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GEOPHYSICAL STUDIES RELATING TO THE TECTONIC STRUCTURE OF KOS ISLAND (GREECE)

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ABSTRACT

The tectonic investigation of Kos Island is outlined in this paper, based on the results of a multi-disciplinary geological and geophysical research for the evaluation of the geothermal regime of the island. Detailed gravity and magnetic work has shown the existence of a graben extending over most of the western part of the island, which exibits most of the geothermal interest. A plausible model of the upper crustal layers of western Kos was attemted, based on the residual gravity anomalies and other geophysical constraints, arising mainly from detailed seismic refraction work carried out at the western part of the presented gravity anomaly model. The Vulcania Fault appears to be a predominant feature along the western boundary of the graben; it has a downthrow to the NE of more than 2000 m, playing an important role and allowing thus the upwelling of geothermal fluids, which may reach the geological formations near the surface and cause intense hydrothermal alterations. The Vulcania area is associated with magnetic anomalies of relatively lower magnitude compared to the adjacent regions. The probable existence of a modelled acid intrusion at depth to the immediate vicinity of the Vulcania Fault on the NE, is finally discussed relating to the various regional tectonic processes.

KEY WORDS: Tectonics, Gravity, Magnetics, Kos Island, Greece.

1. INTRODUCTION

Kos Island represents at interesting field for study regarding its geological and tectonic significance. However, since it comprises part of the southeastern termination of the Hellenic Volcanic Arc (Fig. 1), it has a geothermal interest, too.

A geothermal approach to the exploration of its western part has already been attempted by the analysis and interpretation of the Audio-Magnetotelluric (AMT) measurements (Lagios et al., 1994, 1998). Emphasis, though, is being given in the tectonic structure deduced by multi-disciplinary geophysical research. Such a research, with gravity surveys for the determination of the tectonic structure and its relationship to the geothermal field, gave valuable results in various places of Greece of geothermal interest (Apostolopoulos et al., 1997).

2. BRIEF GEOLOGICAL SETTING

The alpine structure of Kos is complex, comprising several tectonic units (Desio, 1931; Altherr et al., 1976; Papanikolaou & Lekkas, 1990; Papanikolaou et al., 1995; Fig. 2):

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1. The relative autochthonous unit, cropping out in the northern part of Kefalos Peninsula and in the central area of Dikeos Mt. It comprises metamorphic rocks with a lower group of schist formations partly of Palaeozoic age, and an upper group of metamorphosed carbonates, partly of Mesozoic age. This basal unit is covered by a lower Miocene molasse of a few hundred meters thickness in the Kefalos area.
2. The allochthonous wild flysch of Thermi, cropping out in the eastern part of Kos. It contains Mesozoic blocks of the upper tectonic units and it is in contact with the Palaeozoic of the autochthonous unit by an important sub-vertical fault, striking NNE-SSW.
3. The Zias nappe, which is lying over the autochthonous. It is not metamorphic and it can be correlated to the Tripolis nappe of the mainland of Greece. It is also observed in direct tectonic contact over the Miocene monzonite of Dikeos Mt. A small tectonic klippen of this nape occurs also in Kefalos Peninsula, in Western Kos, over the Lower Miocene molasse and below the Upper Miocene volcanics.
4. The Prophitis Elias nappe, which usually lies over the Zias nappe. It contains characteristic pelagic sequences, which may be correlated to the Pindos Unit of mainland Greece.

The post-Alpine structure is characterized by thick Miocene sedimentation, which mainly extends along the northern slopes of Dikeos Mt. and adjacent hills at an almost E-W direction (Desio, 1931; Bφgger, 1978; Besenecker & Otte, 1978) . The main neotectonic structure, however, is the Antimachia tectonic basin (Fig. 2), extending between the Kefalos Peninsula and the western slopes of Dikeos Mt. This area has considerably subsided during Miocene-Pliocene times, and several hundreds of meters of sediments have been accumulated. The two marginal tectonic zones of the graben are different, although they trend to the same NW-SE direction. The eastern boundary, towards Dikeos Mt., has been created by a high-angle inverse fault bringing the Alpine basement, together with the intruded monzonite, over the Miocene sediments to the west. This tectonic movement seem to be fossilified by the deposition of the shallow marine sediments of Plio-Quaternary age, and it should thus represent a Miocene structure. According to Papanikolaou and Lekkas (1990), this compressive structure should be related to the intrusion of the Upper Miocene monzonite of Dikeos Mt.

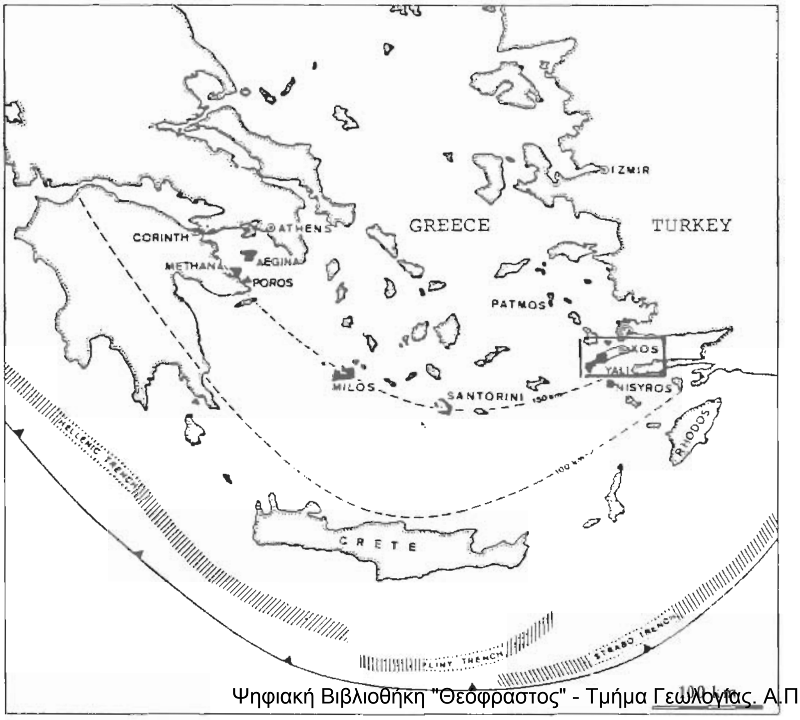

Figure 1:
Map outlining the main places of geothermal interest along the Hellenic Volcanic Arc. Dashed lines indicate the average depth of the subducting plate.

On the contrary, the Western boundary of Antimachia Basin, towards the Kefalos Peninsula, is created by a zone of normal faults with some minor dextral strike-slip component, which has been active throughout the Middle Miocene - Holocene period. This continuity of the tectonic activity is proved by the fact that:

(i) The Alpine basement has been considerably subsided within the graben, whereas,

(ii) the Plio-Quaternary marine sediments are bounded by this tectonic zone, not prolongating to the west and

(iii) the Upper Pleistocene volcanics have subsided during Holocene more than 60 m within the graben with respect to the Kefalos Peninsula.

The occurrence of Vulcania area on this active zone of normal faulting, separating the Antimachia tectonic graben from the Kefalos horst, is emphasizing the relation between the neotectonic activity and the recent volcanism.

The overall neotectonic geometry across the Antimachia Basin shows an asymmetric block, with tilt towards the WSW, where the Upper Pleistocene-Holocene volcanic formation crops out at very low altitudes, in contrast to the eastern boundary, where the Miocene sediments crop out at altitudes between 200-300 m. Finally, a tilt of the neotectonic block of the Antimachia Basin towards NNW has occurred in both Plio-Quaternary and in Holocene times, as it is indicated by the recent volcanics having a steady slope towards the northern coast, plunging below sea-level, whereas, along the southern coast, these volcanics are observed at higher altitudes, about 100-150 m.

3. THE GEOPHYSICAL RESEARCH

3.1 Gravity Measurements

More than 400 gravity measurements were carried out on Kos Island. Emphasis was given more to the western part of the island, where the coverage was denser and of greater accuracy. That is, detailed gravity profiles (stations every 100-150m and levelling work with ±0.02 m elevation accuracy) were made at the western part of Kos, while the rest of the island was covered in a less dense way, using altimeters and spot heights from maps of 1:5,000 as height control of ±0.3 m elevation accuracy). According to the achieved elevation accuracy, and allowing a 10% error in the value of the calculated terrain coefficient of every gravity station, the error estimation of the calculated gravity anomalies varies from 1 gu (levelling height determination) to better than 3 gu (spot heights).

The gravity anomaly map (Fig. 3) was subsequently compiled. The most interesting feature (Fig. 3) is the gravity low (about 600 gu) at the center of the island, corresponding to the Antimachia Basin. The gravity anomaly associated with this major tectonic feature is about 200 gu. This basin seems to be apparently fault-bounded, as it is indicated by the steep gravity gradients on its both margins. The gravity field attains also high values on the western part of the island (more than 1000 gu), and on the south-eastern one (900 gu). For the first case, the relatively high gravity values seem to be reasonable, because we have the abundant presence of the volcanic rocks, and the outcropping of the crystalline basement to the NW of Kefalos. For the second case, the eastern gravity high should be associated with the Dikeos massif, while to the NE, away from the mountainous mass, the field values decrease again.

A 21-Dimensional model was made (Fig. 4) from the residual gravity anomalies along the AB profile (Fig. 3). A possible upper crustal structure is thus outlined in the attempted model (Fig. 4).

The two faults on the WSW part of the profile were also determined by deep seismic refraction studies carried out by the Institute of Geology and Mineral Exploration (IGME (1990), in Lagios 1992). This seismic profile commences at about the 4th kilometer and ends at about the 7th kilometer of the modelled gravity profile (Fig. 3). It was then possible to analytically define the superficial layers to a depth of about 600 m. The vertical extend of these layers and the determined positions of these faults were used as constraints in the gravity modelling. The determined seismic velocities of the superficial layers helped in the evaluation of their [illegible]

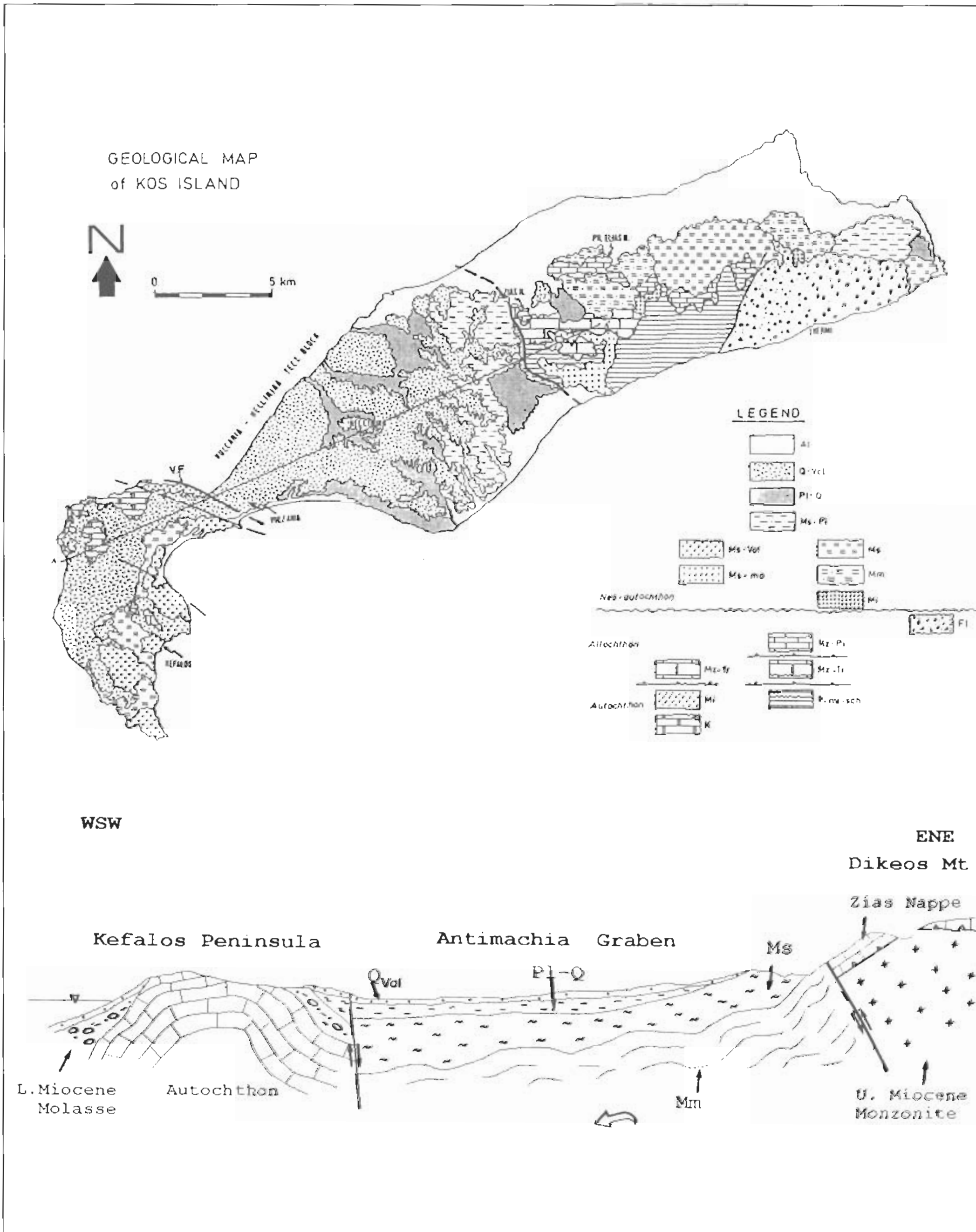

Figure 2: Sketch geological Map of Kos Island; AA' represents the trace of the underlying geological cross section (Papanikolaou & Lekkas, 1990).

Al:Allouvial, Q-Vol: Quaternary Volcanics, Pl-Q:Pliocene-Quaternary sediments, Ms-Pl: Miocene-Pliocene sediments, Ms-Vol:U.Miocene Volcanics, Ms-mo: U.Miocene monzonite, Ms:U.Miocene sediments, Mm:M.Miocene sediments, Mi:L.Miocene sediments, Mz-Tr:Mesozoic-Triassic carbonates, Mi:L.Miocene Molasse, K:Cretaceous marbles (Autochthon), Mz-Pi:Mesozoic pelagic sediments-Pindos, Mz-Tr:Mesozoic neritic sediments-Tripolis, P-mr-sch:Paleozoic metamorphics (Autochthon), Fl: Wild Flysch-Eocene.

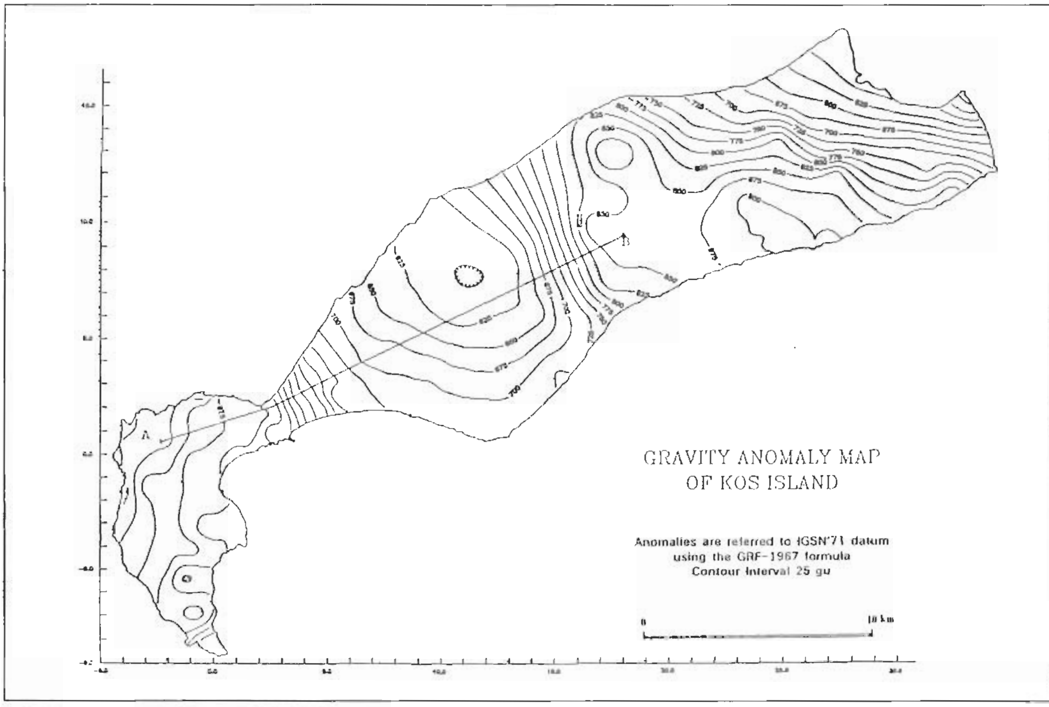

Figure 3: Gravity anomaly map of Kos Island (Axes represent the Local National Grid in km. 1 mGal = 10 gu)

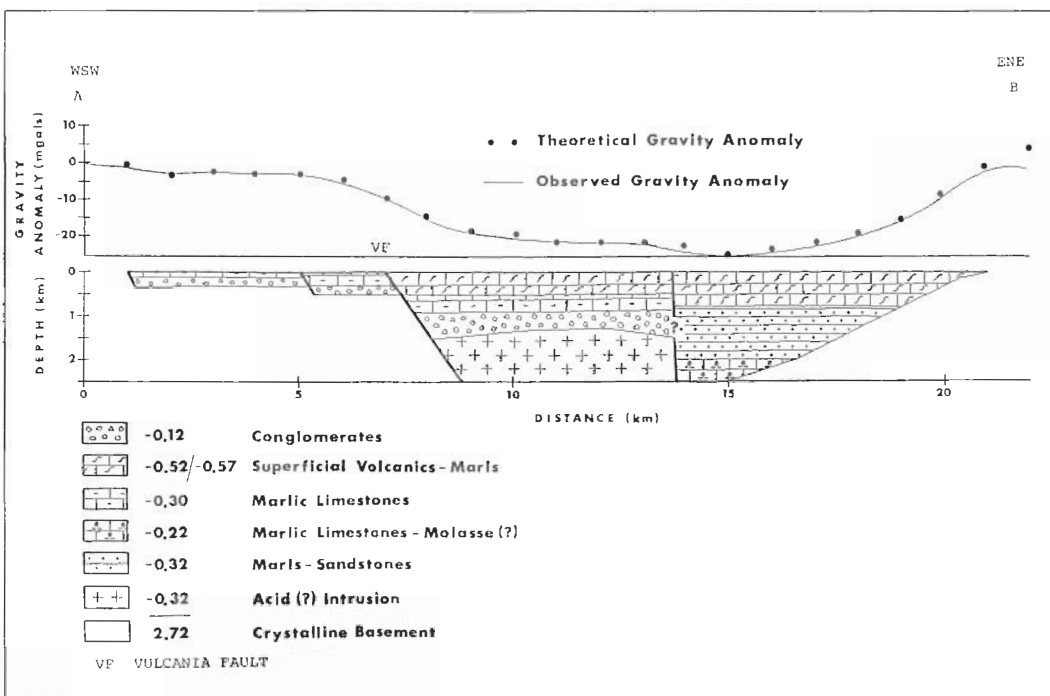

Figure 4: A possible 2½-D gravity model of the western part of Kos along AB profile

The crystalline basement in the gravity model (Fig. 4) is the (autochthonous) Cretaceous limestones. The volcanic depositions, which within the basin constitute the superficial layer of about 20 m thickness, are not shown on the constructed model, even though their calculated effect was incorporated in the final gravity result.

Subsequently, the marls and, at greater depths, the marly limestones are met. In the center of the basin, the lateral transition of the marlic limestones, on the west, to marls and sandstones on the east is assumed. At the base of the marly limestones, the conglomerates are normally met, overlying the Cretaceous limestones of the crystalline basement. There is, however, a possibility that between the previous two formations the presence of a small thickness layer of other molassic sediments, of Lower-Middle Miocene age, may occur.

There are a few characteristic points related to the constructed model (Fig. 4). One is the major feature of the fault in the Vulcania area, which seems to downthrow the conglomerates to a depth of at least 1000 m. This faulting feature, which at the ground surface has a direction of about NW-SE, should be extended at even larger depths and play an important role in the geothermal fluid circulation of the area, something which is indicated by the spatial AMT data analysis (Lagios et al., 1994).

Another significant feature is the modelled intrusion (Fig. 4) at the half western part, at the base of the graben, with its upper surface at a depth of about 1300 m. Such an intrusion, most probably a granitic one, is very likely to exist, and seems to be compatible with the broader geological regime of the island (presence of granites also at the eastern part). This intrusion is confined (at least down to a depth of 2500 m) by the Vulcania Fault to the SE, and probably another fault to the NE. The latter fault, together with the Vulcania Fault seem to constitute one of the most interesting features deduced by the geophysical research. It extends approximately under the center of the graben and is apparently covered by the Neogene sediments, since it does not have any obvious superficial trace.

The presence of the previous fault at the centre of the basin inevitably becomes a boundary not only for the intrusion at depth, but also for the carbonate and the clastic rock formations of Upper Miocene - Lower Pliocene age, regarding their different depositional rates on both sides of this fault. Moreover, the existence of this fault at depth is rather necessary from the point of view of geophysical modelling, so that its generated gravity effect fits that particular part of the observed gravity anomaly (which is a small amplitude fault-shape anomaly) of profile AB at the center of the basin. The eastern part of the constructed model (Fig. 4) shows a gradual change of the interface between basement rocks and the superimposed sediments, and in any case, it does not indicate a major normal fault, which would make the basin to be fault-bounded to its eastern part. The dip of this interface is not steep at all, and, if any fault does exist at this eastern end of the basin (Fig. 2), it should be a relatively minor feature.

3.2 Magnetic Measurements

Parallel to the gravity measurements, the magnetic coverage of Kos Island took place, by performing measurements of the Earth's total magnetic field. It can be easily seen that there are magnetic anomalies of more than 290 nT in the magnetic anomaly map (Fig. 5). Most of these local anomalies, especially in the western part of the island, are correlated to volcanic rock formations. Characteristic is the closure of the magnetic high (150 nT) corresponding to the impressive volcanic dome south of Kefalos (Dalabakis, 1987). The highest, however, magnetic anomaly values are observed at the north-eastern part of the island, where amplitudes of more than 250 nT are met. The lowest magnetic anomaly values are observed in Vulcania and Hellinika regions. These two areas are characterized by relatively low anomaly amplitudes, ranging from 30 to 90 nT, which could be attributed, as a first approximation, to the high degree of geothermal alteration of the rocks (Lagios et al., 1994), at least at the surface, in these two regions. The compilation of the magnetic anomaly map offers a complementary picture of the area under investigation, and contributes in a sort of indirect way to the geothermal research of the area by rather identifying zones of intense hydrothermal alterations.

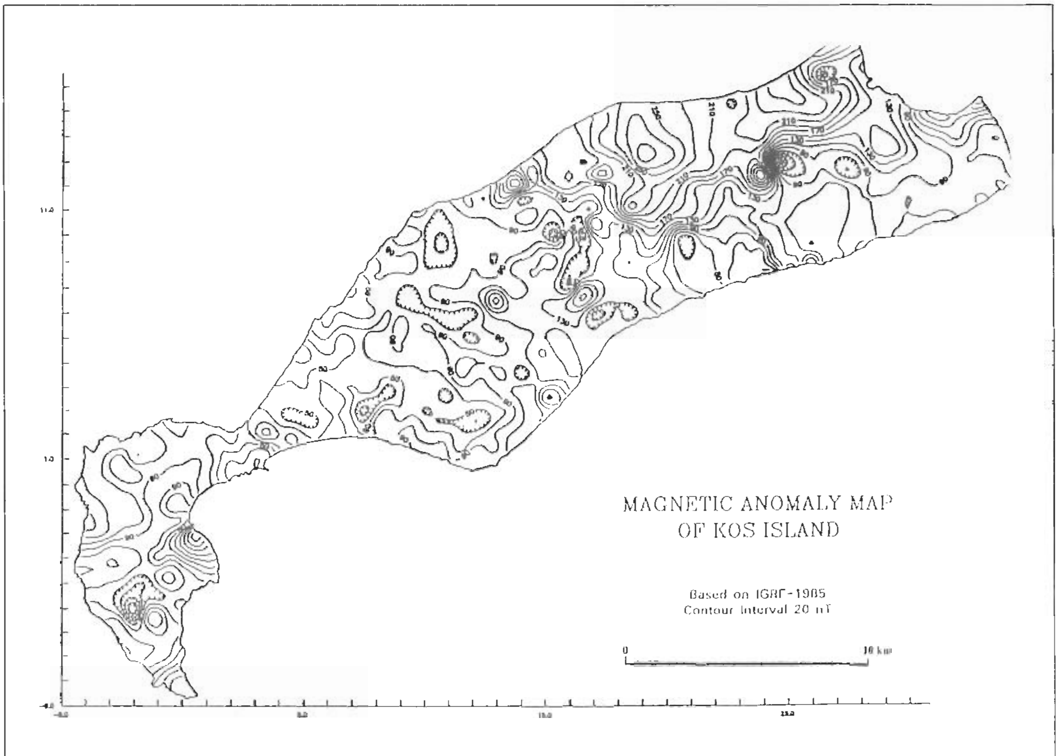

Figure 5: Magnetic Anomaly Map of Kos Island. (Axes represent the local National Grid in km)

4. DISCUSSION - CONCLUSIONS

The new element, which is inferred by the geophysical research, is the probable existence of an intrusion at depth, most likely a granitic one (Fig. 4). Its upper surface has been modelled at 1300 m below ground surface, and seems to extend from the center of the graben to the Vulcania Fault on the west. The latter was envisaged on the basis of the gravity interpretation, but indications are also from the ground magnetics.

It has been discussed (Lagios, 1979) that areas underlain by granitic masses are, most of the time, characterized by magnetic anomalies of small amplitude, as granites normally exhibit weak intensity of magnetization in most places of the world. As a consequence, the lowest magnetic anomaly values observed (< 50 nT) eastwards of the Vulcania Fault, confined in the Vulcania area and the southern part of Hellinika region, could be attributed to the existence of the granite at depth. It is likely that, even though no detailed analytical modelling of the magnetic anomalies was attempted, the configuration of the 60 nT magnetic anomaly contour (Fig. 5) and the smaller value ones (<50 nT), possibly outline the areal extent of the granitic body and its upper surface undulations.

Since the same value of density contrast (-0.32 gr/cm^3) was used for both the modelled (acid?) intrusion and the marls-sandstones (Fig. 4), it may apparently be invoked that the modelled intrusion might be extending to the east, covering thus the whole bottom of the graben. However, a body of larger density (as molasse (~2.50 gr/cm^3) or conglomerates (2.62 gr/cm^3)) than the value of the modelled intrusion is required to be placed at depth, east of the central fault, so that the overall theoretical (model) gravity anomaly values fit the observed ones.

Certain geological phenomena could also be explained by envisaging a granitic body at depth, because such intruded bodies assign certain characteristics to the regions they underlie. It is known that areas overlying granite batholiths have demonstrated greater stability during geological periods, when extensive vertical tectonic motions (subsidence) take place, compared to the adjacent regions not underlain by granitic masses. The presence of granites at depth drastically reduces the vertical rate motion and has an effect on the sedimentation rate of the overlying strata, compared to the adjacent regions, where the sedimentation rate is considerably higher, and the development of major fault zones (depending on the vertical rate movements) is formed between these regions, and at the margins of the granitic bodies, as actually happens in the Southern Uplands of SE Scotland (Lagios, 1979).

It is understood that within the framework of the Alpine, post-Alpine evolution of the island, the volcanism and its associated magmatism is of significant character on both sides of the graben. However, in Central Kos, a considerable emergence of plutonic granodioritic bodies is marked, whereas in the Kefalos Peninsula, we have only the volcanic extrusions, with the plutonic bodies remaining at some depth.

The central area of the island seems to be relatively not active during Plio-Quaternary, whilst the activity seems to continue at the western area in Late-Pleistocene to Late-Holocene. Thus in the western boundary of the graben there is probably a co-existence of Upper-Miocene granitic bodies with Late-Pleistocene intrusive bodies. The conceivable presence of the granite at the bottom of the basin could moreover explain the following phenomena:

(i) The formation and development of the major fault zones (Vulcania Fault and the likely one at the centre of the basin) laterally of the granitic mass (Fig. 4).

(ii) The probable lateral transition, at about the centre of the basin, of the marly limestones (on the half western part of the basin) to successions of marls and sandstones (on the half eastern part of the basin).

(iii) The relative uplift of the southern part of the tectonic block of Vulcania-Hellinika, compared to its northern part, which subsides (Papanikolaou and Lekkas, 1990). That would suggest that the granitic body underlies mainly the southern part of this tectonic block, towards and under the marine area of the Kefalos Caldera; the latter is also consistent with the picture inferred by the magnetics discussed above.

(iv) It is the Vulcania Fault, developed at the SW margin of the granite (Fig. 4), which offers the possibility of upward geothermal fluid circulation.

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