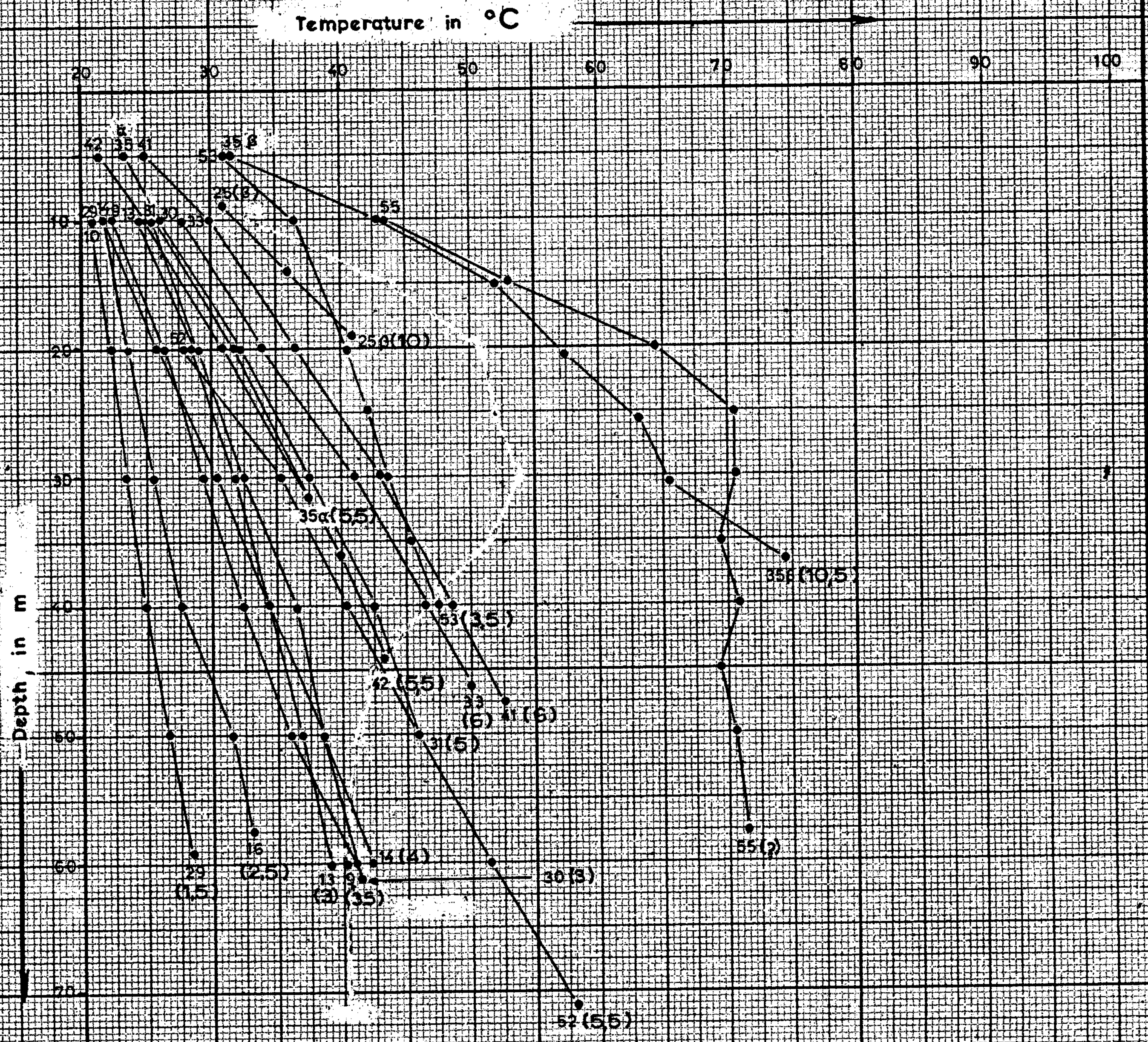


Sketch of the southern Aegean area (after Papazachos 1973) In heavier black the downgoing lithospheric slab.



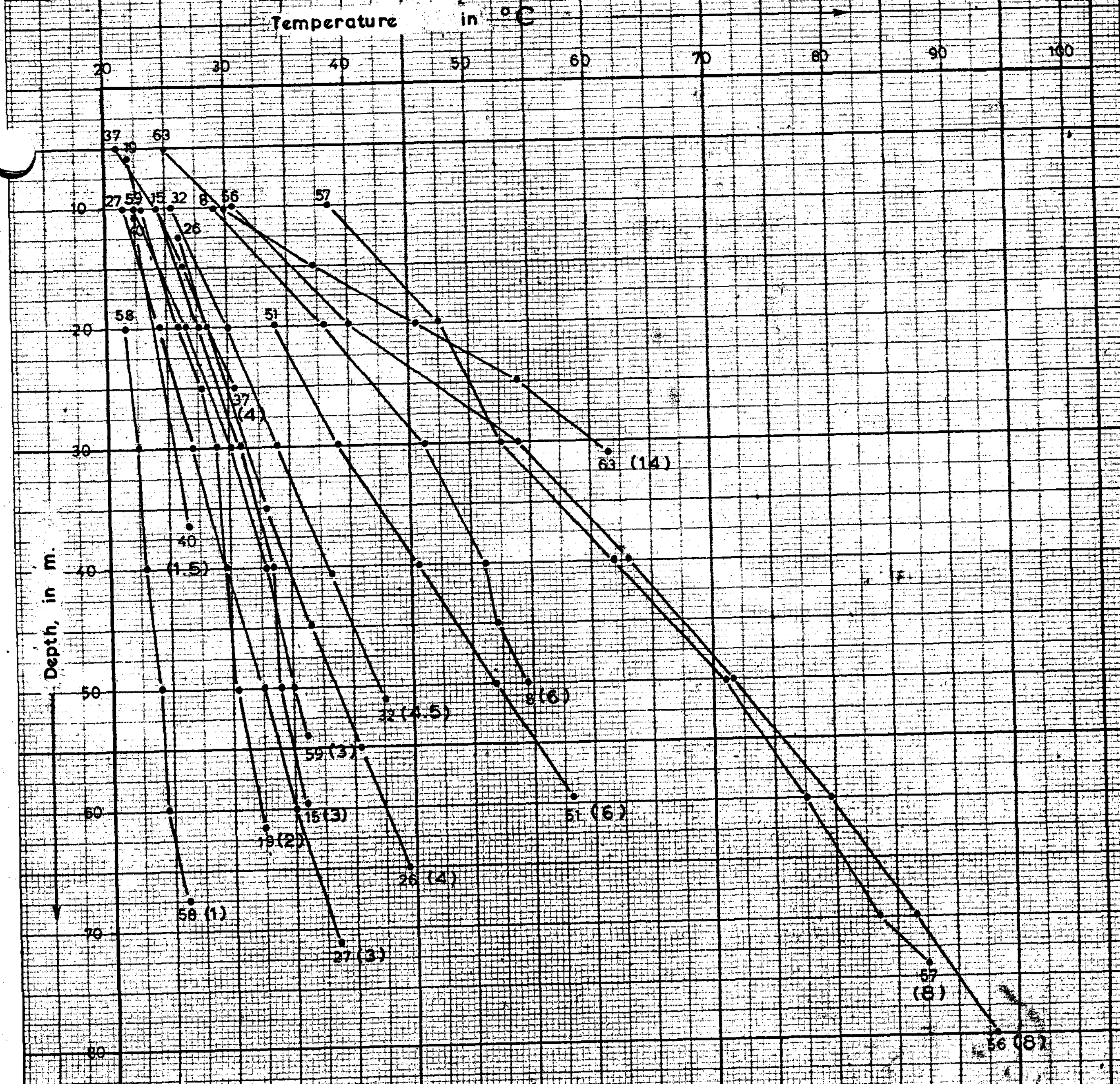
Geothermal gradients in Milos island.

7(4) Borehole N°7 has a mean gradient of 4° C per 10m



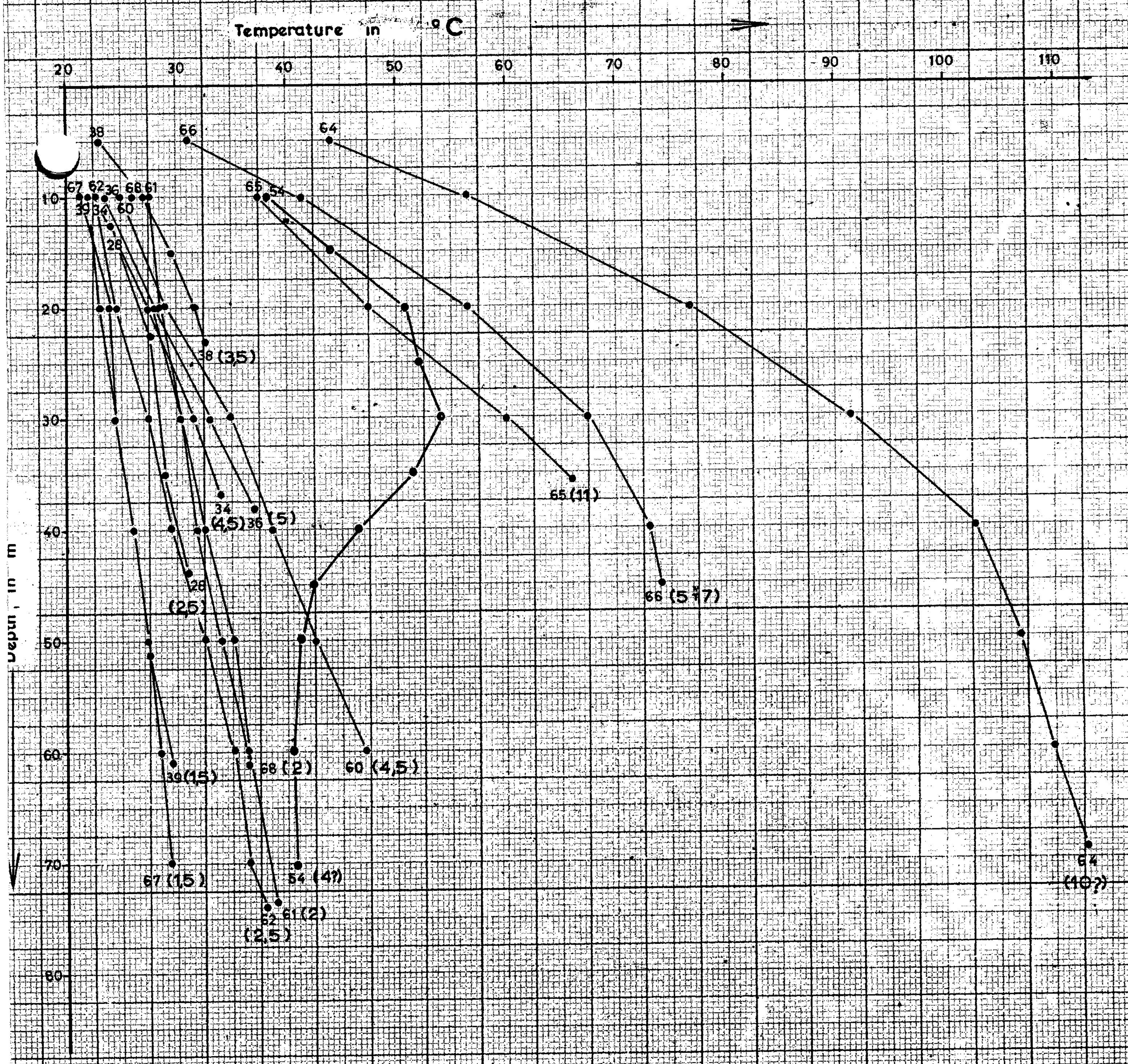
Geothermal gradients in Milos island.

52(5.5) Borehole N° 52 has a mean gradient of 5.5° C per 10 m



Geothermal gradients in Milos island.

26(4) Borehole N° 26 has a mean gradient of 4° C per 10 m



Geothermal gradients in Milos island.

61 (2) Borehole N° 61 has a mean gradient of 2° C per 10 m