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ΦΛΩΡΙΝΑ, 5-7 ΜΑΪΟΥ 1993

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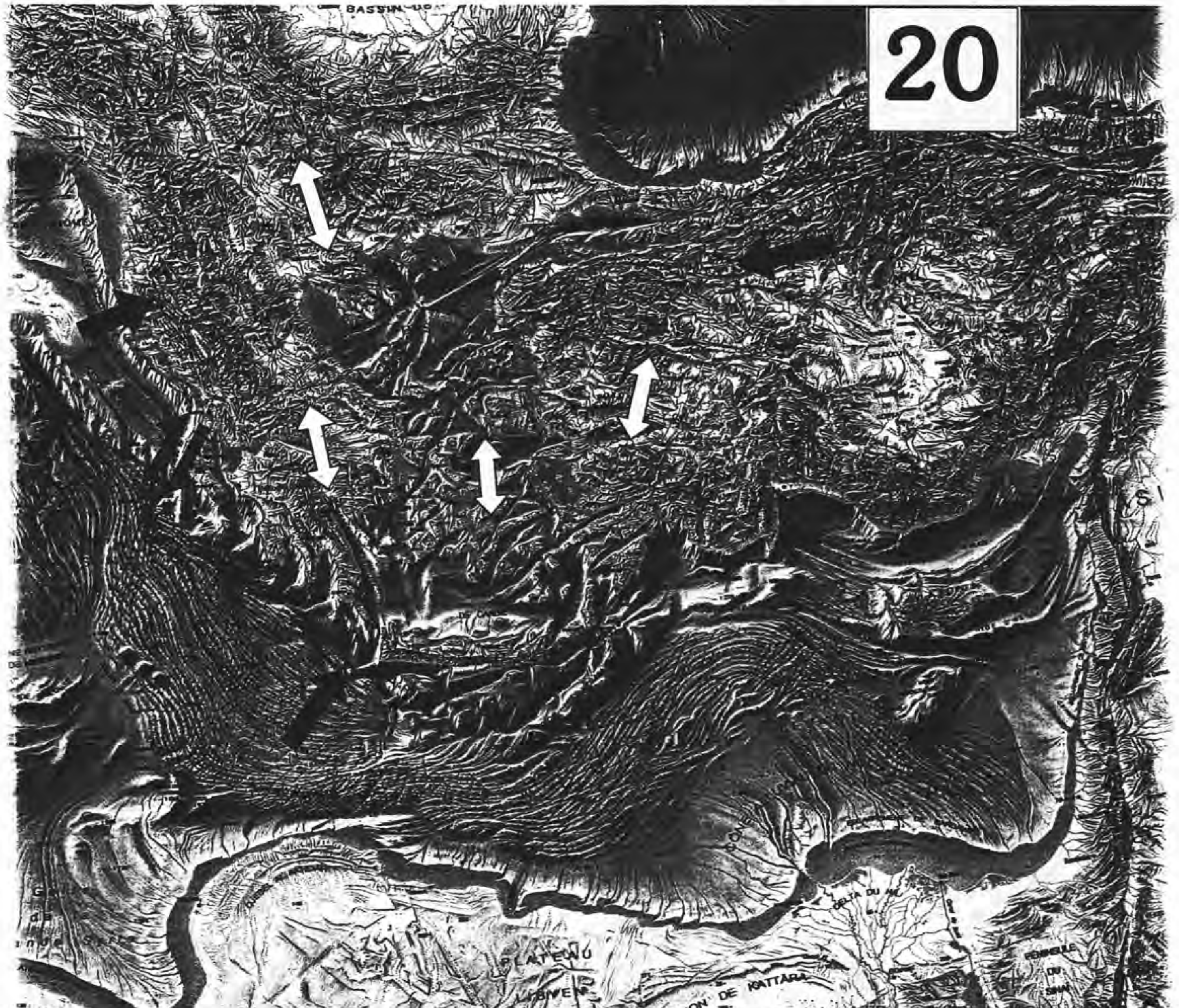

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PROCEEDINGS

OF THE 2nd CONGRESS OF THE HELLENIC GEOPHYSICAL UNION

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2. GEOPHYSICAL PROSPECTING
3. PHYSICS OF THE EARTH'S INTERIOR

CONTRIBUTION TO THE STUDY OF TECTONIC DEFORMATION IN SOUTH-EAST THESSALY, GREECE: GEOMAGNETIC DEEP SOUNDING AND SEISMOTECTONIC OBSERVATIONS

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A B S T R A C T

7 wide-band (100-0.01Hz), five component magnetotelluric soundings were performed within the periphery of Volos-Velestino-Mikrothives-N. Angkhialos, to explore regional geoelectric structural features and contribute to the understanding of the regional tectonic regime and deformation patterns in SE Thessaly. In the present study, only elements from the Geomagnetic Deep Sounding (GDS) part of the survey are presented; these can identify lateral geoelectric gradients and hence the location and strike of important structural features. The most significant result of the GDS survey is the identification of the principal structural components at great depths, (>20km), which develop parallel to the direction N-60° -70°-W and include deep linear conductors. The seismological data identify two simultaneous active tectonic trends, aligned with the directions N-60°-80°-W and N-70°-80°-E. The co-existence of deep conductors and seismically active tectonic features along the direction N-60°-80°-W may be interpreted in terms of a predominantly extensional stress field, oriented at N-10°-30°-E. Such a field is compatible with the observations and may, in turn, produce normal dextral faults with a predominantly E-W direction (e.g. N.Angkhialos fault).

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Τζάνης,Α., Μακρόπουλος,Κ., Martin,J.L., Cormy,G. και Δρακόπουλος,Ι.

Π Ε Ρ Ι Λ Η Ψ Η

7 μαγνητοτελλουρικοί σταθμοί ευρέος φάσματος (100-0.01Hz), πέντε συνιστωσών, μετρήθηκαν εντός της περιφερείας Βόλος-Βελεστίνο-Μικροθήβες-Ν.Αγχίαλος, προς αναγνώριση γενικών χαρακτήρων της γεωηλεκτρικής δομής και συμβολή στην διευκρίνιση του περιφερειακού τεκτονικού καθεστώτος της ΝΑ Θεσσαλίας. Στην παρούσα εργασία δίδονται αποτελέσματα Γεωμαγνητικής Βαθοσκόπησης (ΓΒΣ) μόνον· η ΓΒΣ δύναται να εντοπίζει περιφερειακές γεωηλεκτρικές βαθμίδες και εξ αυτών την θέση και διεύθυνση των σπουδαίων τεκτονικών ζωνών. Σημαντικότερο αποτελέσματα της ΓΒΣ

υπήρξε ο εντοπισμός των πρωτευουσών δομικών συνιστωσών σε μεγάλα βάθη, (>20km), οι οποίες αναπτύσσονται κατά την διεύθυνση Β-60°-70°-Δ και περιλαμβάνουν βαθείς γραμμικούς αγωγούς. Τα σεισμολογικά δεδομένα εντοπίζουν δύο σύγχρονες ζώνες τεκτονικής παραμόρφωσης με διεύθυνση Β-60°-80°-Δ και Β-70°-80°-Α. Η συνύπαρξη βαθέων αγωγών και σεισμικώς ενεργού τεκτονικής κατά την διεύθυνση Β-60°-80°-Δ ερμηνεύεται με την παραδοχή κυρίου επεκτατικού πεδίου τάσεων κατά την διεύθυνση Β 10°-30°-Α. Ενα τέτοιο πεδίο είναι συμβιβαστό προς τις παρατηρήσεις και υπό προϋποθέσεις, δύναται να παράξει κανονικά δεξιόστροφα ρήγματα με κυριαρχούσα διεύθυνση Α-Δ (π.χ. ρήγμα Ν.Αγχιάλου).

INTRODUCTION

Seismicity and geotectonics: Contemporary tectonic processes in SE Thessaly, (22°E-23.5°E and 39°N-39.8°N), quite often express themselves in a violent manner. Eight earthquake sequences with main shock magnitude Ms>6 occurred in the area during the present century only, (1905, 1911, 1930, 1941, 1954, 1955, 1957, 1980) and include twelve shallow earthquakes with Ms>6. Of these, all the post-1954 earthquakes occurred within the rectangle 22.5°E-23.3°E and 39°N-39.5°N in the periphery of Volos, Velestino and Almyros cities. Thus, the seismicity of the area is high and the earthquake hazard considerable, (e.g. Kouskouna, 1991), while recent work on long term earthquake prediction (Papazachos, 1991), assigns a high probability for the occurrence of a large earthquake (M>5.7), in the region within the next decade. Such properties of the area render necessary, the thorough understanding of geological structures and processes which may be related to the tectonic deformation of the area.

The post alpine evolution of SE Thessaly began during the Pliocene with tectonic movements guided by a conjugate system of normal faults with general directions NW-SE and NE-SW and resulted in the formation of NW-SE trending basins, including the tectonic depression of Almyros basin-Pagasitikos gulf, which remained active through the Quaternary. Traces left by this tectonic episode on the surface of SE Thessaly can clearly be seen in the lineaments of Figure (1a), drawn from observations of LANDSAT images (Polyzos 1977, Kronberg and Guenther, 1977).

A younger phase of tectonic activity began in the Pleistocene and continues until the present. Based on focal mechanism analysis of major earthquakes, Drakopoulos and Delibasis (1982) proposed that the main stress field has an approximately N-S direction and the resulting normal faults an approximate E-W strike. Additional work by Papazachos et al., (1983) and Taymaz et al., (1991) concurs this notion.

During 1982-83, a detailed geotectonic study of the Volos-Almyros area took place, with analysis of satellite images, aerial photography and surface observations (Cratchley, 1983). The resulting geotectonic map can be seen in Figure (1b) and reveals a tectonic fabric dominated by fault structures with directions NE-SW, ENE-WSW and NW-SE. In most cases, these fault zones correspond with morphological and morphotectonic characteristics of the area.

Of particular interest is the shaded area to the north of

Almyros basin, which shall be the focus of our investigation. All three major tectonic zones according to Cratchley (1983), may clearly be observed there. One can discern faults striking at N-80°-E, which are generated by contemporary deformation processes; an example is the well known Nea Angkhialos fault zone. A second faulting zone strikes at N-60°-80°-W; it can be traced from the east coast of Pelion peninsula, up to the west end of the investigated area. Finally, a third tectonic direction with approximately N-50°-60°-E orientation, can also be observed.

As stated previously, the tectonic direction N-80°-E is known to be generated by contemporary deformation processes, while the direction N-50°-60°-E may represent older (Pliocene) tectonic episodes. The tectonic direction N-60°-80°-W is not mentioned in existing literature as a major fault zone and its significance is still unknown; it comprised one of the prime targets of the investigations presented herein.

To the south of Almyros basin, only two tectonic directions are apparent. The first strikes approximately at N-80°-E and may be correlated with the same contemporary tectonic processes, which generate N.Angkhialos fault zone. The second strikes at N-60°-70°-W and according to Mariolakos and Papanikolaou (1987), it defines the boundary of a tectonic dipole. It may be possible to correlate this tectonic direction with the similar direction N-60°-80°-W observed to the north of Almyros basin, but conclusive results have not been given as yet.

The data and a physical basis for the analysis: In this study, we will attempt to correlate and jointly interpret geoelectromagnetic and seismological data, as part of an effort to investigate the important tectonic structures of SE Thessaly, where by the term "important" we refer to deep rooted features which may be profoundly related to the deformation patterns of the study area.

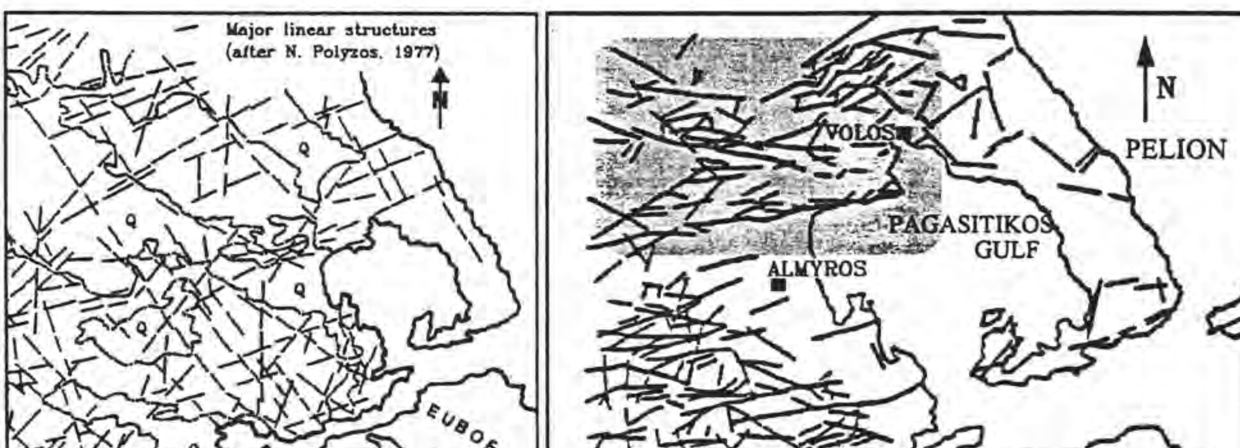

Fig.1. Left-(a): Lineaments from the Pliocene tectonic episodes, as traced from LANDSAT images; Q denotes the Quaternary basins; reproduced from Polyzos (1977). **Right-(b):** The tectonic analysis of Gratchley (1983); shading highlights the primary target area of the reported investigation.

The electromagnetic (EM) data was acquired during a magnetotelluric reconnaissance survey in the summer of 1992. A total of seven stations were occupied, the distribution of which can be seen in Figure (2a,b). Fairly standard observation procedures were followed, leading to the acquisition of five cartesian components of the natural EM field, (two horizontal electric and two horizontal magnetic, forming mutually orthogonal pairs, plus one vertical magnetic component), over the nominal frequency bandwidth 100Hz-0.01Hz. Data quality was good to very good, so that fairly standard processing techniques, (e.g. Sims et al, 1971), were sufficient to provide satisfactory Earth response functions with low levels of uncertainty. In this study we will present only results from the Geomagnetic Deep Sounding (GDS) component of the survey; GDS comprises the analysis of the three cartesian components of the magnetic field and is particularly suitable for locating conductive structures, because it is sensitive only to currents flowing in the volume and on the surface of conductive inhomogeneities.

One principal source of seismological data is the catalogue of Makropoulos et al., (1989), which contains all the M>4 events since 1900. Moreover, after the 1980 (M=6.1) earthquake, the need for close up monitoring of the seismicity in the region of SE Thessaly and Central Greece, prompted the installation and observation of a local, telemetric, digital network, by the Department of Geophysics and Geothermy of the University of Athens and the British Geological Survey (see Kouskouna, 1991 for a concise description). Code named VOLNET, this network operated from 1982 to 1985 and recorded the seismicity of the area with satisfactory precision. In the present study we shall use the entire VOLNET data set obtained in 1983 and 1984, which comprises all events with M>0.

Prior to engaging into the detailed description and discussion of the results, we consider it necessary to emphasize the following important points, inasmuch as they comprise the rationale upon which this study is based.

In areas of crustal extension and at shallow-intermediate depths, (upper crust), active normal faults are usually associated with elongate conductors along their strike; by spreading apart, they facilitate the circulation of water through the fault planes. It follows that the higher the deformation (extension) rates are, the better are the conductors, since larger volumes of water are allowed to circulate. Likewise, the more extensive the faulting zones are, the more extensive are the conductors they are associated with.

The formation of conductive zones in the lower crust, (>20-30km), is somewhat more complicated than the simple model described above. Note however that in tectonically inactive areas, even in the realm of ancient (e.g. Caledonian) subduction zones where the temperature now is too low to give an in situ decrease in resistivity of the major metamorphic rock facies, the lower crust is conductive. In a thorough review of the phenomenon, Haak and Hutton, (1986), attribute it to free water of 0.1% by volume or less, within shear zones from older overthrusting episodes, continuously recharged from the upper mantle. Sanders, (1991), also based on detailed studies of exhumed lower crust in Ireland, refined this idea proposing that the high grade metamorphic rocks of the lower crust form dry, kilometre scale lenses wrapped around by anastomosing, retrograded, brine soaked, electrically conducting shear zones. Although these studies refer to quasi steady state conditions for the lower crust, which are probably not applicable in an area such as is SE Thessaly, they may serve as a starting point for an interpretation of deep conductors, since they all indicate the existence of natural, free saline water at great depths. At any rate, it should be clear that brines are important fluid phases in metamorphic rocks and were actually found in the deep upper crust by the Kola borehole (Kozlovsky, 1988).

When the lower crust is stretched by extensional forces, it is expected that the concentration and circulation of brines will be facilitated along the planes of maximum shear, where the principal horizontal stress is minimal (i.e. perpendicularly to the extensional field). Increased supply of brines from the sheared and rising upper mantle may be anticipated and new water sources from the upper crust (due to faulting) are expected to appear; the concentration and circulation of these brines will also be facilitated along the planes of maximum shear. Thus, in areas of crustal extension, one expects to observe good conductors perpendicularly to the direction of the extensional field.

As a consequence of the above, in areas of active crustal extension, the study of EM data may assist in delineating and mapping important fault zones, even if they deform aseismically. Moreover, if it is possible to correlate elongate conductive zones with elongate zones of earthquake activity in the upper and lower crust, then it is simultaneously possible to constrain with confidence the orientation of the principal extensional field, as well as the fundamental mode of crustal deformation.

Particular attention should be paid to deep (regional) conductors, since they represent fundamental (background) structures and processes and are not affected by the complexities often encountered in the upper crust. Note that in the area of SE Thessaly, the occurrence of earthquakes at depths greater than 20-25km is sparse in space as well as in time, so that there exists only a limited number of adequately (reliably) located events at great depths. On the other hand, the natural EM fields can easily penetrate and explore the lower crust and therefore, they comprise a unique tool in investigating its properties.

GEOMAGNETIC DEEP SOUNDING OBSERVATIONS

Method of Analysis: Geomagnetic Deep Sounding is based on the physical principles of natural (passive) electromagnetic induction, in which horizontal, plane polarized magnetic source (primary) fields enter into the subsurface and induce electric currents in a source free inhomogeneous conducting Earth medium. The induced primary currents will, in turn, generate secondary (anomalous) magnetic fields and secondary (anomalous) currents. Because the vertical component of the source field is negligible, any vertical magnetic field component measured at the surface of the earth is essentially a secondary or anomalous field, generated within the Earth, the magnitude of which comprises a measure of the degree of transversal inhomogeneity present in the underlying geoelectric structure. The physical principles underlying GDS can be found in Rokityansky (1982). Due to the nature of the data acquisition procedure implemented in the reported survey, only a study of point (single site) observations is possible, based on the analysis of the single-site magnetic transfer function (MTF).

The MTF is essentially a rank 1 tensor which maps the measured horizontal primary and secondary magnetic field components H_x and H_y onto the secondary vertical component H_z, according to the relationship

$$\mathbf{H}_z = X_{zx} \cdot H_x + X_{zy} \cdot H_y = \mathbf{X} \cdot \mathbf{H}$$

and {x,y,z} is the Cartesian experimental coordinate system. The spatial characteristics (principal direction) of the geoelectric structure can be found by determining the horizontal magnetic field component, which contributes maximally to the generation of Hz (and thus exhibits maximum correlation with H_z). This can be achieved with maximum response analysis (MRA), which comprises a mathematical rotation of the experimental MTF until it is referred to the Cartesian coordinate system *{x,y,z}*, intrinsic to the geoelectric structure. Notably, MRA is the method of choice for determining the spatial properties of complex (3-D) geoelectric structures. The method of MRA used herein, is based on the theory of three-dimensional transformations in complex space, (Tzanis, 1988, 1992), initially developed to address the equivalent problem of principal component analysis of the magnetotelluric impedance tensor. The rotation utilizes an operator $\mathbf{U}(\Theta,\Phi)$ in the group SU(2) of 2x2 unitary rotation matrices, which describes rotations about the y±iz axis of a complex Euclidean space {x,y±iz}, which is isomorphic to the real Cartesian space {x,y,z}. Θ, Φ are real parameters representing the rotation angles. On using such an operator the MTF becomes:

$$H_z = \mathbf{X} \cdot \mathbf{H} = \mathbf{X} \cdot \mathbf{U} \cdot \mathbf{U}^{+} \cdot \mathbf{H} = (\mathbf{U}^{+} \cdot \mathbf{X}^{+})^{+} \cdot (\mathbf{U}^{+} \cdot \mathbf{H}) = \mathbf{X}(\Theta,\Phi) \cdot \mathbf{H}(\Theta,\Phi)$$

where + the transposed complex conjugate,

$$\mathbf{X} = \mathbf{X}(\Theta,\Phi) \cdot \mathbf{U}^{+}(\Theta,\Phi) = |\mu \quad 0| \cdot \mathbf{U}^{+}(\Theta,\Phi)$$

and μ is the maximum response. Thus, $\mathbf{X}(\Theta,\Phi)$ represents the observed $\mathbf{X}$ transformed into the intrinsic coordinate system *{x,y,z}*, which rests at an azimuth Φ and an inclination Θ with respect to the experimental coordinate system {x,y,z}. The definition of the rotation is such, that Φ is aligned with the strike of the geoelectric structure. Then, the horizontal component exhibiting maximum correlation with H_z is $H(\Theta,\Phi+90°)$. It can further be shown that an alternative representation of he inclination Θ in the real Cartesian space *{x,y,z}* is that of the ellipticity of the magnetic field; moreover, for 2-D eoelectric structures we must obtain $\Theta=0°$. Thus, the existence of non-vanishing Θ angles is diagnostic of the dimensionality of the geoelectric structure.

Results: Figure (2) illustrates the maximum responses (MR) averaged over the frequency intervals 10Hz-0.1Hz (Figure 2a) and 0.05Hz-0.005Hz (Figure 2b). By independent analysis of the simultaneously recorded magnetotelluric data, it has been established that the former interval corresponds to effective depths of EM field penetration within the range 1km-20km, where most earthquakes occur, and the latter to effective depths greater than 20km. Although this information will not be used herein, it is interesting to note that the structure is 3-D almost everywhere (elliptically polarized fields) and that at great depths, (Figure 2b), the degree of three-dimensionality decreases from S to N.

The geoelectric structure of the upper crust, (Figure 2a, 10Hz-0.1Hz, 1km-20km), is very complex and may be distinguished into an East sector, (sites 1-3) and a West sector, (sites 4-7).

The East sector comprises structures with a well defined principal direction of N-60°-W, which compares remarkably well with the orientation of the fault zone appearing in the vicinity of the measurements, (Velanidia fault), which, as also was verified by the authors, comprises a south-westerly dipping normal fault. Thus, it appears conceivable that the two features be connected with an effect-and-cause relationship, in the sense that the geoelectric structure generating the MR is produced by the same processes generating the tectonic feature on the surface.

The West sector comprises structures with a mean N-S to N-20°-E orientation, which are interrupted by a N-110°-W trending feature in the vicinity of site 7. Thus, it appears that there exist at least two different geological features, generating the MR of the West sector.

The WSW-ENE orientation of the structure nearby site 7, is conspicuously parallel to the normal fault structures generated by contemporary regional deformation processes and, therefore, may be attributed to them. As a matter of fact, the site is located on the hanging wall of a fault, which according to Cratchley's (1983) analysis, is related to the Chalkodonio-Aerino fault, which was responsible for the powerful M6.8 earthquake of 1957.

The existence of conductive, N-S to NNE-SSW oriented structures is unexpected and puzzling, inasmuch as they cannot be directly associated with some apparent surface geological feature. Therefore, their nature cannot be specified with certainty, using only the available, limited data set. Another important observation also related to the existence of these structures, is the conspicuous as much as enigmatic absence of a geoelectric signature from structures pertaining to N.Angkhialos fault zone, even at site 6 which is located directly on the fault line. It appears that N.Angkhialos fault is 'waterproof', at least in the vicinity of site 6, a result which is rather unexpected for an active (spreading) normal fault. This, in turn, either indicates that N.Angkhialos fault is not a typical normal fault, or that it is not as significant as it is conventionally considered to be (it does not generate significant rates of deformation, if any).

The deep structure, (Figure 2b, 0.05Hz-0.005Hz, >20km), exhibits a definite and uniform N-60°-70°-W principal direction throughout the study area, which also comprises the direction of the deep (lower crustal) conductors. In the East sector, the transition to the deep structure is rather smooth, because the maximum responses do not vary significantly with respect to their upper crustal counterparts (in the interval 1km-20km). In the West sector however, the transition is quite dramatic and takes place with a spectacular counterclockwise rotation of the MR at sites 6,5 and 4, as well as a small clockwise rotation at site 7.

When Figures (2a) and (2b) are considered together, it becomes apparent that the East sector of the study area comprises structures which remain practically invariant at all depths and apparently are generated by the same background processes. The West sector however, comprises an upper and a lower structural unit with very different characteristics. The former, (upper crustal depths, <15-20km), is associated with NNE-SSW to NNW-SSE principal directions. The latter (lower crustal depths, >20km), has principal directions, identical to those of the East sector. Thus, it appears that at great depths, the same processes which generate the structures of the east sector spread over the entire study area. It may be concluded that the direction N-60° -70°-W comprises the fundamental (background) principal direction of geoelectric processes underneath the study area, which also appear to generate a clear surface expression in the East sector.

SEISMOTECTONIC OBSERVATIONS

The method of seismotectonic analysis adopted here is the simplest possible. It comprises investigation of the horizontal distribution of earthquake epicentres, in order to determine linear features which can, then, be associated with active fault zones and contemporary tectonic trends. This type of analysis is performed and presented in two modes.

* In the first, we attempt to study earthquakes of moderate and large magnitudes (M>4); the distribution of the epicentres of all events which occurred during the period 1900-1987 is shown in Figure (3a), taken from the catalogue of Makropoulos et al (1989).

* In the second, we attempt to study the small earthquake activity using all the events detected during 1983-1984 by VOLNET. The distribution of epicentres is shown in Figure (3b).

In both modes, the earthquakes have been divided into three classes according to their hypocentral depths, namely Class I with 0km<D<5km, Class II with 5km<D<10km and Class III with D>10km. This classification is based on previous analysis and appears to be particular to the area under investigation (e.g. Kouskouna, 1991 and references therein).

Considerable caution needs to be exercised before attempting an analysis on the basis of this data set. It is well known that the epicentres of earthquakes can be determined with considerable error, which increases inversely with the magnitude of the event and adequacy (density and proximity) of the seismographic network which detected it. This is particularly true for earthquakes of the pre-digital era, and especially the older ones which have

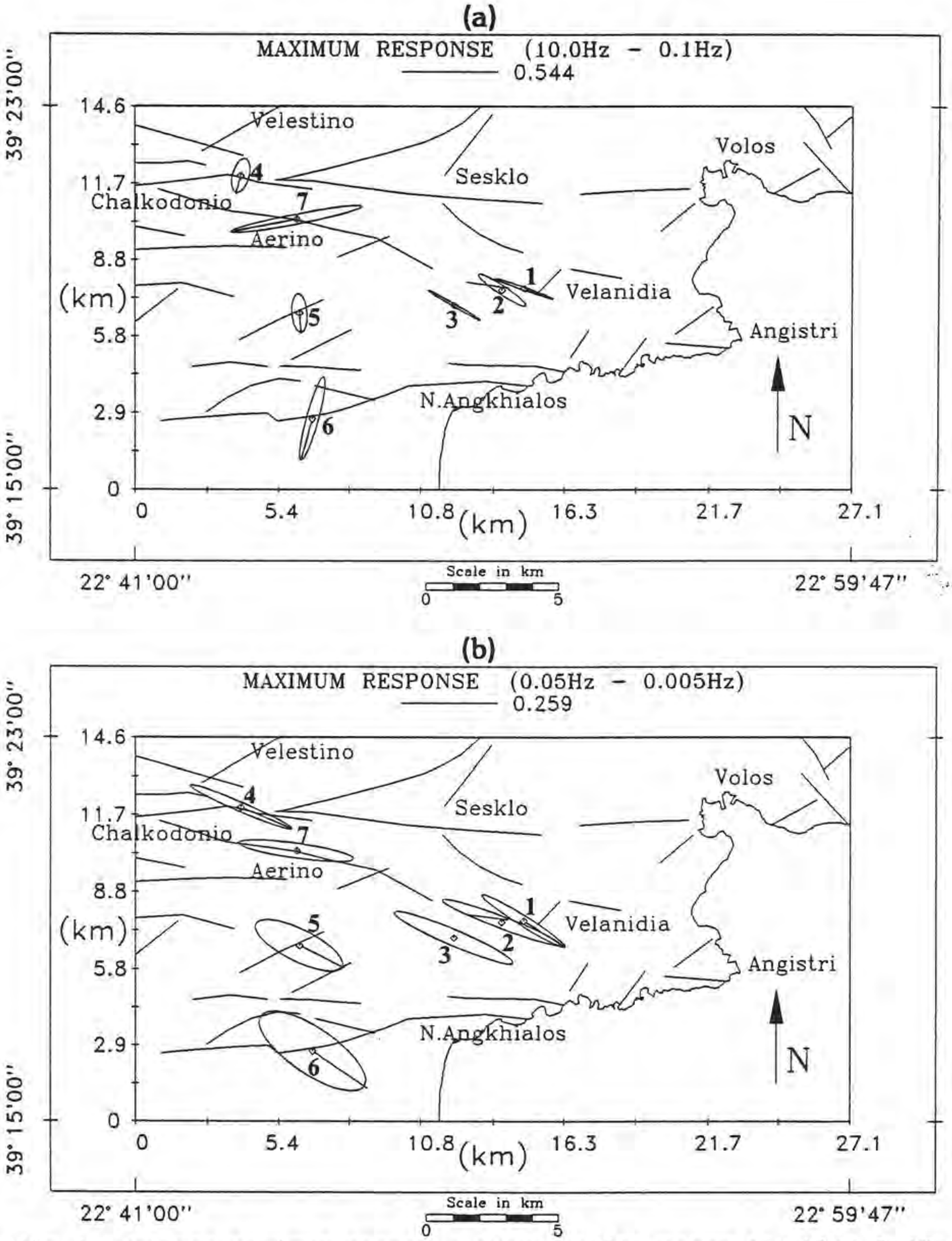

Fig.2. Average maximum response over the frequency **(a)** 10Hz-0.1Hz (depth range 1km-20km approximately) and **(b)** 0.05Hz-0.005Hz (depths >20km). The main fault zones of Cratchley (1983) have also been superimposed to facilitate comparisons.

been detected by sparse or distant seismographic networks. The catalogue of Makropoulos et al (1989) contains several such events; although all the earthquakes listed there have been relocated carefully (e.g. Makropoulos, 1978), the reliability of some epicentres may still be questionable. In this case one hopes that if there exist some definite preferred directions of earthquake occurrence, they will be determined statistically from the accumulation of a large number of events. The VOLNET epicentres are derived from a local, relatively modern digital network, which permits the accurate location of events occurring within its aperture. Thus, there is little question about the reliability of VOLNET's epicentres, at least for the purposes of this presentation.

Let us turn our attention to Figure (3a) first (all events with M>4). The known problems of old earthquake locations do not allow delineation of seismicity lineaments to the desired level of detail, albeit several linear features can easily be seen. Straight line segments are used, in order to emphasize possible alignments of earthquake epicentres (seismicity lineaments). Where in doubt, the corresponding line segment is marked with a question mark. Moreover, when the three classes of hypocentral depths are analyzed separately, it is possible to define seismicity lineaments corresponding to different depth intervals. This kind of information cannot be presented analytically due to space limitations, but the thusly delineated linear features are shown with appropriate annotation, so that they can be distinguished easily. An S denotes lineaments of Class I events and an I denotes lineaments of Class II events; either a D or no annotation at all is used for Class III lineaments. Several detectable linear features strike at N-70° -80°-E and probably correspond to the well known Nea Angkhialos Fault zone. A second group of lineaments which can be drawn from Class I and II earthquakes, (possibly also including some Class III ones), strikes at N-70°-75° -W and correlates well with the direction N-60°-70°-W detected by MRA (Figure 2b). A very interesting and probably important observation relates to the absence of significant seismicity within the shaded (magnetotelluric survey) area.

The same method of presentation as per Figure (3a), is adopted for the VOLNET data (Figure 3b). The well constrained epicentre locations of this data set, allow the identification of several seismicity lineaments, the most outstanding of which, are associated with the directions N-60°- 70°-W and N-70°-80°-E. There also exist some evidence of shallow earthquakes occurring parallel to the direction N-20°-30°-W, which will not concern us any more. Thus, the VOLNET data apparently indicate the simultaneous existence of two active faulting zones. The following, possibly important observations can also be made: **(A)** As in Figure (3a), different epicentre alignments can be distinguished for the three different classes of hypocentral depths, so that a horizontal variation of seismicity lineaments as functions of depth can be observed. This phenomenon appears to be rather systematic for each of the three tectonically active directions of Figure (3b), with particular reference to the direction N-70°-80°-E. With the data at hand, it is not possible to assess the significance of this observation; such an attempt would require additional data and intensive analysis. (B) The magnetotelluric survey area is still void of significant seismicity.

From the standpoint of seismology, the outlook of the contemporary tectonic regime of SE Thessaly is complex and very difficult to interpret at present. This picture may change in the future since the data set of Figure (3a) is incomplete and the seismic activity shown in Figure (3b) corresponds to a relatively brief time window, which does not reassure that all the faults with potential to generate large magnitude earthquakes have been activated. Nevertheless, it is not expected to change significantly, so that one may postulate the existence of two simultaneous, tectonically active directions.

DISCUSSION

There appears to be significant correlation between structural directions delineated by electromagnetic and seismological means. The GDS observations detect a fundamental geoelectric structure with a N-60°-70°-W orientation, as well as secondary feature(s) confined in the west sector of the study area and striking N-S to NNE-SSW. The seismological observations reveal the existence of active faulting along the directions N-60°-80° -W and N-80°-E, the latter corresponding to the well known N.Angkhialos fault system. Thus, the primary structural direction appears to be N-60°-80°-W. With the available evidence, it is possible to attempt a preliminary assessment of its significance and contribution in the geological evolution of SE Thessaly.

The most important result of GDS, pertains to the detection of the fundamental (lower crustal) geoelectric structure and the determination of the principal conductive direction underneath the study area. As illustrated in Figure (4), this is N-60°-70°-W and is apparently associated with contemporary deformation processes, inasmuch as there is very significant Class III earthquake activity along N-60°-80°-W. These observations are compatible with a predominantly extensional stress field, directed at N-10°-30°-E; such a field would generate maximum shear planes parallel to N-60°-80°-W and facilitate the concentration of fluids (brines).

The main normal faults generated in the upper crust by such a stress field, are expected to exhibit WNW-ESE orientation and be correlated with good conductors parallel to their strike. Both of the above conditions are fulfilled by the (Angistri)-Velanidia-Aerino-Chalkodonio fault zone which will henceforth be called the Principal Fault (PF). Notably, Cratchley (1983) has already associated Chalkodonio-Aerino fault in the West sector, with Velanidia fault in the East sector. The elongate conductive structures associated with this zone are denoted by Z1 in Figure (5). It should be noted however, that the continuity of Z1 between the east and west sectors is not directly supported by the available data. There exist only reasonable arguments to justify this assertion, such as is the apparent continuity of the principal fault line structure and the observation that both of its branches are associated with elongate conductors which, eventually, are expected to merge.

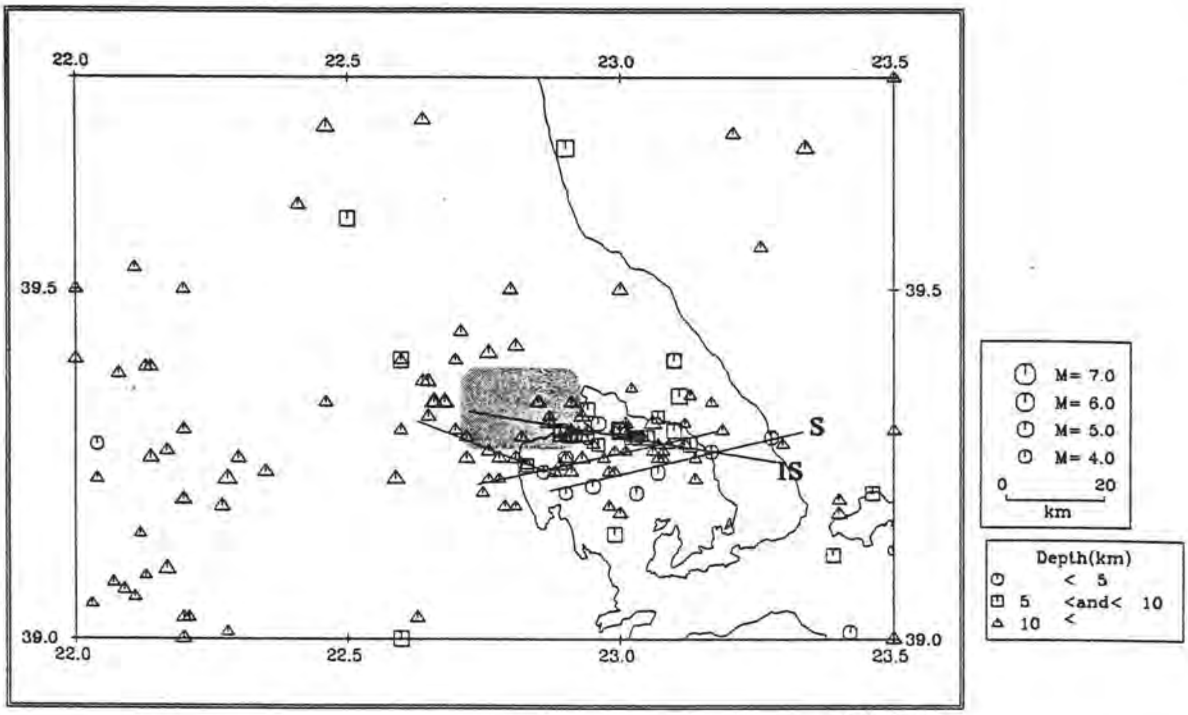

Fig.3a. Distribution of epicentres of all M>4 earthquakes during the period 1900-1987 Makropoulos et al., (1989). S denotes lineaments comprising Class I earthquakes; I denotes lineaments comprising Class II earthquakes. The shaded region outlines the magnetotelluring survey area.

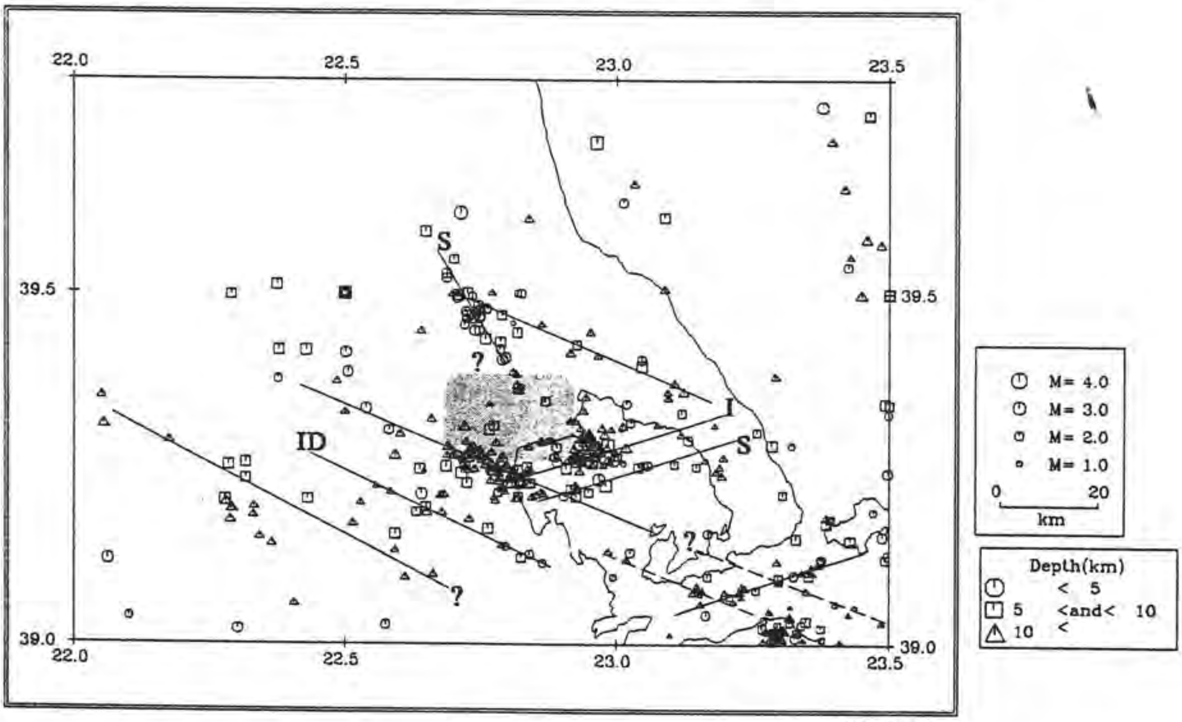

Fig.3b. Distribution of epicentres of all M>0 earthquakesss recorded by VOLNET during the period 1983-84. The symbols S and I as per Figure 3a; D refers to Class III earthquake lineaments. The shaded region outlines the magnetotelluric survey area.

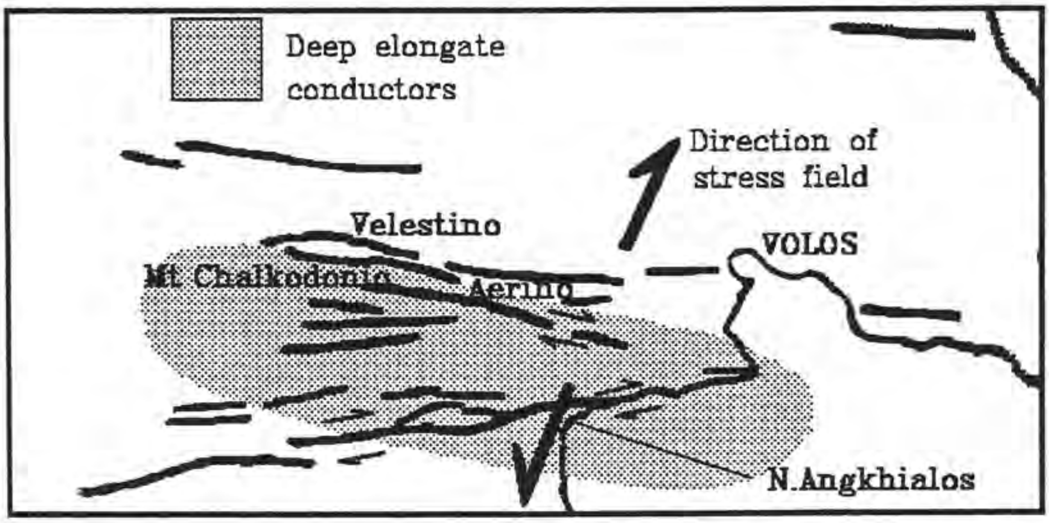

Fig.4. Lower crustal conductors and their interpretation.

Consider now that in order to be fully compatible with the other geological features, as well as with the seismicity patterns of the area, the N-10°-30°-E (predominantly extensional) stress field should also be able to generate E-W normal faults, such as are the Sesklo-Volos and N.Angkhialos faults respectively (either northerly or southerly dipping). From a dynamic and kinematic point of view, this is possible, provided that it can also generate a sufficient, (albeit arbitrarily small), dextral horizontal slip component. This in turn, requires that all the faults in the area be dextral and exhibit a sufficient, (albeit arbitrarily small), strike-slip component.

An interesting connotation of the above assertion, (the validity of which remains to be tested with future investigations), is that the deformation pattern of the area should involve dextral block rotations. Such a block may be defined by PF and N.Angkhialos fault. This may well account for the clustering of small magnitude, Class III earthquakes in the vicinity of cape Angistri and N.Angkhialos-site 6. Furthermore, it may assist in explaining the peculiar NNE- SSW conductors of the of the west sector (upper crust, zone Z2 in Figure 5), as a shear zone produced between the moving block of the east sector and the fixed block of the west sector.

Additional problems which must be addressed, include the absence of seismicity in the Angistri-Velanidia-Aerino branch of the principal faults, as well as the role and significance of N.Angkhialos fault. There is a satisfactory mechanism to account for the first problem which, ironically enough, cannot be convincingly presented with GDS data only. It is, however, contained in the magnetotelluric data and will be elaborated elsewhere. It explains the absence of earthquakes by the presence of abundant water at depths 10-15km, which forces the rocks into an aseismic (ductile) deformation mode, (the brittle mode then,

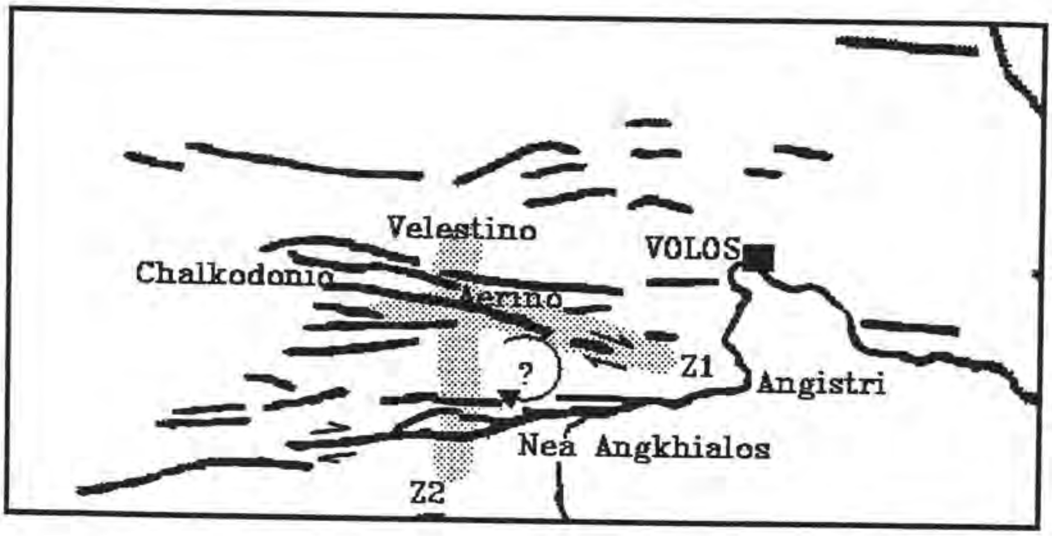

Fig.5. Conductive zones in the upper crust and their interpretation.

migrating to the south along N.Angkhialos fault and to the west along Chalkodonio-Aerino fault).

The conventional model of contemporary tectonic deformation processes in SE Thessaly involved a pure N-S extension of the crust, with the main activity (stretching) taking place in E-W faults such as is N.Angkhialos fault. The model derived herein is different, in that it defines the extensional field to be NNE-SSW, the main activity to take place along WNW-ESE normal faults, and also introduces the concept of block rotations. Thus, it demotes the E-W faults to an auxiliary role in terms of the long term geotectonic evolution of the area, although it still allows for their capacity to produce large magnitude earthquakes.

The geotectonic model of SE Thessaly derived herein, should be perceived as a general framework of the tectonic deformation patterns and will certainly require refinement and augmentation in the future, when additional deep EM and seismological data become available. The evidence presented above indicate that the geological structure, the tectonic fabric, stress field patterns and deformation processes in SE Thessaly are more complex than previously thought to be. If further detailed studies confirm our findings, several important questions will still need to be answered, as for instance are the quantitative aspects of regional deformation. The solution of such problems should not be easy and would require extensive investigations and most importantly, time. From this point of view, the mere purpose of the present study is to introduce the problem.

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