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THE STRIKE SLIP TECTONIC REGIME AT SOUTHERN AEGEAN SEA AS IMPLIED BY COMPINED MARINE GEOPHYSICAL SURVEY

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ABSTRACT

The processing and analysis of the data, acquired by a precise and dense marine geophysical survey at Southern Aegean sea, shed more light to the particular geometrical pattern of the tectonic deformation of the area. Its dominant feature seems to be a conjugation, of two shear zones sets striking NW-SE and NE-SW. The model, of a distribution of rhombed shaped "pull apart basins", has been applied in order to explain the characteristic local depressions, that comprise the Southern Aegean basin. In addition the construction of deterministic vertical cross section models, adjusted in gravity and magnetic profiles along the NE-SW direction, suggest the presence of compressional tectonic structures (active or non active ?), at the southern borders of the basin.

ΣΥΝΟΨΗ

Η επεξεργασία και ανάλυση των δεδομένων, μιάς λεπτομερικής θαλάσσιας γεωφυσικής διασκόπισης στο Νότιο Αιγαίο, αποκαλύπτει μια νέα διάσταση στην γεωμετρική εικόνα της τεκτονικής παραμόρφωσης της περιοχής. Κύριο στοιχείο της φαίνεται να είναι μιά συζυγία οριζοντίων ζωνών διατμητικών τάσεων, με προσανατολισμούς ΒΔ-ΝΑ και ΒΑ-ΝΔ. Γιά την ερμηνεία, των χαρακτηριστικών τοπικών λεκανών της περιοχής, προτείνεται ο μηχανισμός διάνοιξης εγκαρσίων λεκανών διαστολής. Επί πλέον από την σύνταξη φυσικογεωλογικών τομών, προσαρμοσμένων στα βαρυτικά και μαγνητικά δεδομένα κατά την διεύθυνση ΒΑ-ΝΔ, προκύπτει η ύπαρξη συμπιεστικών δομών (ενεργών ή απολιθωμένων;) στις νότιες παρυφές της λεκάνης.

INTRODUCTION

The Southern Aegean sea is an epicontinental sea, located at the boundaries of the European and African collision zone. Its characteristic arcuate shape make it similar to the island arc systems of the pacific type. Geologically it is a complex area, located within the Alpine- Himalayan orogenic system. The rocks outcropping in this region form part of the Mesozoic-Tertiary folded chain, which can be traced from the Hellenides, through the outer island arc, up to the Taurides (Abouin et al 1963, Smith & Moore

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1974, Kuss and Thorhecke 1974).

The Southern Aegean sea is a region affected by a remarkable volcanic activity, belonging to the Pliocene- Pleistocene tectonic phase, which became intensive during the Quaternary (Fytikas et al. 1976). Most of this activity can be traced out on a sequence of islands (Milos, Santorini, Nisiros, Kos), located in an arcuate arrangement, known as the volcanic arc.

Moreover any seismicity map indicates, that the Southern Aegean area is the most active in Europe (Fig. 1). This seismic activity is mostly concentrated along a zone, which coincides with the Hellenic trench.

Many geophysical aspects of the area have already been studied. Among the various works, we can consider as most important the following, dealing with gravity and magnetism (Morelli et al. 1975), heat flow (Erickson et al. 1979, Jonsma 1974), seismic reflection (Jonsma et al. 1977, Bartole et al. 1983, Mascle & Martin 1990), refraction (Makris 1977, Makris et al 1986), seismicity (Papazachos & Comninakis 1978, Drakopoulos & Delibasis 1982).

Most researchers attribute the Neogene geodynamic evolution of the area, to subduction by the African plate or a Tethys platelet of African affinity (Galanopoulos 1963, 1972, 1974, Caputo et al. 1970, Papazachos & Comninakis 1971, 1978, Comninakis & Papazachos 1972, 1976, Ninkovitch & Hays 1972, Alvarez 1973, Parazachos 1977, Le Pichon & Angelier 1979).

According to their hypothesis, the basin of the South Aegean is a back arc basin, mainly dominated by extensional deformation. However although the simple application of "lithospheric plates" theory in this case has been popular among the geoscientists, its complete acceptance is still in doubt. More specifically a series of researchers estimate, that the existence of a Benioff zone in Southern Aegean is not very well defined.(Scwilling 1972, Makris 1976, 1977, 1978, Mercier 1977, Makropoulos & Burdon 1984).

Some of the main aspects of question, that put this point of view in discussion, can be summarized as following: a) A trench along the "Hellenic arc", comprised by a series of rather narrow and relatively shallow sediment - starved "trenches", b) A volcanic arc of widely spaced small volume complexes, with ages decreasing toward the "trenches", c) A highly seismic upper lithosphere separated from a non descript Benioff zone, by an aseismic wedge-shaped lower lithosphere, d) A nonuniform back-arc basin believed to be result of regional extension, but exhibiting a typical "Basin and Range" topography, suggesting a more complicated stress field.

Moreover the most perhaps significant for the geodynamic evolution, of the Southern Aegean area, (Zeilinga De Boer 1984) is the difference in sign and direction, of the dominant (NNE-SSW) extension in the upper lithosphere and the (NE-SW) compression, arising by the subducted slap. Thus as Mckenzie (1978) characteristically points out, until the history of the deformation behind the arc is known in some details, it is not possible to make reconstruction to discover, where pieces of the sinking slab were subducted.

Starting on this basis, it was attempted to shed more light to the peculiarities of the geodynamic mechanism, that are responsible for the creation of the Cretan basin. This effort was approached, through the tracing out of the geometrical pattern, revealed by the horizontal distribution, of several morphological or geophysical parameters, which should be related in one or other way with, the tracks of the tectonic deformation of the area.

For this purpose, the gravity and magnetic field as well as the bathymetry of the area were precisely resurveyed (Fig. 2), during five exploration cruises, with the Greek R/V "Aegaeo" (19-26/7/86, 2-10/10/86, 20/1-17/2/86, 10/11-18/12/87 and 2/11-16/12/88) and one with the German R/V "Sonne" (26/3-18/4/86). The survey gave the chance, to collect data for new more precise gravity, magnetic and bathymetric maps of Southern Aegean area.

MAGNETIC FIELD

The main feature of the local magnetic field (Fig 3) is the alternation, of very well defined zones of different magnetic character. More specifically we can separate two main areas, of high amplitude and short wave length anomalies. The first is located at the NWestern part of the map (Mirtoo sea area), including the volcanic system of Milos. The second is located at the central part of the map (Cretan sea area), including the volcanic system of Santonini. The above areas are separated by zones of relatively quiet magnetic field. It is worth to say that their boundaries are selectively striking NW-SE and NE-SW. These two directions seem to dominate, among the trends followed by the field deformation and they are clearly observed, at the map of its first derivative (Fig. 4) (Ackerman & Dix 1955).

Applying spectral analysis (Bhattacharyya 1966, Spector & Grant 1970, Παυλάκης 1992), it was possible to estimate and map, the upper (Fig.5) and lower surface (Fig.6) of a "magnetic basement". Obviously the lower surface coincides with the Curie point temperature, i.e. the temperature at which the materials lose their magnetic properties (about 520-560oC, Buddington & Lindsley 1964).

Although the "magnetic basement" (Fig. 5) is a geophysical theoretically derived discontinuity, it can be correlated with the crystalline basement, since it usually shows higher magnetic susceptibility than its sedimentary covering. However it is interesting, that this surface shows a "basin and range" topography, characterized by alternations of elongated exaltations and depressions, striking NW-SE, which seem to be terminated by boundaries striking NE-SW. It is worth to mention, that its deepest depressions are located at the southern arcuate borders of the area, making it consistent with the existence of the sedimentary arc (Peloponissos-Kythira-Crete-Karpathos-Rodos).

On the other hand, the lower surface of the magnetic basement (Curie point temperature) (Fig. 6) show a zone of local exaltations to 10-9Km, that is located at the central parts of the basin striking NWW-SEE. The zone is getting wider SEEastwords, while its abnormally shallow depths are usually met in high heat flow areas (Bhattacharyya & Leu 1975, Okubo et al 1985).

Finally a first estimation, of the distribution of the magnetic susceptibility, at the magnetic basements upper surface was attempted (Παυλάκης 1992) (Fig. 7). The striking feature on these map is the development, of high susceptibility zones towards the NE-SW direction. This situation is particularly obvious, at the central and western parts of the map. On the contrary at the NEastern part of it, we can observe the margins of a high susceptibility zone striking NW-SE. Along these zones, the parameter seems to reach maximum values, at the crossing places with the volcanic arc. However it is worth to say, that local susceptibility maximums can be observed also in other places, outside the volcanic arc.

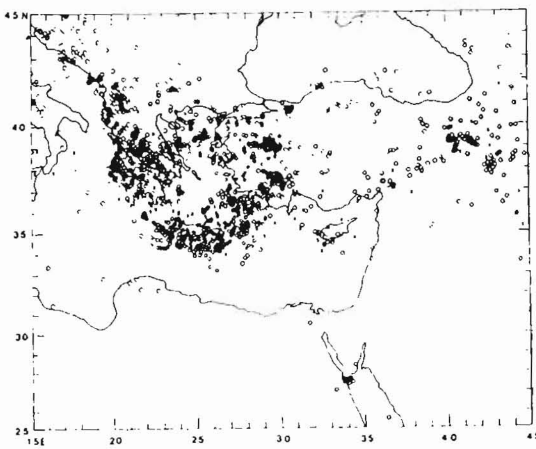

Fig. 1 Earthquake epicentres for the period 1961-1974, as located by U. S. Coast & Geodetic Survey. Earthquakes deeper than 50km are marked by an x and those shallower than 50km by circles.

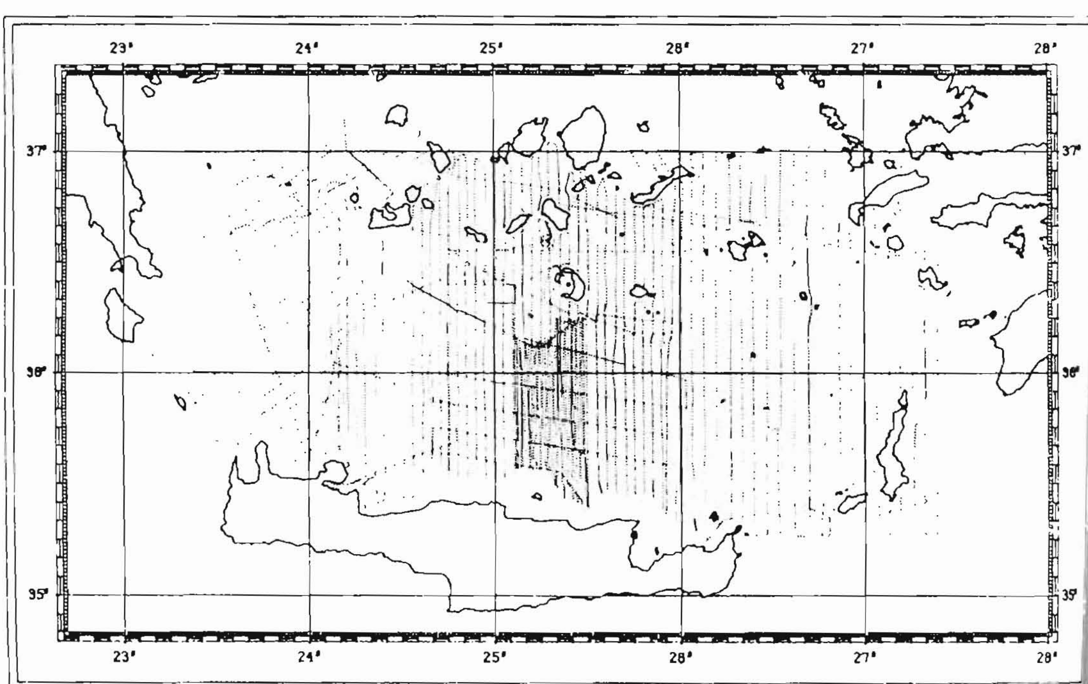

Fig. 2 Vessel tracs over which the measurements were made during the period 1986-89.

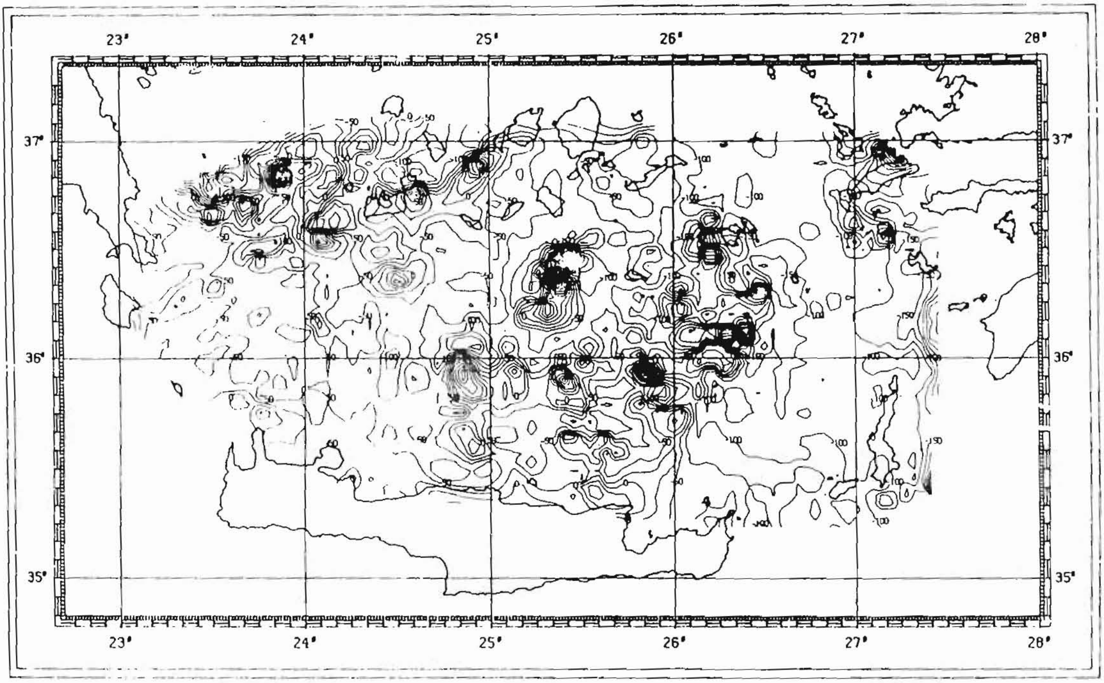

Fig. 3 Local magnetic field of South Aegean (C.I. 25γ).

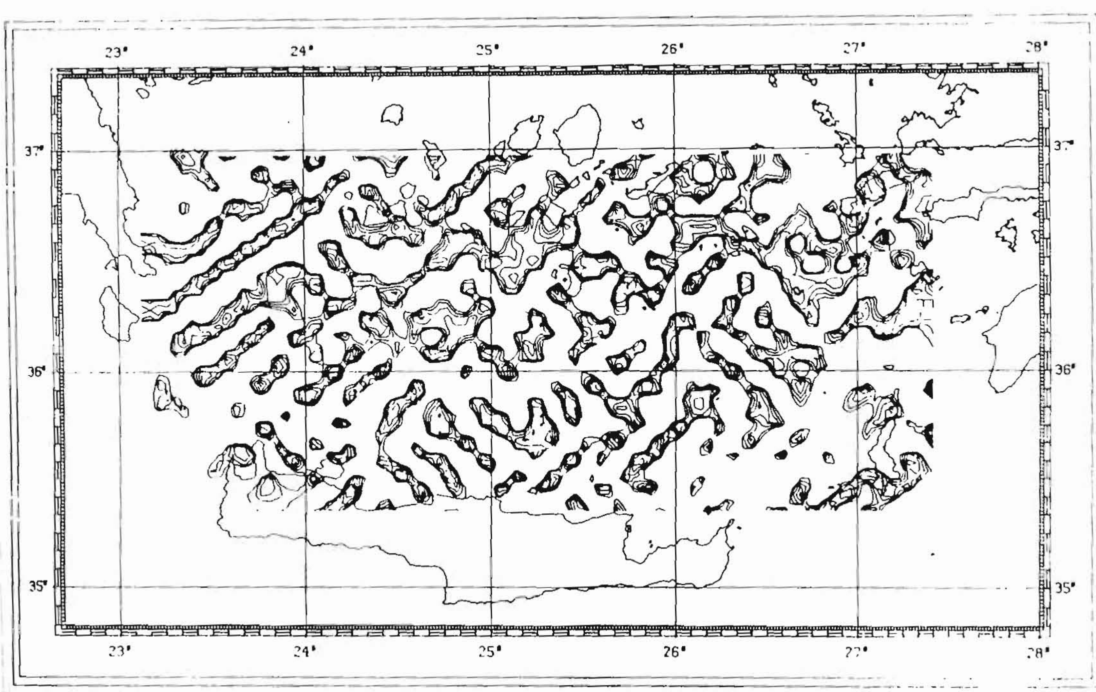

Fig. 4 First vertical derivative of the local magnetic field (contours show negative values).

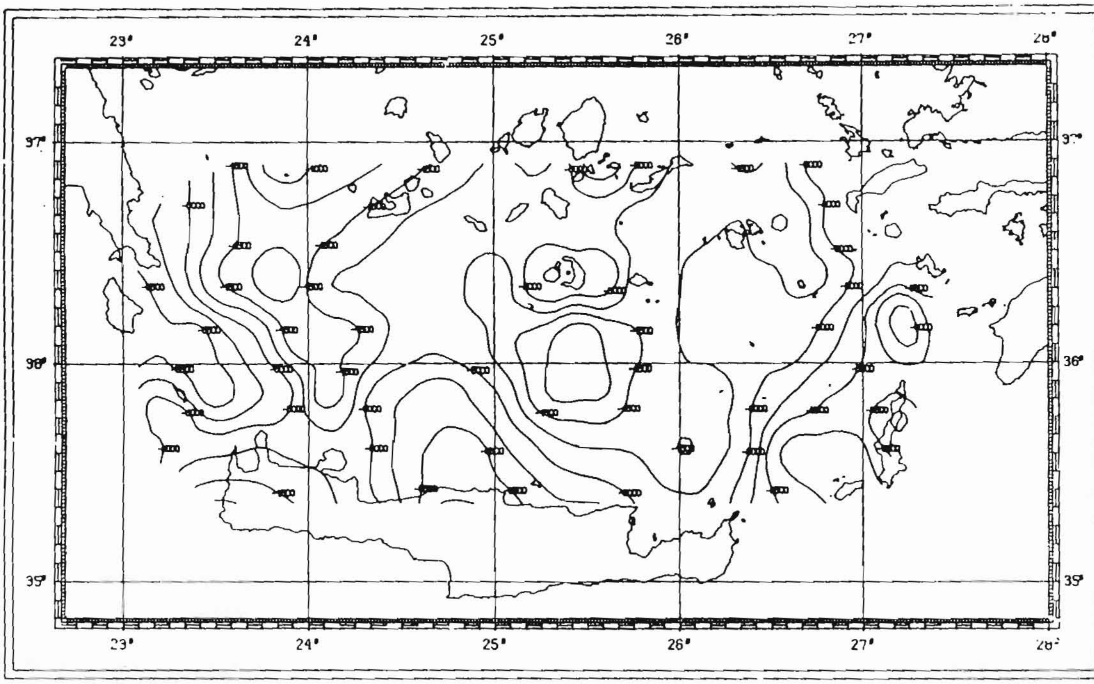

Fig. 5 "Magnetic basement". Depths from sea level derived by the local magnetic field (C.I 250m).

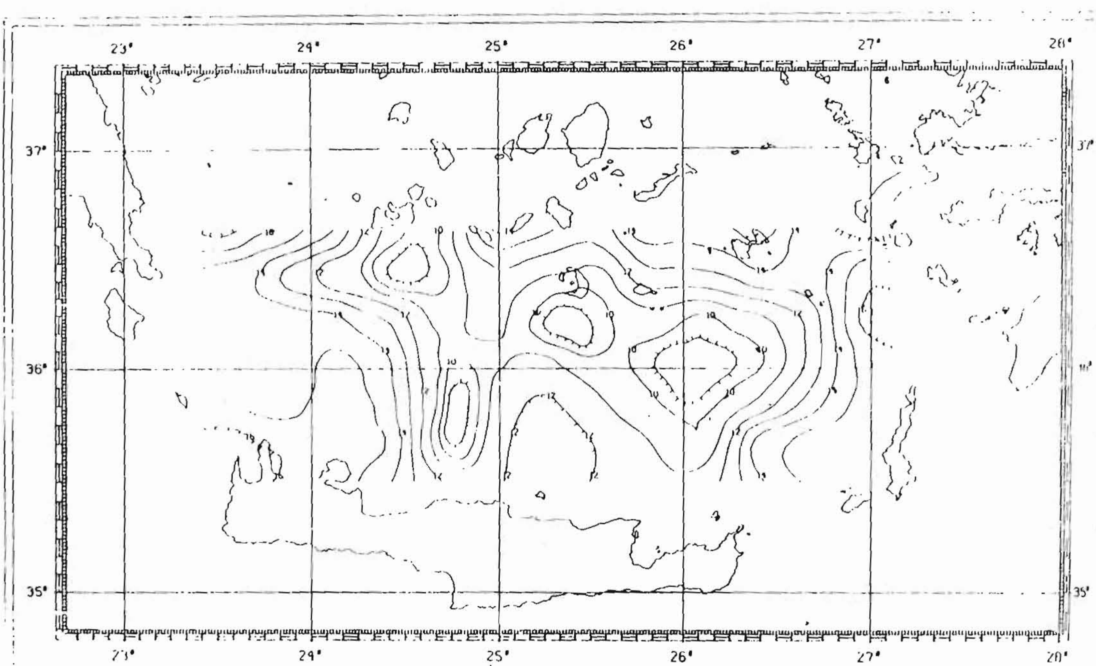

Fig. 6 Curie temperature surface. Depths from sea level derived by the local magnetic field (C.I. 1km).

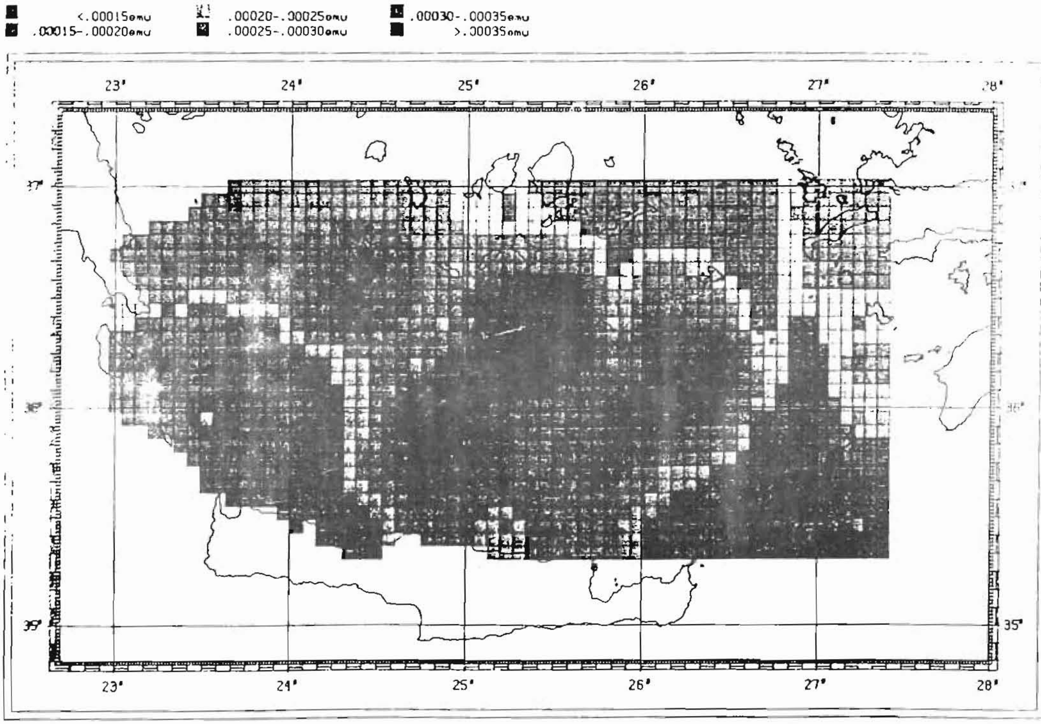

Fig. 7 Magnetic susceptibility distribution of the "magnetic basement".

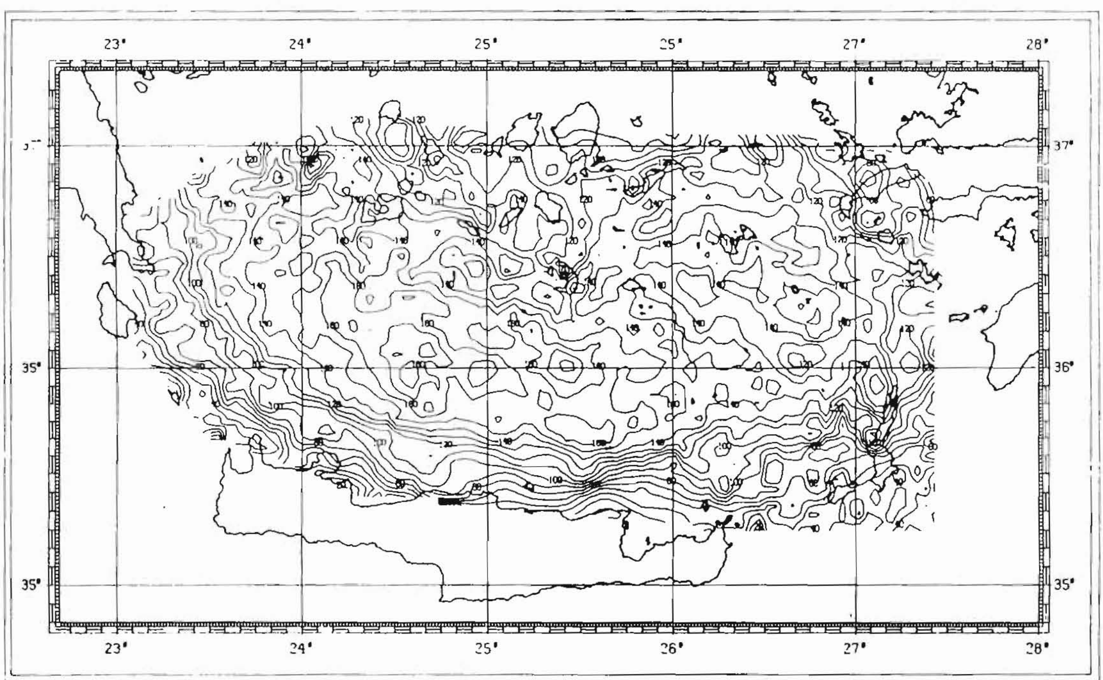

Fig. 8 Complete Bouguer gravity anomaly of South Aegean (C.I. 10mgal).

GRAVITY FIELD

The main features of the Bouguer gravity anomaly are already known by previous studies (Morelli et al 1975). However the present work yielded a remarkably more detailed Bouguer map (Fig. 8). Hence it is possible to reveal the geometrical pattern of the tectonic deformation, by reducing it to its first derivative (Fig. 9).

Although there are differences between the picture, presented by this application, with the relevant one of the magnetic field (Fig. 4), it is obvious that ones more, the predominant features seem to be, the very well defined crossing zones which are striking mainly NW-SE and NE-SW.

The most intensive appearance of such zones is observed in the western part of the map (Myrtoo sea area). It is worth to say that the NE-SW strikes, dominating in this area, are almost perpendicular to the normal faults previously mapped at this place, by seismic reflection surveys (Jongsma et al 1977 Bartole et al 1983, Mascle & Martin 1990) (Fig. 10). An other interesting appearance of strong linearity is passing through the volcanic island of Santorini striking NE-SW. This zone seem to be crossed, in the center of the area, by another striking NW-SE. On the contrary the eastern part of the map seems to be dominated, by NW-SE striking narrow zones, crossing almost perpendicularly the elongated basin, that is located westwards of Karpathos island (Fig. 11).

Concluding so far we can say, that these results support the existence of major tectonic lines, not only parallel to the arc, as it was mostly believed, but also perpendicular to it.

DEFORMATION OF THE BOTTOM TOPOGRAPHY

It is well known that the sedimentation is smoothing the roughness of the sea bottom, mainly caused by tectonism. Therefore the study of the bottom roughness offers a good way, to trace out the surface expressions of recent tectonic deformations. In this case the dense bathymetric data (Fig. 11), acquired by this work, permitted the application of a detailed analysis.

Arranging the data in a normal grid (3 nmiles interval) (Παυλάκης 1992) and passing, using the least square method, a plane surface at each elementary grid sell, we estimated its dip, strike and the standard deviation of the bottom roughness.

The results showed (Fig. 12) that higher values of the topographic slopes are mostly concentrated, at very well defined narrow zones. These zones more or less separate the area, in well defined rhombed shaped blocks. This is clearer at the western part of the area, while at the eastern part the situation becomes ambiguous, suggesting an either more severe or more resent tectonism. An analogous picture is revealed on the map of dips and strikes (Fig. 13), of the elementary grided topographic planes. What is interesting here is that the zones of the major slopes are mostly striking E-W. On the other hand, the appearance of major zones of slopes striking NW-SE and NE-SW is rather eliminated. Exceptions to those can be observed at the SWestern and SEastern parts of the map.

The map of figure 14 shows the distribution of the standard deviation, of each elementary plane fit. Obviously this map reveal a first picture of the bottom roughness, which seems to be more severe at the SEastern part of the map. Probably this implies either a more intense or a more recent tectonic deformation happened at the SEastern part of the area.

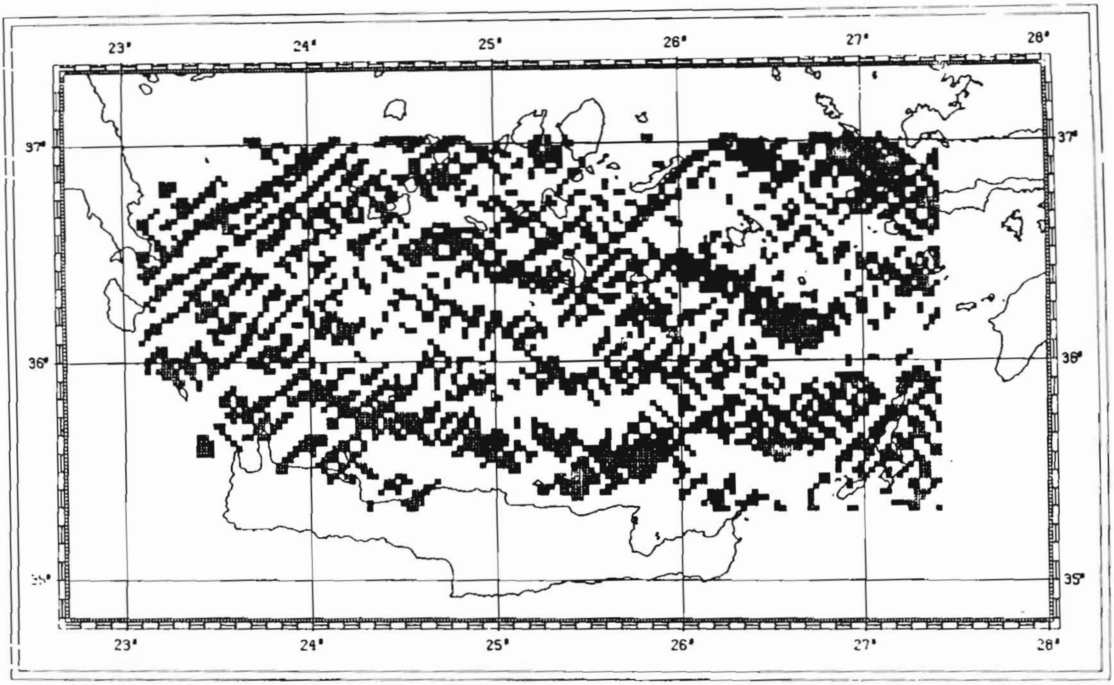

Fig. 9 First vertical derivative of Bouguer gravity anomaly (shaded areas show negative values).

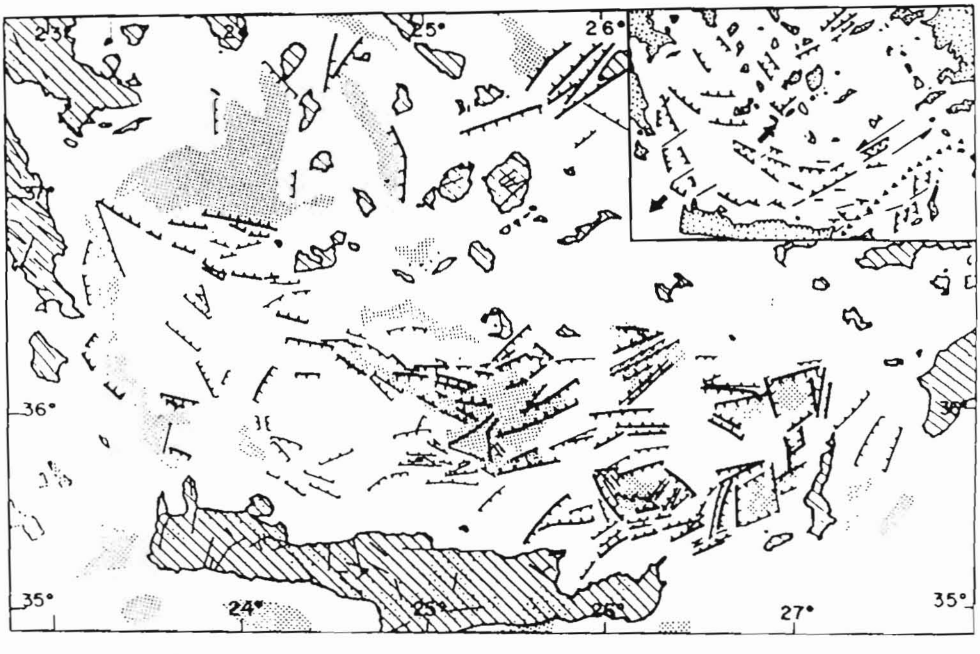

Fig. 10 Surface expression of the main faults in South Aegean. maped by seismic reflection profiles. (Mascle & Martin 1990).

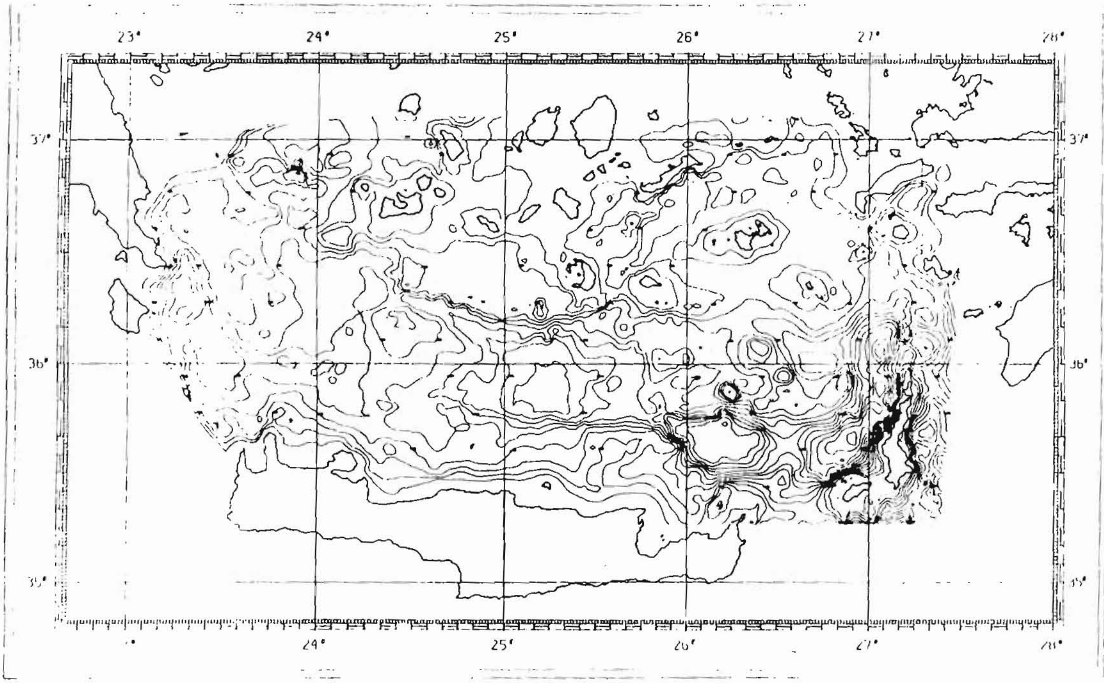

Fig. 11 Bathymetry of the South Aegean (C.I. 150m).

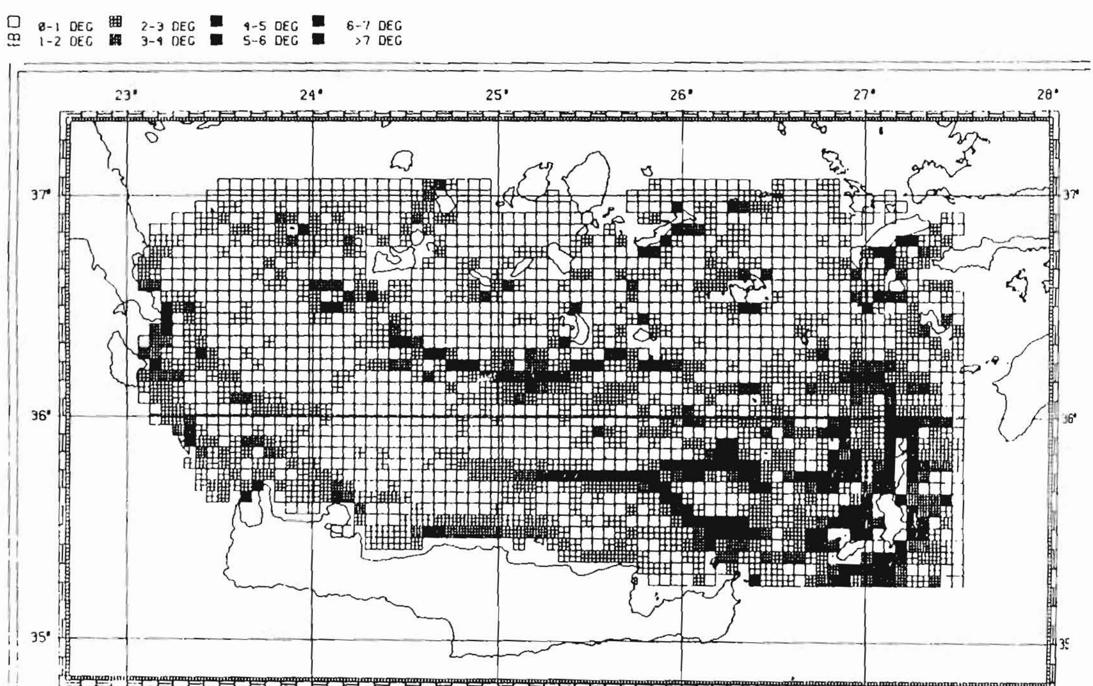

Fig. 12 Slope magnitude distribution of South Aegean bottom topography.

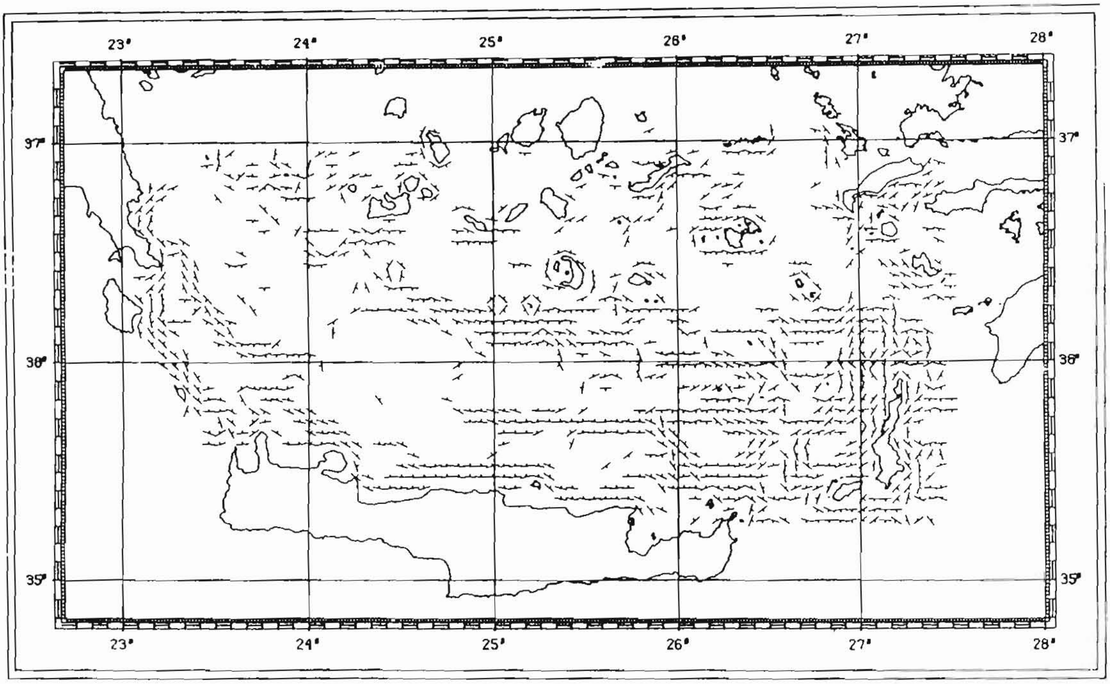

Fig. 13 Strike and dip directions of major (>2 degrees) slope zones in South Aegean.

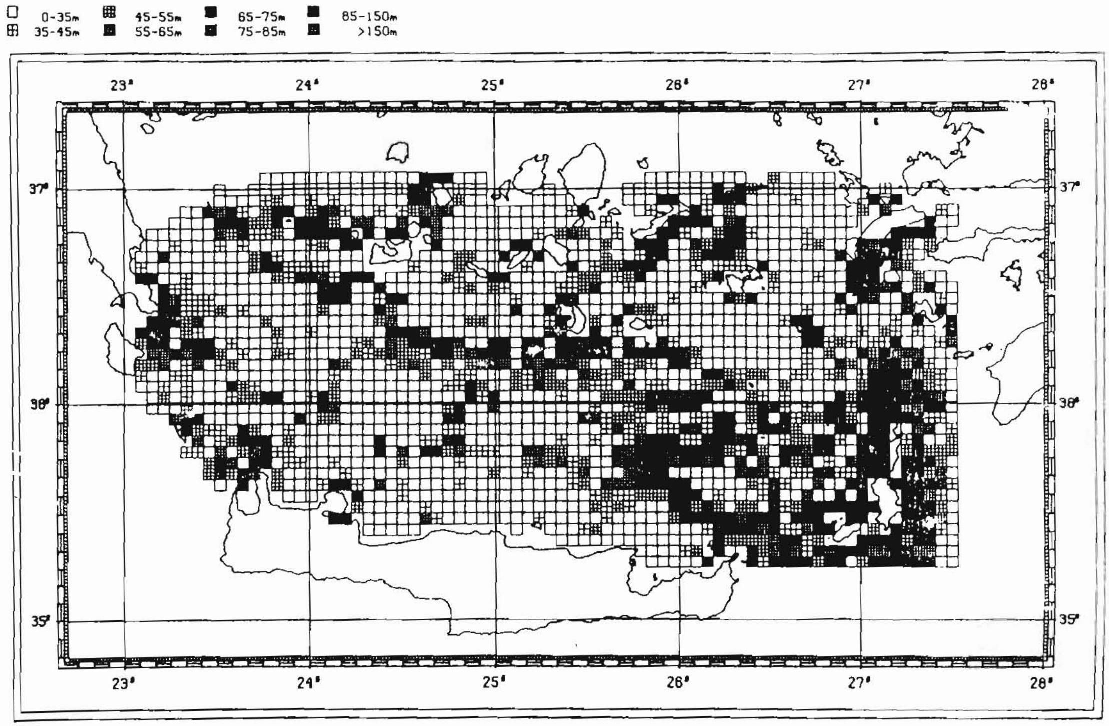

Fig. 14 Roughness of topographic relief in South Aegean.

The most striking feature on this map, is that higher values of the operator are mostly concentrated, along long narrow zones. The predominant directions of those zones seem to be the NW-SE and NE-SW, while the E-W direction is rather eliminated. Comparing it to the maps of topographic slopes (Fig. 12,13), we can see that some of these zones correspond to zones of great slopes, while some others not. A interesting example is the very well defined zone that is passing, through the volcanic island of Santorini striking NE-SW. This zone does not show any important correspondent on the topographic slopes. On the other hand in many cases, at their cross points with the E-W striking major slope lines (Fig. 13), the dip arrows of the latter, reverse orientation. These remarks are important since they manifestate a strike slip origin for these horizontal tectonic discontinuities, unveiled because of their high topographic relief.

GEOPHYSICAL CROSS SECTIONS

In order to study the vertical tectonic structure of the area, four geophysical cross sections, striking NE-SW were adjusted on gravity and magnetic profiles (Tallwani & Heirtzler 1964). The main geological/ geophysical discontinuities, as well as their parameters which formed the control settings of the adjustment procedure, where implied both by the present analysis and the previous seismic reflection (Jongsma 1974) or refraction studies (Makris 1977). More specifically the models were composed by the following main geological/geophysical crustal discontinuities.

a) The Mohorovicic (M) and Conrad (G) discontinuities (the order of their depths were estimated by seismic refraction studies, Makris 1977).

b) The Curie temperature surface (C) (Fig. 6).

c) The sediment/basement discontinuity (Fig. 5).

d) The consolidated/non consolidated sediment discontinuity (its depths were estimated by seismic reflection profiles (Jongsma et al 1977, Bartole et al 1983).

e) The bottom surface (Fig. 11).

The densities of the layers were estimated by the seismic velocities (Makris 1977, Nafe & Drake 1973), while the magnetic susceptibilities by the present analysis (Fig. 7).

Starting by this simplified crustal synthesis, we mainly attempted to approach the tectonic structure, which could be perfectly adjusted both to the gravity and magnetic profiles.

The resulted two models at the western side of the area (Fig.15a,15b) show a sequence of faults, which are turning from normal to reverse from NE to SW. The sequence of faults at the third model (Fig. 15c) is different. They are reverse at the NEast side of the section, become normal at the center and turn to reverse approaching the zone of collision. Finally the fourth model (Fig. 15d) shows a sequence of low dip reverse faults, which become normal at its NEastern side.

An interesting feature that appears on the sections is the presence of local crustal exaltations, accompanied by uprising of the Curie temperature surface. Higher tectonic deformation, is implied at the cross points of the sections with the volcanic arc. At these places the deformation seems to be expressed as normal faulting, with the exception of the third section (Fig. 15c) (near Astypalea island), where the faults turn to reverse. At this place, the derived faults show great throws, while there is an accumulation of the

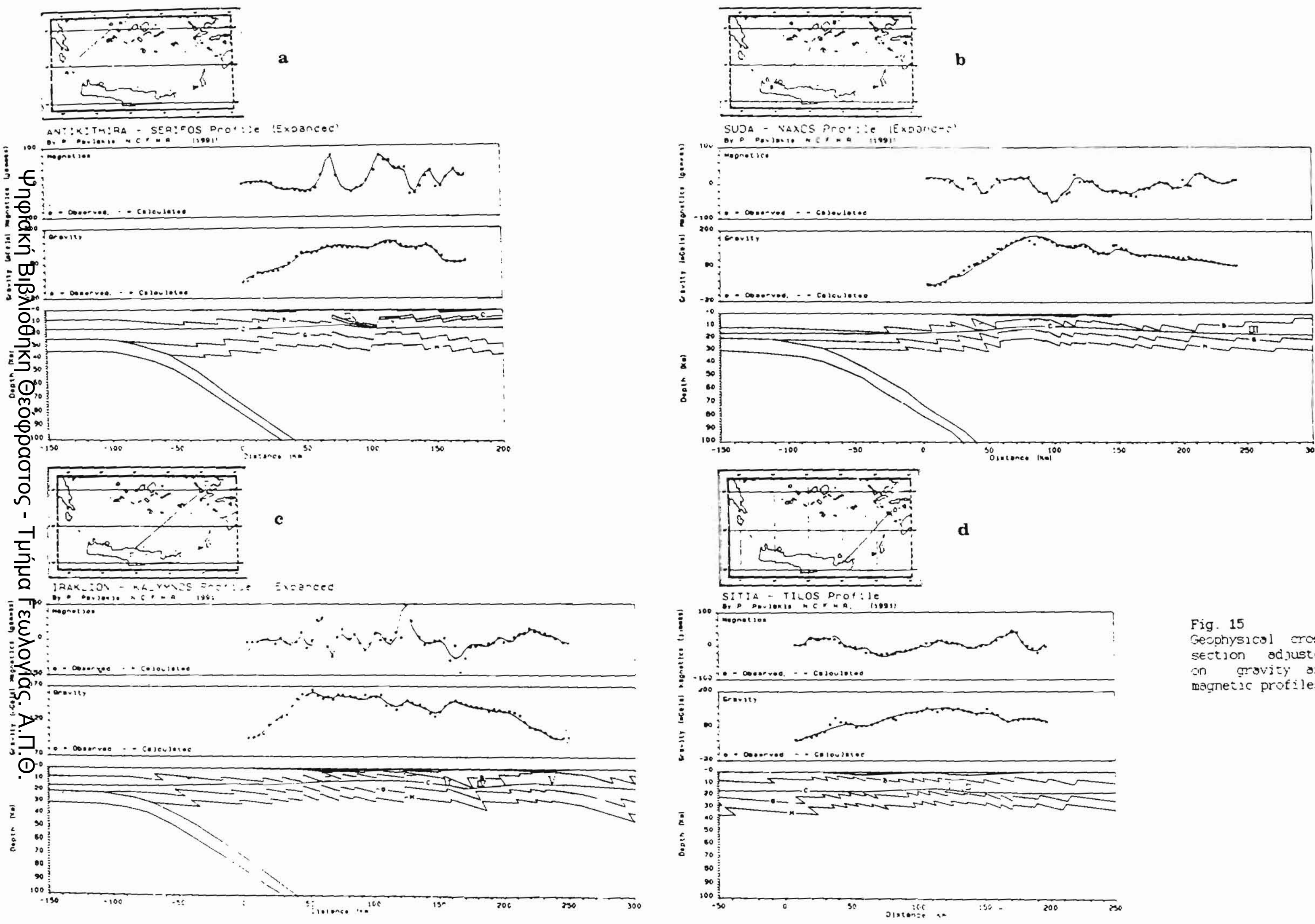

Fig. 15
Geophysical cross section adjusted on gravity and magnetic profiles.

sedimentary layer, manifestating the existence of a major overthrust.

Based on the fault character as they implied by the four geophysical cross sections, we proceeded to a classification of the area in sectors of compressional or extensional deep tectonic structures (Fig. 16). This was attempted by dividing the area firstly in zones striking NE-SW, bounded by the most possible lines of lateral tectonic discontinuities, revealed by the maps of the previous analysis (Fig. 14).

By the implied classification (Fig. 16) we can see places where the stress field change sign, across the assumed (NE-SW) lateral discontinuities. This is particularly apparent across the boundary, that is passing through the volcanic island of Santorini. Obviously this is one more evidence, supporting its possible strike slip origin.

Furthermore another important implication, resulted by this classification, is the presence of compressional structures at the Southern arcuate border of the basin. By a first look such a tectonic scenery should be easily accepted, since we are dealing with a boundary of a subducted slab. However the existence of the local basins at the SWestern and SEastern corners of the map (Malea and Karpathos) (Fig. 11), as well as the great normal faults of Crete island (Angelier et al 1982), suggest the influence of an extensional stress field. In order to resolve this contradiction, we have first to put the question: Are these deep structures non active or active?

In case that nothing but the first is true, they obviously concern structures created either during the general compressional period (Eocene-Miocene) or in the periods, of isolated compressional episodes (Mascle & Martin 1990). In case that the second is true, then how can those deep structures be compatible with the extensional structures which are observed on the surface?

Zeilinga de Boer (1989) inquires the possibility of a detachment mechanism as the link between the two. However the detachment mechanism alone, in a compressional environment, could possibly justify surface gravity faults or horst structures (Crete island), but the creation of very well defined local basins remain still in question.

ANGLE RELATION OF TECTONIC DEFORMATION ZONES AND "PULL APART BASINS"

The difference in sign, between upper and lower stress fields, is not unusual among the peculiarities of the crustal tectonics. It has been already understood, that the normal faults, observed at the surface, do not imply a priori regional lithospheric extension, i.e. we can not exclude their origin, as secondary structures, of an almost transversal compressional field (Μαριολάκος & Στείρος 1989).

An example is the creation of "pull apart basins" between terminated strike slip faults (Rodgers 1980), in the frame of a regional compressional field (Milani 1989). More specifically, the relative movements on the thrust faults are likely to create strike-slip component. Subsequently, movement on systems of this type leads to local extension, generally termed as transtension. Thus normal fault systems are developed obliquely inclined to the main fault strike and their relative orientation is usually governed by pre-existing weakness. If however they are initiated by the shear motion in structureless rocks (Ramsay & Huber 1987), they should form obliquely [illegible] ees ("rhombed basins").

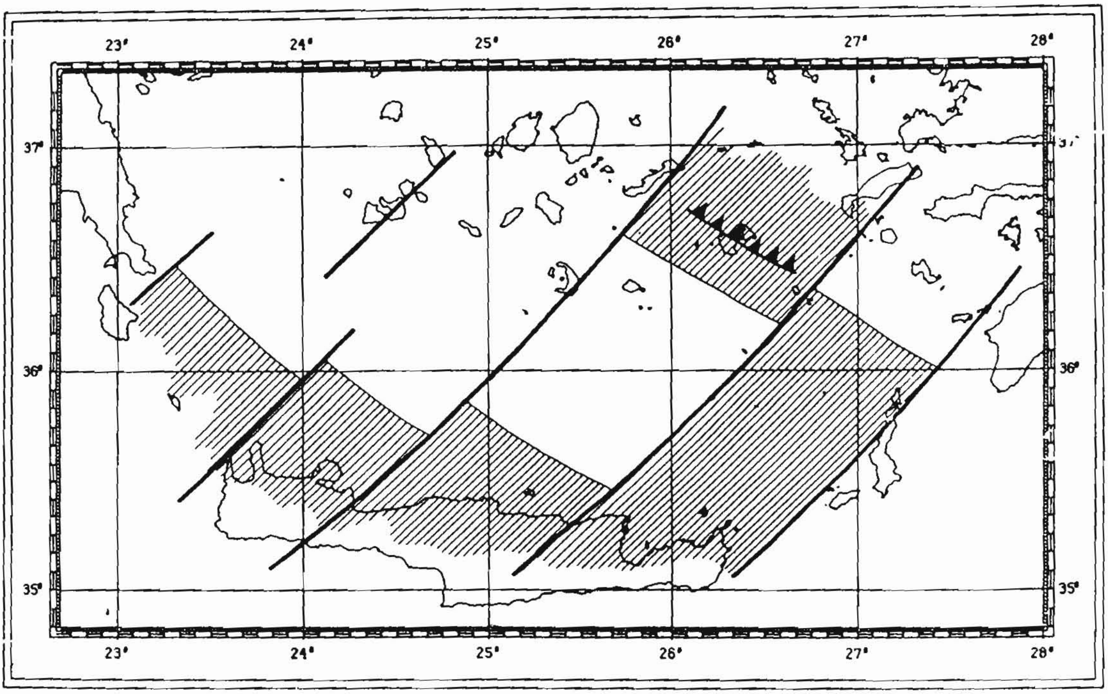

Fig. 16 Sections of compressional (Shaded) and extentional (non shaded) deep structures, derived by the geophysical models (Fig. 15).

a

b

Fig. 17 Proposed mechanisms of "pull apart basin" creation in compressional (a) or extentional (b) regional field.

A synthesis of this mechanism, representing the relative motion and angle relations of the moving blocks, is schematically represented by the tectonic model of figure 17a. Following the same geometrical reasoning we can also construct, a tectonic model linking local extensional structures on the surface with deep extensional ones (Fig. 17b). Obviously comparing the two models it appears, that the change in sign of the deep stress field, leads geometrically to changes in the orientation of the angle and motion relations.

Therefore it is quite important for our analysis, that the predominant angle relation, between the W-E striking zones of slopes (Fig. 12,13) and the NE-SW and NW-SE striking zones of deformation (Fig. 4,9,14), is approximately 45 degrees.

The above observation is also evident by the statistical analysis, of the slope distribution at three equal sectors of the area (Fig. 18). Obviously the three rose diagrams show that the E-W direction is predominant. On the contrary, with the exception of the western part, the NE-SW and NW-SE directions are greatly eliminated. Therefore the correlation of these zones with a conjugation of strike slip deformation pair set seem to be quite possible.

In that case we can postulate the existence, of the necessary link between the local extensional structures, observed on the surface, with the deep compressional or extensional tectonism, yielded by the geophysical sections (Fig. 15,16). Under this point of view, we can claim that the fault plane of the deep structure is a detachment surface, over which the opening of a "pull apart" basin is taking place, due to horizontal differentional movement.

Hence accepting the local basins of the South Aegean (Fig. 11,13) as "pull apart" basins and taking into account all the above results, we derived an ideal lateral tectonic synthesis of the area, with obvious kinematic implications (Fig. 19). This model yields a particular geodynamic way, which seems to be responsible for the general opening and crustal thinning of the Cretan basin. More specifically the development of the basin cames through the local creation of "pull apart" basins, resulted by the interaction between a dextral NE-SW orientated strike slip zone set and a sinistral NW-SE orientated strike slip zone set. However it is worth to mention, that the last pairs of both sets, close to the boundaries of the Hellenic arc seem to reverse their movement. This is a necessary implication, in order to explain the relative position of the two basins, at the SWest and SEast places of the area (i.e. Malea and Karpathos basin correspondingly).

DISCUSSION

The present work lead to a more refine tectonic model, of crustal deformation of the Southern Aegean area, with obvious geometrical reasoning. The conjugation of shear stress zones, to the NE-SW and NW-SE direction, has been implied to be the key of the geodynamic mechanism. Direct results of the tectonic interaction due to this conjugation are the "pull apart" basins. Subsequently the wide distribution of such transtensional rifting lead to crustal thinning, and uprise of the isotherm surfaces, causing localities of abnormal high heat flow and disturbance of the local isostasy, characterized by short wave length free air gravity anomalies (Morreli et al 1975).

Hence this way of deformation can perfectly explain the local uprises of the Curie temperature surface (Fig. 6), also the typical "basin and range" topography of the bottom (Fig. 11) and the

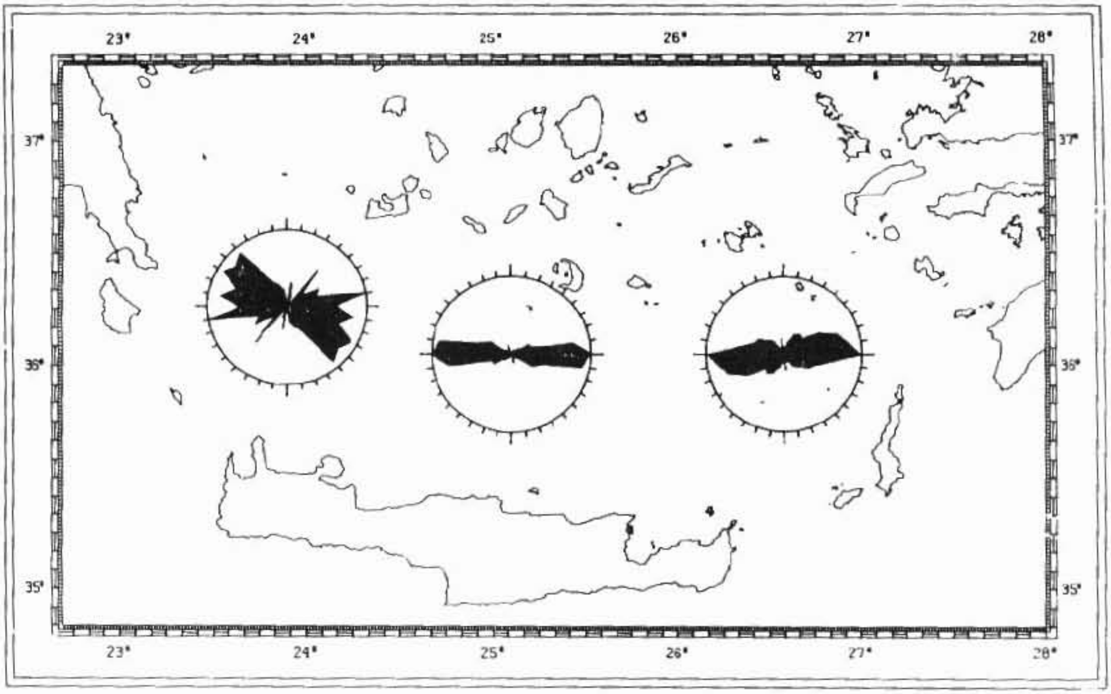

Fig. 18 Rose diagrams of major (>2 degrees) slope zone strikes, for three equal area sectors of South Aegean bottom topography.

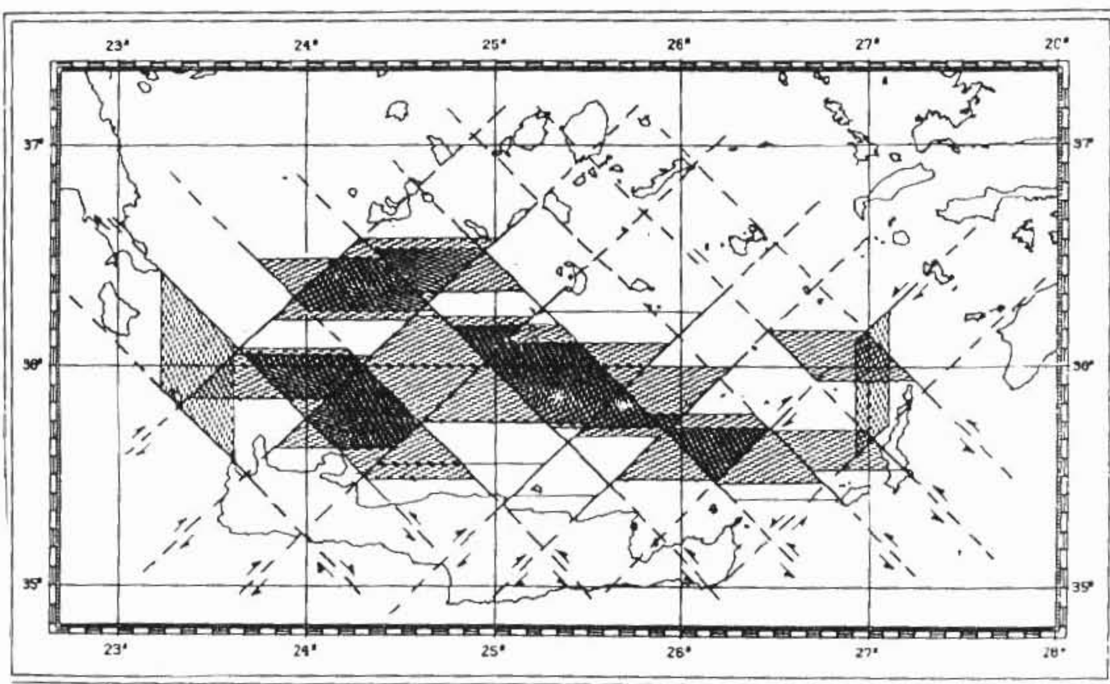

Fig. 19 Proposed ideal shear set conjugation, which defines the "rhombed shaped" local basins of the South Aegean.

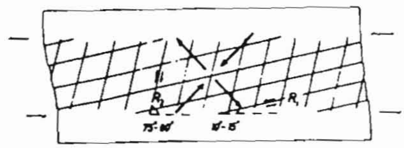

Fig. 20 Conjugate Riedel shears R1 and R2 resulting from secondary fault development in a zone of left-hand shear. The heavy arrows show the principal axes of incremental strain developed as a result of simple shear in the zone (By Ramsay & Huber 1987).

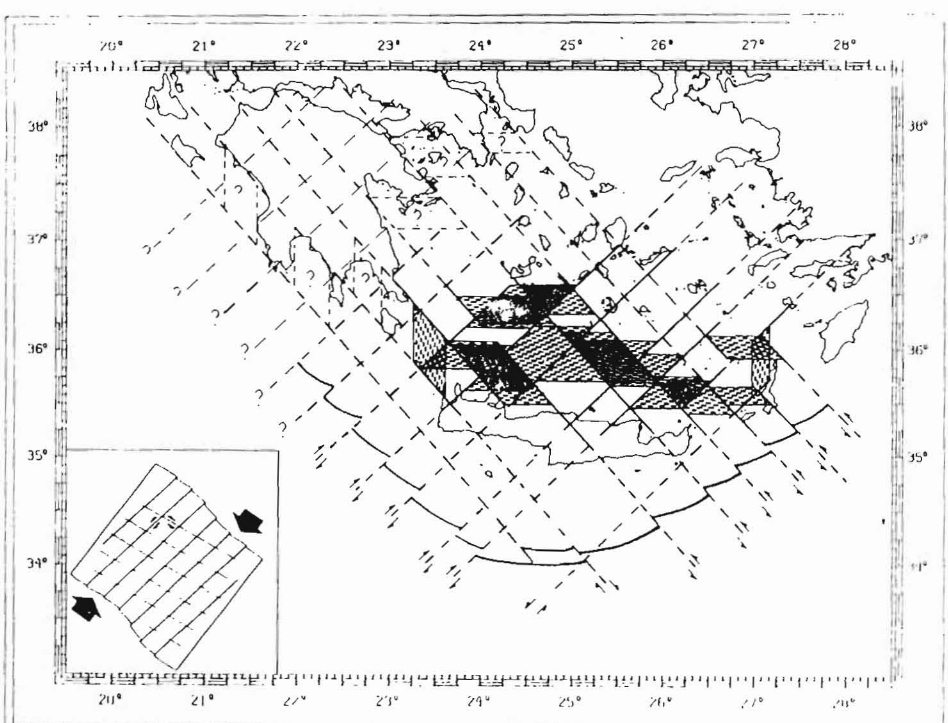

Fig. 21 Correlation of the extrapolated shear set conjugation (Fig. 19) with the major coastal morphological features of Southern Greece. The model down left shows the deformation of a plate undergoing a dextral simple shear and the resulting secondary Riedel conjugation.

"magnetic basement" (Fig. 5). In addition looking through this mechanism, we can easily resolve the difference in sign and direction, between the surface stress field (extension) and that one caused by the subducted slab (compression), along the Hellenic arc.

However the existence of such a conjugation leads to further considerations. More specifically it has been shown experimentally (Cloos 1955, Riedel 1929), that a conjugation of two crossing shear sets, of opposite motion known as Reidel shears, can be developed by the application of a simple shear. The direction of the mother simple shear is slightly oblique to the shear set of the conjugation having the same motion (Fig. 20).

Under this point of view we can postulate as the reason of the conjugation, a main dextral simple shear, that crosses the Aegean plate striking SSW. Thus looking through such an extrapolation, we could resolve probably a series of tectonic and morphological elements, that comprise the Aegean plate. An obvious example (Fig. 21) is the perfect compatibility, between the lines of the proposed ideal conjugation pair sets, with the morphological features of the Hellenic coast line, as well as the arrangement of the Cycladic islands.

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