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THE STRUCTURE OF THE UPPER CRUST IN THE KARDITSA SUBBASIN (CENTRAL GREECE) AND THE CONTINUATION OF THE OPHIOLITES BENEATH ITS SEDIMENTS

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ABSTRACT

The relief of the basement is studied beneath the sediments of the Karditsa subbasin by the use of gravity and aeromagnetic data. These data were supplemented by susceptibility and remanent magnetization measurements on the ophiolites at the margins of the subbasin, density measurements on rock samples and a Nettleton profile. The basement appears to dive eastwards of the mountain chain and it is uplifted near the city of Sofades. The magnetic map shows clearly the continuation of the ophiolites under the subbasin. Spectral filtering and deconvolution revealed the existence of two discernible bodies on NW-SE ranging alignment while forward modeling was employed to quantify their characteristics.

ΣΥΝΟΨΗ

Η ανύψωση του υποβάθρου κάτω από τα ιζήματα της Καρδίτσας μελετάται με τη χρήση βαρυτικών και αερομαγνητικών δεδομένων. Τα δεδομένα αυτά συμπληρώνονται με μετρήσεις μαγνητικής επιδεκτικότητας και παραμένουσας μαγνήτισης στους οφειόλιθους στα όρια της υπολεκάνης, μετρήσεις πυκνότητας σε διάφορα δείγματα και μία τομή Nettleton. Το υπόβαθρο φαίνεται να βυθίζεται ανατολικά από την οροσειρά και ανέρχεται κοντά στην πόλη των Σοφάδων. Ο μαγνητικός χάρτης δείχνει καθαρά τη συνέχεια των οφειολίθων κάτω από την υπολεκάνη. Φασματική ανάλυση και αποσυννέλιξη δείχνουν την ύπαρξη δύο διακριτών σωμάτων με ΒΔ-ΝΑ γραμμική ανάπτυξη ενώ απ' ευθείας μοντέλα χρησιμοποιήθηκαν για την ποσοτικοποίηση των χαρακτηριστικών τους.

ΕΙΣΑΓΩΓΗ - INTRODUCTION

The subbasins which form the plain of Thessalia (central Greece) are morphologically well defined features. The plain itself (fig. 1) is the largest one in Greece and covers parts of four isopic zones (Aubouin, 1959). From east to west these zones are the Axios-Vardar, Pelagonian, Subpelagonian and Pindos (Mountrakis et al., 1983).

The alpine regional geology of the major area is well known with respect to the description of the main lithological units and stratigraphy (Aubouin, 1959; Vergely, 1988; Katsikatsos et al., 1986; Kilias and Mountrakis, 1987).

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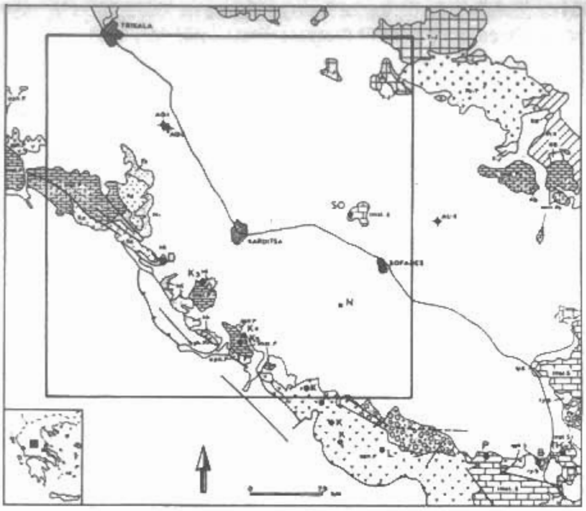

Fig. 1: The plain of Thessalia is shown by the dark area and the studied area is enclosed by a solid line. Rock samples were extracted at the places marked by dark circles. The main geological zones are denoted as **P**=Pindos and **S**=Subpelagonian. Other notations are as follows:
oph: Ophiolites, **lmst:** Limestone, **fy:** Flysch, **AGN1, AGN2, AL4:** Boreholes, **N:** Nettleton profile, Formations: **Fa:** Fanari, **Mi:** Mitropolis, **Ka:** Kanalia, **Le:** Leonardi

Σχ. 1: Η πεδιάδα της Θεσσαλίας φαίνεται από τη σκιασμένη περιοχή ενώ η περιοχή έρευνας περικλείεται από τη συνεχή γραμμή. Δείγματα πετρωμάτων λήφθηκαν από τις περιοχές που σημειώνονται με μαύρους κύκλους. Οι γεωλογικές ζώνες σημειώνονται ως: **P**=Πίνδος και **S**= Υποπελαγονική. Οι υπόλοιποι συμβολισμοί έχουν ως εξής:
oph: οφειόλιθοι, **lmst**: Ασβεστόλιθος, **fy**: φλύσχης, **AGN1, AGN2, AL4**: Γεωτρήσεις, **N**: τομή Nettleton, Σχηματισμοί: **Fa**: Φαναρίου, **Mi**: Μητρόπολης, **Ka**: Καναλίου, **Le**: Λεονταρίου

Caputo (1990), Caputo and Pavlides (1991, 1993), and Pavlides (1993) studied the post-alpine evolution of the tectonic regime and suggest a model consisting of two distinct extensional phases. The oldest one, dated during late Miocene-Pliocene, was caused by a N51°E extentional field. This field reactivated the structures which had been created by an apline phase. It mainly deepended the graben structures which form the NW-SE trending subbasins of Karditsa and Larissa. The younger phase, which is still active, has given structures ranging E-W, which are clearly visible in the Eastern part of the plain of Thessalia.

Very high seismic activity has been observed during the present century (Papazachos et a., 1983; Papastamatiou and Moyaris, 1986; Ambraseys and Jackson 1990), making this the study of the tectonic setting of the subbasins very interesting.

Papazachos et al., (1993) concluded that the active deformation rate in the corresponding seismic belt is very high at present, mamely 1-2cm/yr. Therefore, the probability for the generation of moderate magnitude ($M_s \geq 5.0$) or even of large magnitude ($M_s \geq 6.0$) shock in the next decade is high.

The present study attempts to define the structural setting of the subbasin of Karditsa (fig. 1). This feature occupies the south-western part of the plain of Thessalia. Magnetic and Gravity data have been used. These data were implemented by density, apparent susceptibility and remanent magnetization measurements and the results of 3 deep drillings.

Ophiolites outcrop all around from the north-western to the southern margins of the studied subbasin. Thus, the analysis of the magnetic data aimed also to reveal their existence or not beneath the sediments.

ΣΤΡΩΜΑΤΟΓΡΑΦΙΑ - STRATIGRAPHY

The main lithological units which occur in the studied area can be grouped into two major groups, that is, the Post-alpide sediments and the Alpide and

Pre-alpide series (Caputo, 1990). In particular, the western limit of the studied area (fig. 1) belongs to the Pindos zone (Lekkas, 1988; Caputo, 1990).

The ophiolitic series which crops out along the northwestern and southwestern border of the Karditsa basin consists mainly of mafic and ultramafic rocks, as basalts, peridotites and gabbros. A complex carbonatic series is present in the northwestern margin of the subbasin. Oolitic limestones, calcirudites, pelites, charty limestones and radiolarites compose mainly this series. These are of Jurassic to Paleocene age. A typical intercalation of sandstones and pelites compose the Flysch of Maastrichtian to Early Eocene age (Caputo, 1990). It underlies the ophiolitic and calcareous rocks which refered above as a consequence of the Alpide tectonic action.

All the units mentioned above belong to the Pre-Alpide series of the Pindos zone. Caputo (1990) named all units which deposited to the Alpide paroxysm of this area of the Hellenides as "Late and Post-Alpide sediments". This terminology is followed here.

Generally, in the central-southern part of the plain of Thessalia the ophiolitic-radiolaritic complex of the Subpelagonian zone crops out. It mainly consists of alternated pelites, radiolarities and marly limestones apart from the magmatic rocks as peridotites, dunites, gabbros, serpentinites, diabase-dolerites and diorites. This complex is of Jurassic to Early Cretaceous age. Westwards of the city of Karditsa, at the margins of the subbasin, a terrigenous and clastic sedimentary sequence crops out. This series has been named as "Karditsa sequence" and consists of three formations, the Mitropolis, the kanalia and the Fanari. The first one consists of conglomerates, reddish sandstones and mudstones and it is dated to Middle-Late Oligocene. The second one is a well cemented series in general. It overlies the first one and includes, conglomerates and sandstones. The third one, i.e. the Fanari formation, is the younger of the Karditsa sequence dated to Burdigalian. It mainly consists of grained material as marls or siltstones alternating with sandstones. At the southern margins, a limited outcrop of a Neogene series named the "Leordari series" is present. In general, the basin is masked by a Holocenic sedimentary cover of alluvial origin.

Two deep commercial boreholes were drilled in the subbasin near the village Agnantero. Their exact locations are shown in figure (1) where they have been annotated as AGN1 and AGN2. These boreholes drilled about 200m of Plio-quaternary sediments, 500m of the Karditsa sequence sediments and penetrated the basement (Senonian limestones) at the depth of ≈ 800m up to ≈ 950m. Another commercial borehole was drilled approximately 9Km eastwards of the city of Sophades. The exact location is marked in figure (1) and it is a bit out of the area where gravity data existed. The borehole is annotated as AL4. The metamorphic basement was met at the depth of 690m and it is of ophiolitic origin. The plioquaternary sediments are approximately 330m thick just above a 220m thick Karditsa sequence sediments which lie on the ophiolithic basement.

ΤΑ ΓΕΩΦΥΣΙΚΑ ΔΕΔΟΜΕΝΑ - THE GEOPHYSICAL DATA

The gravity campaign which produced the data used in this study took place in the years 1964 and 1965. It was carried out by the Institute Francais du Petrole (I.F.P.) on behalf of the Greek Institute for Geology and Mineral Exploration (LaPorte and Viltard, 1966). A total number of 1088 stations were measured resulting to density of 1.2 station/Km^2. Also, two Nettleton profiles were carried out each one consisting of 56 points. As it is reported by I.F.P., these profiles were located at the borders of the subbasin, presumably on the units of "Karditsa formation". They resulted in a density contrast of

0.25 t/m^3 between the "Karditsa formation" and the Pre-alpide units However, I.F.P. used a density of 2.10 t/m^3 for the compilation of the Bouguer map.

A Nettleton profile was carried out for the needs of the present study in March of 1993. The profile is marked in figure (1) and it is located close to a village named Agia Paraskevi. A density of 2.10 t/m^3 resulted for the near surface sediments.

The density of rock samples extracted from the main lithological units of the studied area was also measured. The sample were collected for two purposes, to measure the density and to define the remanent magnetization vector. The resulted densities are shown in table (I) along with the remanent magnetization parameters and the in situ measured apparent susceptibilities.

The aeromagnetic data used in this work were produced in 1964. The campaign was executed by the C.G.G. (Compagnie General des Geophysique) on behalf of I.G.M.R. The flight level was 2100m above sea level.

ΕΡΜΗΝΕΙΑ ΤΩΝ ΒΑΡΥΤΙΚΩΝ ΚΑΙ ΜΑΓΝΗΤΙΚΩΝ ΔΕΔΟΜΕΝΩΝ - INTERPRETATION OF THE GRAVITY AND MAGNETIC DATA

Figure (2) shows the Bouguer anomaly map after the extraction of the first order regional trend. The map reflects mainly the relief of the top of the Pre-alpide formations because the dominant density contrast is between them and the lighter Post-alpide units. The main feature is the northwestwards trending gravity low which presumably reflects the Karditsa graben, i.e. the structure which caused the subbasin. The anomaly is well defined and separated from the low values of the northwest corner of the map.

A positive anomaly of more than 12mgals is present NE of the city of Karditsa and coincides with an outcrop of the limestone of the Subpelagonian zone. The anomaly is , presumably, caused by an uplift of the basement as revealed by the outcrop. It will be called onwards, as the "Sofades" uplift for distinction. A gravitational high seems to taper the Karditsa graben in its northwest end. This is lower in magnitude than the anomaly of the "Sofades" uplift and strikes in the NE direction. The probable fractures, as it can be deduced by the qualitative study of the Bouguer map, have been marked by dashed lines in figure (2). The solids lines represent major fractures identified in our field inspection. It can be seen that the NE-SW and NW-SE systems are very pronounced. The presence of the E-W direction is rather limited.

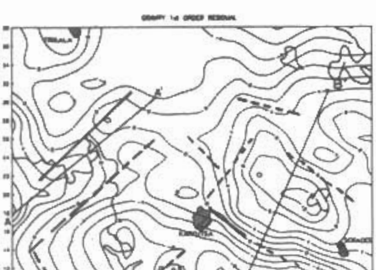

Fig. 2: A first order residual of the Bouguer anomaly map of the area. The contours are in mgals.

Σχ. 2: Υπόλοιπο πρώτης τάξης του χάρτη ανωμαλίας Bouguer της περιοχής. Οι ισανώμαλες είναι σε mgals.

A first order residual total magnetic field anomaly is presented in figure (3). It shows clearly an axis of strong anomalies which strikes NW-SE. This is related to the ophiolitic belt which is concealed under the sediments and other units of the subbasin. As it is shown in figure (1), ophiolites expose themselves at the northwestern and southeastern region out of the studied area. Therefore, they must form a continuous belt which crosses the studied area in the *diagonal sense*.

Since, the data were transformed into the wavenumber domain, 2-D power spectra were calculated as well as their azimuthally averaged versions. The last operation was performed because

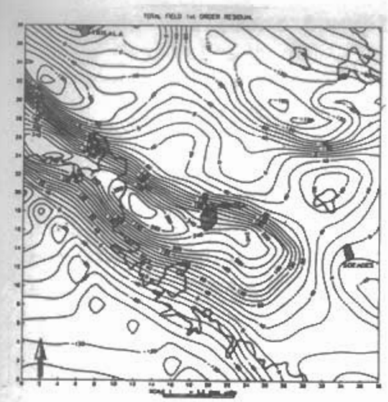

Fig. 3: First order residual total field map of the studied area. The contours are labeled in nT.

Σχ. 3: Υπόλοιπο πρώτης τάξης του συνολικού μαγνητικού πεδίου της περιοχής μελέτης. Οι ισομαγνητικές καμπύλες είναι σε nT.

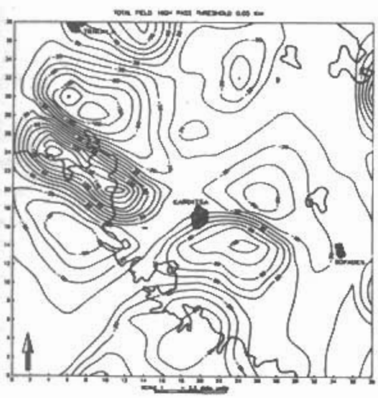

Fig. 4: High-pass filtered magnetic data. The cut-off threshold was set to the wavenumber $0.05Km^{-1}$.

Σχ. 4: Φιλτραρισμένα μαγνητικά δεδομένα υψηλών συχνοτήτων. Ως κάτω όριο αποκοπής συχνοτήτων επιλέχθηκε ο κυματάριθμος $0.05Km^{-1}$.

a linear relationship exists between the depth to certain types of causative source (or group of sources) and the slope of the logarithmic power spectrum of the relevant anomaly. The method is commonly applied along profiles (Spector and Grant, 1970), but it can be also applied to map by radially averaging the 2-D power spectrum (Mishra and Naidu, 1974; Hahn et al., 1976; Kiriakidis and Brooks, 1989). In the azimuthally averaged logarithmic power spectrum of the magnetic total field data, two sources of magnetic disturbances were clearly discernible. Thus, two straight lines were fitted to the linear segments of the spectrum. The least squares line fitted at the relatively lower wave numbers indicated a depth to the upper surface of the source equal to 3.3 Km while the other, at higher wavenumber, a depth of 2.7 Km.

By inspection of the azimuthally averaged power spectrum, wavenumber filters were designed. After multiplication of the filters by the spectrum and return to the space domain, the filtered versions of the maps resulted. It was hoped that such a procedure would isolate the anomalies caused by the ophiolitic bodies. Thus, their spatial distribution would become apparent and further quantitative study could be done. Figure (4) shows such a resulted map after high-pass filtering. The low-cut wavenumber of the particular filter is $0.05Km^{-1}$, representing a wavelength of 20Km, and the roll-off ramp was arbitrarily set to 10% of the whole wavenumber band. Two magnetic anomalies are well posed in the filtered magnetic map indicating the presence of two magnetic bodies.

It has been already refered that ophiolite outcrops occur at the limits of the studied subbasin which are shown in figure (1). In particular, those of the western side belong to the Pindos zone. However, the respective bodies seem to be of small volume since they do not pose themselves in the residual magnetic field map (fig. 3). An attemp was made to isolate their magnetic effect by filtering the map and leaving the high wavenumber (cut-off equal to $0.125\ Km^{-1}$ or approximately to the wavelength of 8Km). Anomalies of much smaller wavelengths than those attributed to the main ophiolitic bodies resulted. Their magnitudes (peak to peak 30nT) are also much smaller. Therefore our initial interpretation was reinforced.

ΑΝΤΙΣΤΡΟΦΗ ΤΩΝ ΜΑΓΝΗΤΙΚΩΝ ΔΕΔΟΜΕΝΩΝ - INVERSE FILTERING OF MAGNETIC DATA

Tsokas and Papazachos (1992) proposed a 2-D inverse filtering scheme which results in transformed anomalies which are centered at the epicenter of the disturbing bodies. Also the lateral extent of the targets is delineated fairly well and the magnitude of the resulting anomalies is a measure of their magnetization. The scheme is based on the consideration of the total field anomaly as being the product of the convolution of two analytically determined functions. One of those is chosen such that it modifies the amplitude of the anomaly while the other controls the pattern (Karousova and Karous, 1989; Tsokas and Papazachos, 1992; Tsokas et al., 1991). The second function was reasonably named as "shape function" and its inverse is computed in the Wiener mode. This is an optimun filter operator, in the least squares sense, to be convolved with the data.

The success of the procedure depends on the proper choice of the model, the anomaly of which will be inverted and serve as filter. Therefore, all the a priori information must be used in its construction. In our case, the available information is that concerning with the strike of the zone, its probable dip and the power spectrum depth estimates. However, a global filter was computed although the power spectrum indicated two sources of magnetic anomalies buried at different depths. Also, the dip was considered unique. This approximation can not affect the result in an observable manner since all other parameters were constrained.

The prism was rotated by $\theta=35$ clockwise with respect to the North. Its dip, φ, was set to 40°, while the length of the dipping side was considered 0.05Km. Its upper surface was a square of $2X2Km^2$. The burial depth, h, was considered as 3.0Km, which is the average depth of the two sources indicated by the power spectrum. The "shape function" was then computed following the McGrath and Hood (1973) algorithm (Grant and West, 1965).

The result, after convolution of the filter produced as described above with the data of figure (4), is shown in figure (5) in the form of a grey scale image. The projection on the surface and the position of the magnetic bodies is revealed in that figure.

ΜΑΓΝΗΤΙΚΑ ΚΑΙ ΒΑΡΥΤΙΚΑ ΜΟΝΤΕΛΑ - MAGNETIC AND GRAVITY MODELLING

The shapes of the magnetic anomalies which were attributed to deep seated ophiolitic bodies lead to a 3-D modeling approach. The method employed to produce the effect of the 3-D bodies is that proposed by McGrath and Hood (1973). The depth to the upper surface of the prisms was constrained by the

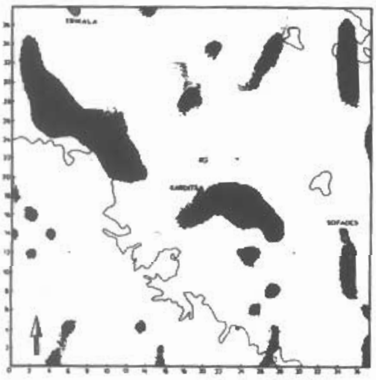

Fig. 5: 16-tones grey scale image of the lateral distribution of magnetization after the application of the inverse filter. Values vary from -10000 to 10000. All values below 500 are depicted with white colour to highlight the result. The range 500-10000 was divided to 15 equal grey levels.

Σχ. 5: Εικόνα 16 τόνων του γκρι της οριζόντιας κατανομής της μαγνήτισης μετά το αντίστροφο φιλτράρισμα. Οι τιμές μεταβάλλονται από -10000 μέχρι 10000. Όλες οι τιμές κάτω από 500 φαίνονται σαν άσπρες για να τονιστεί το αποτέλεσμα. Οι τιμές 500-10000 χωρίστηκαν σε 15 ίσα διαστήματα.

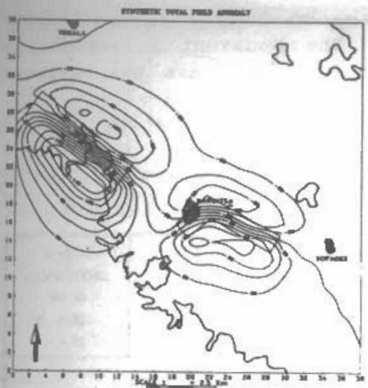

Fig. 6: Projection on the ground surface of the prisms which simulate the two magnetic bodies present in the Karditsa subbasin along with their produced effects.

Σχ. 6: Προβολή στην επιφάνεια των ποισμάτων που προσομοιάζουν τα δύο μαγνητικά σώματα της υπολεκάνης της Καρδίτσας μαζί με την επαγόμενη ανωμαλία τους.

power spectral depth estimates. On the other hand, the lateral dimensions and the position of the bodies were approximately delineated by the inverse filtering.

The plane view of the concluded model along with the produced effect is shown in figure (6). The anomaly of this map matches that of figure (4) in most aspects. The northern body is dipping at an angle of 45°. It is considered to be buried 3.3 Km^2 beneath the flight level and its cross section is 13X14 Km wide. Its extent along the dipping direction s 0.1Km. The Southern body is consisting of two parts which are positioned 70° apart one relative to the other 9Km long. This prism was considered vertical sided and the distance from its upper surface to the flight level is 2.7Km.

The magnetization parameters used are those assigned to the ophiolites of Pindos zone as shown in table (I). It does not mean that the entire ophiolithic belt belongs to the Pindos zone. This is a question to be answered by drilling in the future. Note that only the magnitude of the remanent magnetization differs between the ophiolites belonging to the different zones. The variance is high enough which means that the various components of the ophiolites show a wide and overlapping range of values. Therefore, the remanent parameters can not be assessed without having cores of the material of the bodies.

Modeling of the gravitational field was attempted along the profiles which are annotated as AA' and BB' in the figure (2). The 2-D computational algorithm used was that given by Won and Bevis (1987) which was based on the method of Talwani et al. (1959). That algorithm was used for the Subpelagonian and Pindos substratum which was considered as extending to infinity. The ophiolitic bodies, the Sofades limestone, the Karditsa sequence and the Plio-Pleistocene sediments were considered as being of 2 1/2-D. Their effect was calculated using the Rasmussen and Pedersen (1979) algorithm. The concluded models along the profiles AA' and BB' are depicted in figure (11). The profile AA' crosses the area of the commercial boreholes in the village Agnantero.

The near surface layer was considered as being the package of the Plio-Pleistocenic sediments having a density of 2 10t m^{-3} obtained by the Nettleton profile. The Karditsa sequence which underlies the shallowest formation was considered as having a density of 2.30 $t \cdot m^{-3}$. This value is justified by the measurements of table (I) and the Nettleton profiles which were carried out by I.F.P. The density of the other units were constrainted by the values given in table (I).

The profile BB' crosses the Sofades uplift, which is depicted in figure (7), as well as the Karditsa graben. The Post-alpide units of the graben seems to reach a maximum depth of 650m below sea level. The same quantity reduces to 450m at the Northern side of the profile. The Sofades uplift shows an extent of approximately 12Km.

The thickness of the recent sediments plus that of Karditsa formation is much smaller along the profile AA', as deduced from figure (7). The Karditsa graben seems to reach a maximum depth of 600m below sea level. The graben

Table I: Geophysical parameters on samples from the main lithological units outcropping around the Karditsa subbasin. The apparent susceptibilities were measured in situ; the values presented here are the averages of a large number of readings.

Πίν. I: Γεωφυσικές παράμετροι δειγμάτων από τις κύριες λιθολογικές μονάδες που εμφανίζονται στην υπολεκάνη της Καρδίτσας. Οι φαινόμενες επιδεκτικότητες έχουν μετρηθεί στην ύπαιθρο. Οι τιμές που παρουσιάζονται εδώ είναι μέσοι όροι ενός μεγάλου αριθμού μετρήσεων.

LOCATION	SAMPLES	DENSITY $t\,m^{-3}$	REMANENT MAGNETIZATION PAPAMETERS			LITHOLOGY	APPARENT SUSCEPTIRICITY OF THE FORMA. IN (S.I.)
			MODULUS 10^{-3} Am^{-1}	INCLINATION Degrees	DECLINATION Degrees		
		KARDITSA		**SEQUENCE**			
K3	1	2.267				Sandstone Mitropolis Formation	
D	4	2.360±0.009				Sandstone Mitropolis Formation	
		PINDOS		**ZONE**			
K5	1	2.635				Limestone	
K.1	23	2.697±0.320	500±200	60±10	0±10	Ophiolites (oph. P)	1000×10^{-6}
K4	3	2.600±0.080				Flint	
		SUBPELAGONIAN		**ZONE**			
SO	2	2.700±0.082				Limestone of sofades (lmst.S)	
P	4	2.563±0.018	800±300	60±10	0±10	Limestone (lmst.S)	1500×10^{-6}
B.TH	7	2.487±0.08				Ophiolites (Oph. S)	

north - east of the city of Sofades seems to be o the same depth.

The ophiolitic bodies seem to be overlain by limestone. The density of these structures was considered 2.70 $t\,m^{-3}$, which is the value obtained for the ophiolites of Pindos zone according to table (I). This is a compromise, because the true density of the bodies can not be accuratly assessed without drilling. Any assumption is crude, since the variance of the values for the ophiolites of both zones is very big. Indeed, if we judge only by the location of the bodies, as revealed in figures (5) and (6), it can be concluded that the southern one belongs to the Subpelagonian zone.

ΣΥΜΠΕΡΑΣΜΑΤΑ - CONCLUSIONS

The Sofades uplift bounds the Karditsa graben in its northeastern limit. It seems to consist mainly of limestone of the Subpelagonian zone. It's lateral extend is 12X15Km^2.

The depth of the Karditsa graben, which is responsible for the formation of the subbasin, reaches a maximum of the order of 600m below sea level of about the same order is the depth of the second graben at the northeastern side of the Sofades uplift. These estimates are shallower than the depth to the basement obtained by the boreholes in Agnantero.

The ophiolites which expose themselves all around the Karditsa subbasin, form the northwestern to the southern boundaries, seem to constitute a continous belt. It is concealed under the other units of the subbasin but produces pronounced magnetic effects.

ΕΥΧΑΡΙΣΤΙΕΣ - ACKNOWLEDGMENTS

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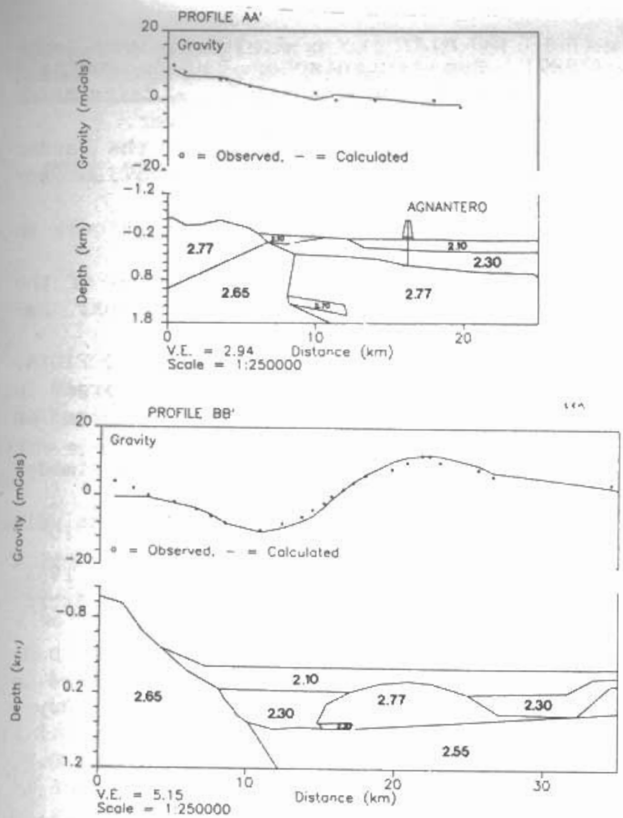

Fig. 7: The gravity interpretation model along the profiles AA' and BB'. The location of the commercial boreholes is properly annotated. The observed Bouguer gravity anomalies and the values derived from this model are also shown.

Σχ. 7: Το μοντέλο βαρυτικής ερμηνείας κατά μήκος των προφίλ AA' και BB'. Η θέση των εμπορικών γεωτρήσεων φαίνεται στο σχήμα. Η παρατηρημένη ανωμαλία Bouguer καθώς και οι τιμές που καθορίστηκαν από το μοντέλο επίσης παρουσιάζονται στο σχήμα.

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