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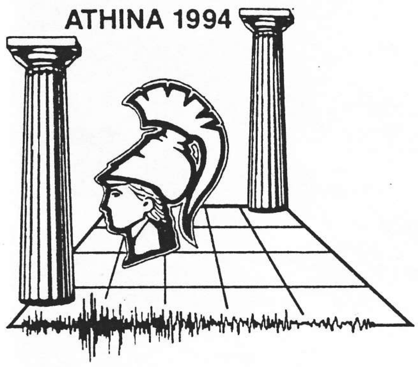


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# A MODEL OF CONTEMPORARY TECTONICS IN SE THESSALY, GREECE, AS DERIVED FROM MAGNETOTELLURIC AND SEISMOTECTONIC INVESTIGATIONS.

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## ABSTRACT

Fourteen wide-band MagnetoTelluric (MT) and Geomagnetic Deep Soundings (GDS), as well as a large scale seismological experiment were carried out (separately) in SE Thessaly, Greece, to investigate its contemporary structural and tectonic regime and deformation patterns. The MT data identify deep elongate conductors of NW-SE orientation, which control induction processes at intermediate and lower crustal depths (>10 km). These may be interpreted in terms of a stress field generating extension and WNW-ESE shear (fault) planes, which facilitate the infiltration of water and development of high conductivity parallel to their direction. Seismotectonic analysis is based on CMT focal mechanism solutions of four large events since 1980, (M5.1-6.4) and several microearthquakes recorded during the seismological experiment. The CMT focal mechanisms indicate either normal, sinistral faulting in NW-SE planes dipping to NNE, or normal to slightly dextral faulting in E-W to WSW-ENE planes dipping to SSE. The focal mechanisms of microearthquakes indicate simultaneous activity with normal to oblique-slip sinistral faulting in NW-SE to WNW-ESE fault planes and normal faulting in E-W to WSW-ENE planes. In both cases, the P-T plane of no shear undergoes an identical rotation from NNW-SSE in the southeast of the study area, to NNE-SSW in the central parts, to NNW-SSE in the northwest; the T-axis has a consistent N-S direction and the rotation is mainly due to changes in the orientation of the P-axis. At least 40% of the total compressive stress acts on the horizontal plane and approx. 25% comprises its E-W component. Both the MT and seismotectonic data are consistent with a geotectonic model involving homogeneous deformation by shearing in two conjugate planes at an angle of 30° (moderate-high internal friction). The configuration of the stress field is such that the E-W plane experiences almost pure N-S extension and expresses normal faulting with a small dextral component, while the NW-SE plane absorbs most of the horizontal compressive stress and expresses normal, oblique-slip faulting with sinistral slip. In this way, the entire system experiences dextral block rotation about the vertical axis, but little or no mass translation. The proposed model has certain differences, but produces the same effect with the block model of distributed deformation by faulting, proposed by Jackson and McKenzie, (1986).

**Introduction.** 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 $M_S$>6 occurred in the area during the present century only, (1905, 1911, 1930, 1941, 1954, 1955, 1957, 1980) and include twelve shallow earthquakes with $M_S$>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. The seismicity of the area is high and earthquake hazard considerable. These factors render necessary, the thorough understanding of structures and processes which may be related to the mode of tectonic deformation in the area.

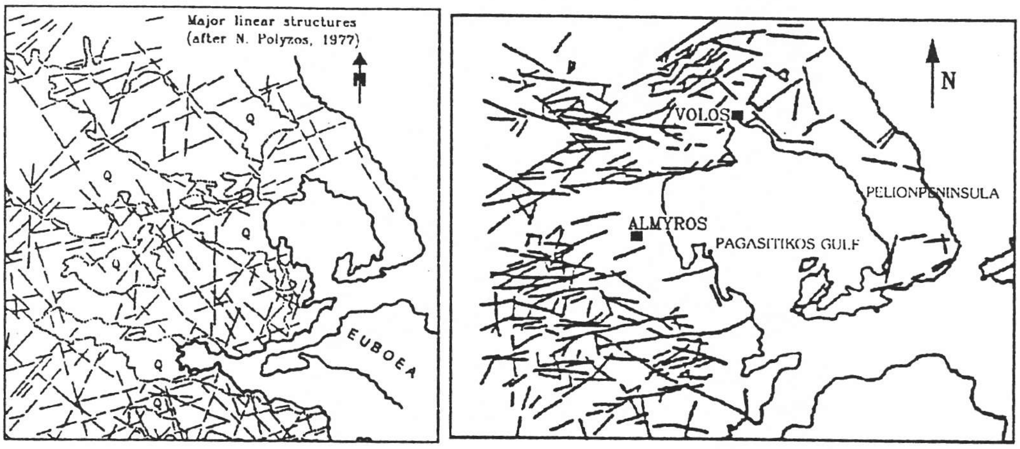


FIGURE 1. Left-(a): Lineaments from the Pliocene tectonic episodes, as traced from LANDSAT images; Q denotes the Quaternary basins; reproduced from Polyzos (1977). Right-(b): The tectonic analysis of Cratchley (1983).

Towards this effect, the present study describes an attempt to correlate and jointly interpret geoelectromagnetic data which are determined by the configuration of the active tectonic structures and seismological data, which are due to the active tectonic structures. The contention for undertaking this exercise is that the common denominator from both lines of evidence will, most probably, provide better constraints and improved understanding of the configuration and relative importance of such tectonic structures, which may be profoundly related to the deformation patterns and seismicity of the study area.

## Seismicity and geotectonics:

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 Fig. 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 (actually NNE-SSW) and the resulting normal faults an approximate E-W strike. Taymaz et al. (1991) concur this notion but Papazachos et al., (1983) argue for a NNW-SSE extensional field.

A detailed geotectonic study of the Volos-Almyros area with analysis of satellite images, aerial photography and surface observations (Cratchley, 1983) revealed a tectonic fabric dominated by fault structures with directions NE-SW (N50°-N60°), ENE-WSW (approx. N80°) and NW-SE (N100°-N130°). In most cases, these fault zones correspond with morphological and morphotectonic characteristics of the area. The tectonic direction N80° (as for instance is the recently activated Nea Angkhialos fault zone), is known to be generated by contemporary deformation processes., while the direction N50°-N60° may represent older (Pliocene) tectonic episodes. The direction (N100°-N130°) is rarely 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. Caputo (1991) and Caputo and Pavlides (1993) assign a lesser, or no significance to these tectonic lineaments at longitudes east of approximately 22.6°E, but they illustrate them as dominant features to the west of 22.6°E. The same authors discuss of deformation in terms of produce geological and tectonic arguments for an approximately N-S extensional field which, however, in their illustrations would clearly be NNE-SSW.

To the south of Almyros basin, only two tectonic directions are apparent. The first strikes approximately at N80° and may be correlated with the same contemporary tectonic processes, which generate N.Angkhialos fault zone. The second strikes at N100°-N130° and according to Mariolakos and Papanikolaou (1987), it defines the boundary of a tectonic dipole. It may be possible to correlate these tectonic lineaments with the corresponding directions observed to the north of Almyros basin, but conclusive results have not been given as yet.

## Magnetotelluric Data Analysis and Results

The magnetotelluric (MT) data was acquired in two phases, summer 1992 (Tzanis et al, 1994) and autumn 1994, providing a total of 13 soundings (Fig. 2). Fairly standard observation procedures were followed, leading to the acquisition of five cartesian components of the natural EM field over the nominal frequency bandwidth 100-0.01Hz. Data quality was sufficient for standard processing techniques, (e.g. Sims et al, 1971) to provide satisfactory Earth response functions with low levels of uncertainty. Rigorous and extensive testing (e.g. Groom and Bailey, 1989; Bahr, 1991), has confirmed the absence of static or other form of galvanic distortion from the data. The dimensionality analysis carried out with Kao & Orr's (1982) approach, indicates a 2-D geoelectric structure with weak-moderate effects on the propagation of the EM field; the relative 1-D structural contributions are in the order of 80% and the relative 2-D structural contributions in the order of 10-20%. In consequence, the geoelectric structure may be quantitatively interpreted with 1-D inversion methods to a fair first approximation. This conclusion was confirmed by the fully analytic, non-linear inverse theory of Parker (1980) which provides the necessary and sufficient conditions for the existence of 1D geoelectric structure.

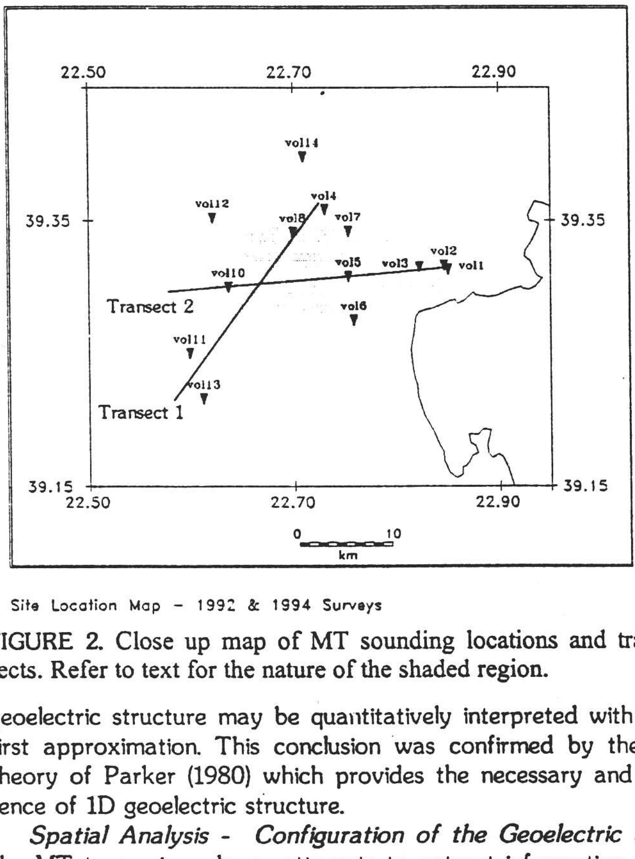


FIGURE 2. Close up map of MT sounding locations and transects. Refer to text for the nature of the shaded region.

*Spatial Analysis - Configuration of the Geoelectric Structure:* The spatial analysis of the MT tensor impedance attempts to extract information about the configuration of the induced natural EM fields, which, in turn, depend uniquely on the geometry and configuration of lateral inhomogeneities in the geoelectric structure. In the reported experiment, the 3D *generalized rotation analysis (GRA)* of Tzanis (1988, 1992) was implemented, which decomposes the observed natural EM field into its principal components of propagation within the Earth; their configuration can, then, be used to find the corresponding configuration of the geoelectric structure(s) producing them and to delineate geoelectric structural blocks and lateral conductivity interfaces.

The spatial properties of the maximum electric field (maximum impedance state) and the maximum magnetic field (maximum admittance state) are presented in Fig. 3, over frequency intervals 10Hz-1Hz and 0.1Hz-0.01Hz, respectively, summarizing the shallower (<10km) and deeper (>15km) parts of the structure. By definition, the maximum electric field (hence the maximum impedance) is *parallel* to the local strike of maximum resistivity. The maximum magnetic field (hence the maximum admittance), indicates the downhill direction of local geoelectric gradient, i.e. points towards the most conductive local structure. The magnitudes of the maximum electric and magnetic fields are respectively proportional to the resistivity and conductivity of the geoelectric structure in the vicinity of the recording station. Using this information alone, one can define the correct configuration of a 2D interface within an ambiguity of 90° and again, only if the lateral resistivity contrast is sufficiently high, so that the mutually orthogonal TE and TM modes can be unequivocally distinguished. In general one can define the configuration of a resistivity interface uniquely, only if vertical magnetic fields are also measured and the Magnetic Transfer Functions (MTF) estimated. This has been only been possible for the 1992 data (Tzanis et al, 1994) and part of the 1994 data (soundings 8, 10, 11 and 12). At any rate, the remarkable similarities in the spatial properties of impedance tensors from the areas covered by both surveys also indicate the existence of corresponding remarkable similarities in their respective geoelectric structural properties.

The shallow (Fig. 3a) structure may be subdivided into three sectors. The *east sector* comprises soundings vol1-vol3; it features a clear and distinctive lateral NW-SE geoelectric discontinuity associated with a conductive zone, evident by the nearly orthogonal maximum electric fields at sites vol2 and vol3 and confirmed with MTF data (Tzanis et al, 1994). This is attributed to a faulting structure of similar orientation (see the inset in Fig. 3a) with throw towards SSW or SW (see also Fig. 4b). The *central sector* comprises soundings vol4-vol7 and vol14. It exhibits N-S to NNW-SSE geoelectric structural directions, which are also confirmed with MTF data. At the vicinity of site vol7, where the MTF data show that this trend is interrupted by an approximately E-W conductive structure (Tzanis et al, 1994). The maximum electric field direction changes to NW-SE at the north of the sector, presumably responding to the structures of the massive Larissa basin which has an identical orientation. The *west sector* comprises soundings vol8-vol13 and may further be subdivided into northen and southern domains. The former comprises sites vol8, vol10 and vol12 and exhibits NW-SE lateral resistivity discontinuities and conductive structures in a mode completely analogous to that of the eastern sector (see inset in Fig. 3a). The latter (southern) comprises sites vol11 and vol13 at the north margin and within Almyros basin respectively; this data is not well constrained due to the lack of MTF data, but it is quite evident that the E-W direction at vol11 and the NW-SE direction at vol13 are respectively consonant with the structural directions of Almyros basin ( see the inset in Fig. 3a and also compare with Fig. 1a).

The most remarkable and <u>ubiquitous</u> property observable in the magnetotelluric data is a swift change in both the spatial and quantitative characteristics of the geoelectric structure occurring in the frequency range 1Hz<f<0.1Hz (equivalently periods 1s<T<10s). The change is clearly illustrated in the differences between Fig.s 3a and 3b (deep structure), while it may better be seen in the spatial properties of the magnetic fields (maximum admittance state) producing significant angular separation between the electric and magnetic field directions, of the order of 30°-40°. This feature could possibly be attributed to geoelectric anisotropy influencing the propagation of the EM field. The effect is stronger in the east half of the study area than in the west half. The transition to the postulated anisotropic structure occurs at depths 10km<D<15 km and as it will be shown, it coincides with a relative conductor of apparent WNW-ESE orientation. The deep geoelectric structure exhibits NW-SE structural directions.

*Quantitative Analysis - The Resistivity Structure:* The dimensionality tests have shown that the geoelectric structure may adequately interpreted with 1-D inversion tools. In the present study we implemented 1D analytic inversions of the (half)trace invariant -scalar- impedance which has the physical meaning of a spatially smoothed variation of resistivity with depth. The

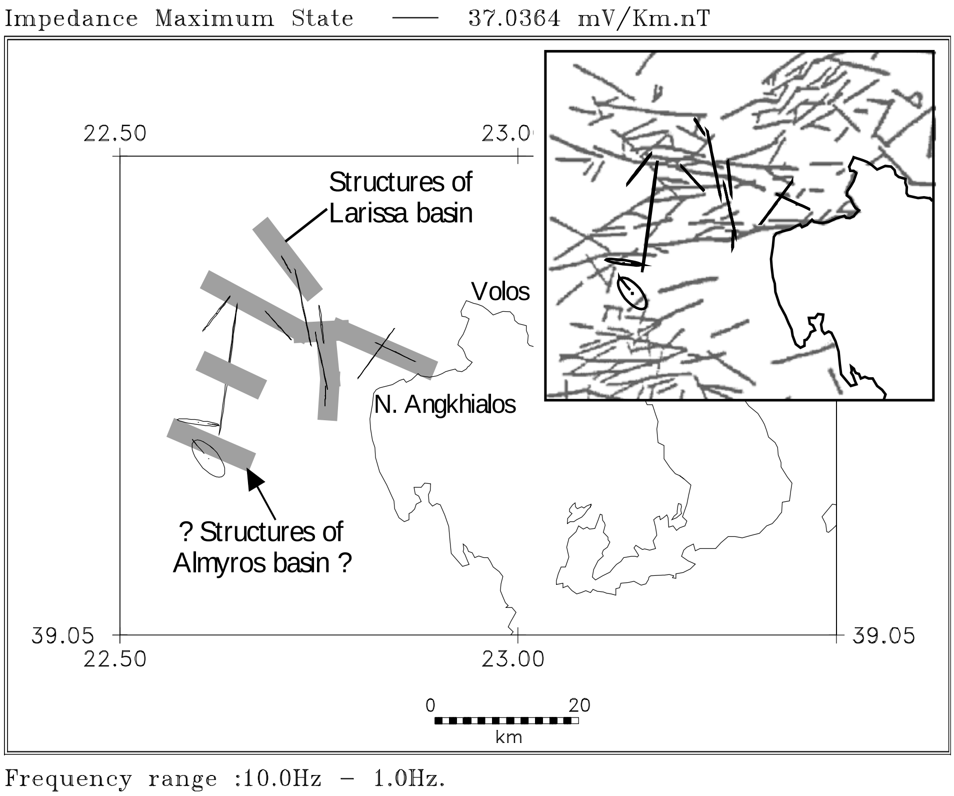


**FIGURE 3a.** Frequency averaged maximum electric field corresponding to D<10km. The maximum magnetic field is coincident with the electric. Thick grey lines indicate the major conductive zones detected. Insert compares electric field spatial properties and tectonic lineaments (Cratchley, 1983).

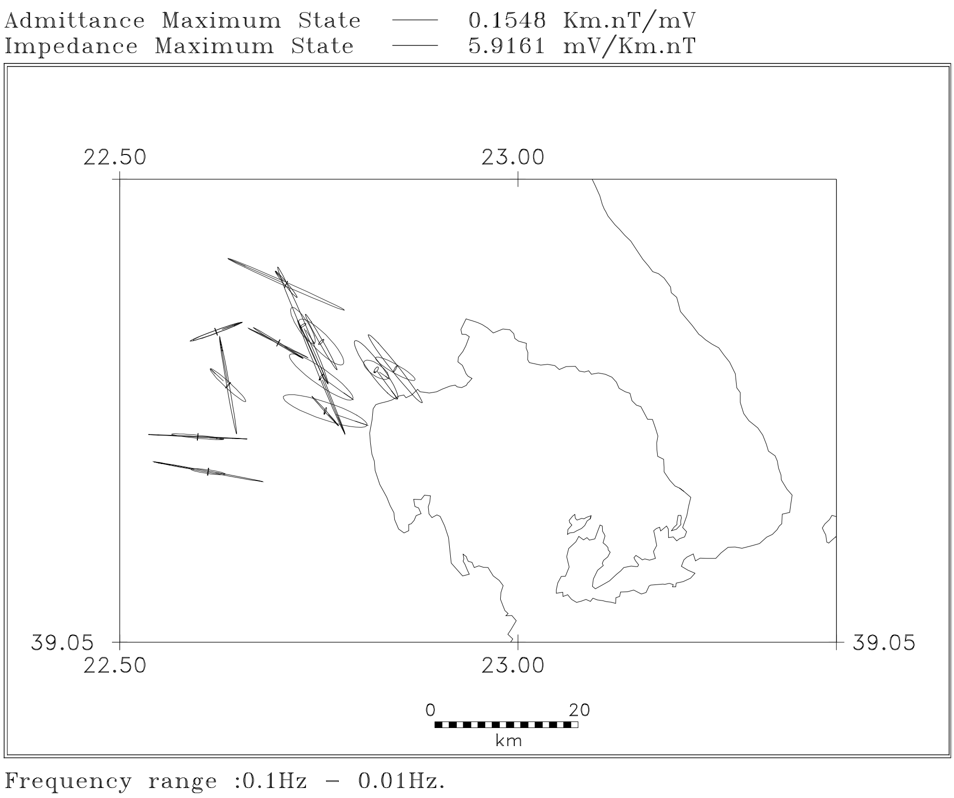


**FIGURE 3b.** Frequency averaged maximum electric (black) and magnetic (grey) fields, corresponding to D>13-15 km.

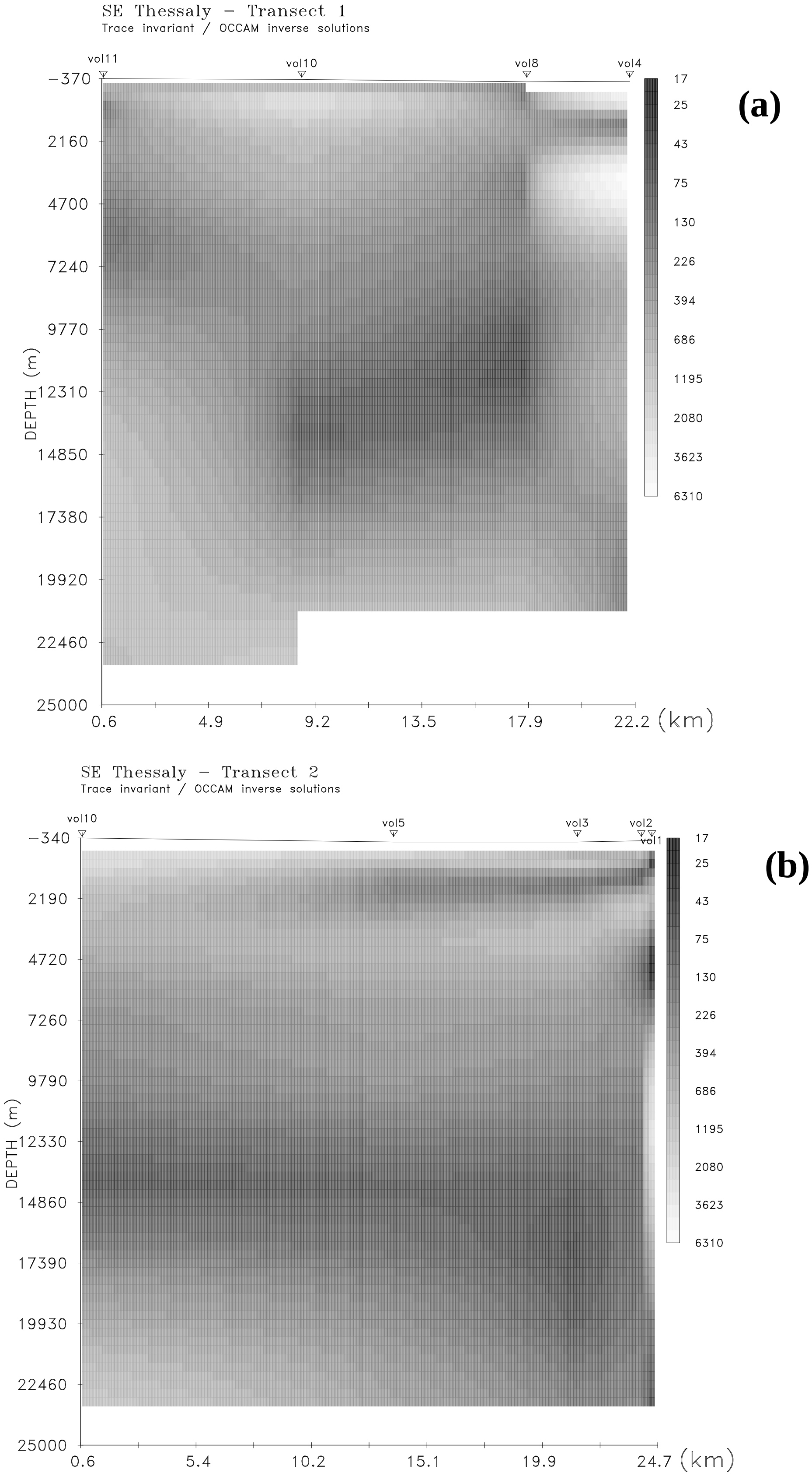


**FIGURE 4.** True resistivity pseudosections along **(a)** Transect 1 (NE-SW), and, **(b)** Transect 2 (W-E) of Figure 2. The resistivity scale is logarithmic and common to both. A natural (1:1) depth scale is used in each individual Transect, but *not* relatively to each other.

inversion was carried out with the minimum structure algorithm of Constable et al, (1987. The results are presented in the form of two true resistivity pseudosections (transects) in Fig. 4.

The shallow structure cannot be resolved in detail due to the sparse distribution of MT soundings. Only the discontinuity between sites vol2 and vol3 can be resolved dependably, at the east extreme of Transect 2 (Fig. 4b); the throw is clearly from vol2 to vol3. The most interesting characteristic of the two transects is the relatively conductive formation observed at depths of 10-15 km, at all soundings included within the shaded area of Fig. 2. This apparently WNW-ESE trending feature corresponds to the geoelectric structural transition zone postu-lated in the spatial analysis section above and may represent a boundary or a transition between the upper and lower crust.

## Seismological Data Analysis and Results

*The 1992 seismological experiment:* One important source of seismological data has been a large scale multi-national European seismological experiment in the area of S Thessaly and NW Sterea Hellas conducted in the summer of 1992, by deploying a local network of 75 seismographs for a period of two months (July-August 1992). Of more than 500 events recorded during the experiment, we present only 85 which were located in the area of SE Thessaly with highly accurate source parameter determinations (rms< 0.3, erh<3km and erz<3km using HYPO71) with 0.5<M<3.5 and depths 0<D<15km. Thirty of these events would provide well constrained focal mechanism solutions with a minimum of ten clear and azimouthally distributed first P-wave arrivals. The results are shown in Fig. 5a. As can be seen the study area has been sub-divided into 5 domains, each associated with apparently distinct seismotectonic properties. In Area A, N-S to NNW-SSE extensional stress field appears to be generating E-W to ENE-WSW normal faults. Moreover, some form of structural discontinuity also appears to exist between this and the adjacent areas B and C, which display considerablty different seismotectonic features. Area B is characterized by NNE-SSW predominantly extensional stress field generating NW-SE normal fault planes dipping to the SW. In Area C, a similar field produces E-W to WNW-ESE normal to oblique-slip faults, the majority of which dips to SSW; wherever distinguishable, the slip is sinistral. The same is true for Area D, in which faulting is sinistral, oblique-slip on NW-SE oriented planes dipping to the NE. Finally, Area E is characterized by NW-SSE stress field producing normal/oblique-slip to strike-slip faulting with dextral dislocation; notably, this area belongs to the domain of the (dextral) N. Aegean trough and fault system emerging into the Greek mainland.

Two important observations can be made: First, note that our results indicate simultaneous seismic (tectonic) activity in two directions, a WSW-ENE and A NW-SE. Second, note the apparent rotation of the P-T plane from NNW-SSE in Area A to NNE-SSW in areas B,C,D and back again to NNW-SSE in Area E. In all cases there is a predominant N-S extensional component and a small E-W compressional component (with exception of Area B). Such a behaviour of the stress field points towards a mode of deformation rather more complex than the pure N-S extension suggested hitherto, probably involving shearing in conjugate planes.

*The 1980 sequence.* The second main source of seismological data was the catalogue of Makropoulos et al. (1989), from which we extracted the summer 1980 earthquake sequence. This data set was augmented with all M>3.2 events of the 1980 sequence listed in the ISC bulletin. The data is presented in Fig. 5b; superimposed are all the available CMT focal mechanisms computed for the sequences of 1980 and 1985 (see Table 1).

As it can be seen, the distribution of the aftershocks does exhibit an E-W elongation, which is very irregular and unsystematic to constrain the actual fault plane. A large number of epicenters appear to cluster in a NNW-SSE preferred orientation at the east end of the activated area, while certain E-W and ENE-WSW lineaments are observable. In hindsight, we also know that the hypocentral depths of many events of the '80 sequence in the ISC bulletin (including the main shock) are in error by a factor of 3-4 at least; this raises several questions

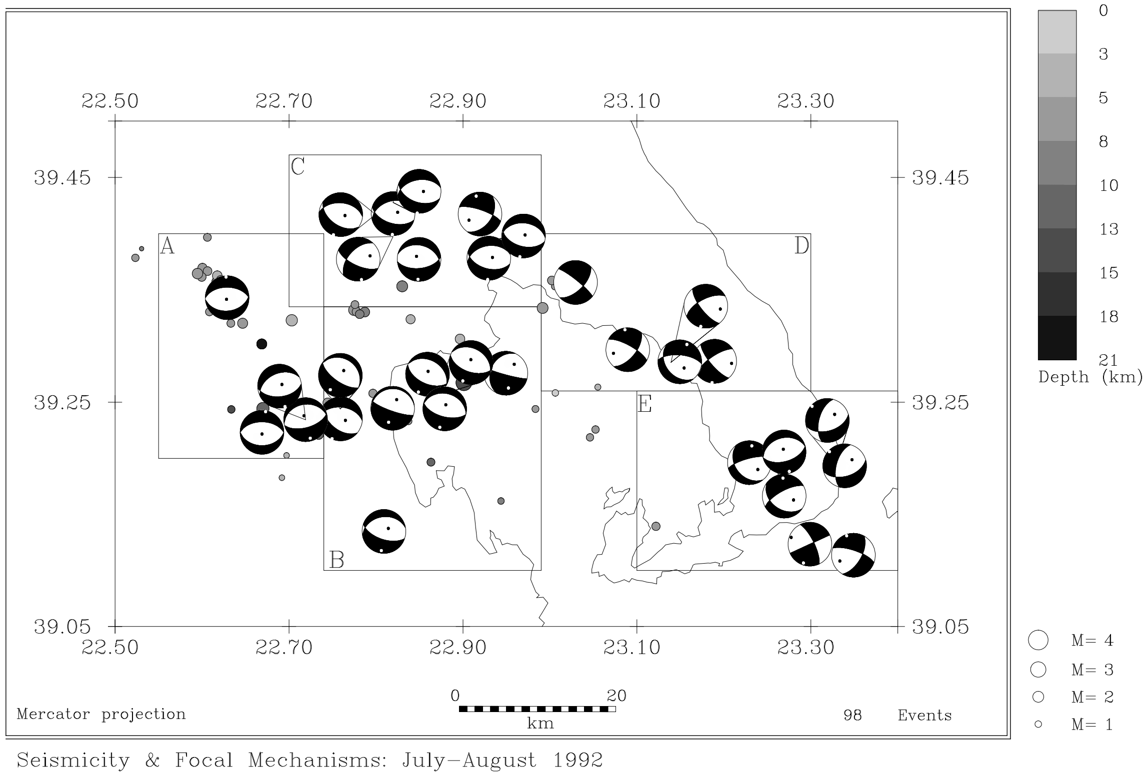


**FIGURE 5a**

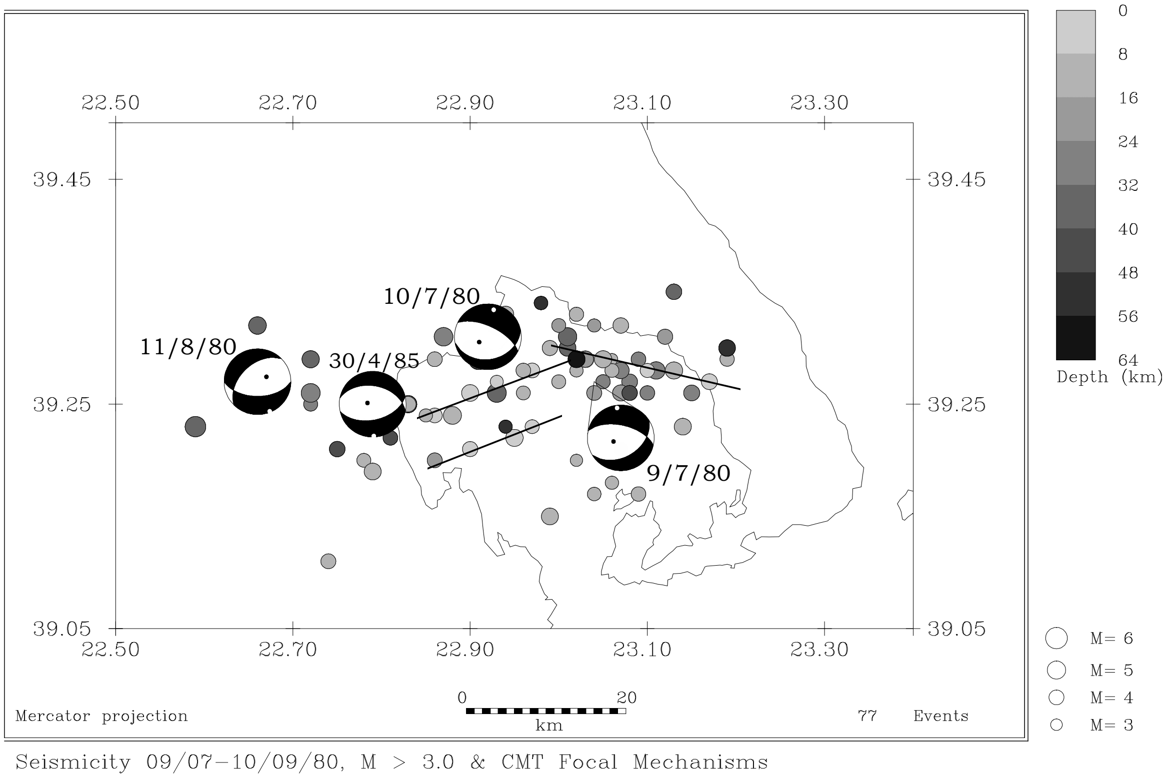


**FIGURE 5b**

on the credibility of inferences made on the basis of the aftershock data only. In consequence, the focal mechanism data of Figure 5b can be interpreted in two ways:

A. The sequence occurred in one continuous fault of WSW-ENE direction dipping to the S and running parallel to the northern coast of Pagasitikos Gulf. This is the conventional interpretation and is *apparently inconsistent* with the results of our 1992 experiments. Note that the focal mechanisms of the 9 and 10 July 1980 shocks on the east half of the study area show dextral slip, while the shock of 10 August 1980 would have an opposite (sinistral) sense of movement. This would appear contradictory but considering the relatively small magnitude of the latter event, it could possibly be attributed to elastic rebound.

B. The sequence occurred in two intersecting faults (or fault segments), one of WNW-ESE direction dipping to the NNE with sinistral slip, yielding control to one WSW-ENE oriented fault dipping to SSE, with sinistral slip. This interpretation is consistent with our 1992 experiment results, (Fig. 5a) both in terms of stress field patterns (*identical* rotation of the P-T plane implying the same dynamics and kinematics), as well as the interpreted faulting patterns. In this case also, the shock of 10/8/1980 is an misfit; as we'll indicate later, the sense of movement on the WSW-ENE plane should be dextral. Thus, in foresight, and again considering its relatively small magnitude we'll again attribute it to elastic rebound, but for a different set of dynamic and kinematic reasons. The fact remains however, that this explanation is not satisfactory in neither Case A or B above.

Table 1: The CMT Focal Mechanism Solutions illustrated in Figure 5b

| Origin Time | Location (NEIC) | Depth | Ms | Focal Planes (Az, Dip, Rake) |
|---|---|---|---|---|
| 09/07/80 02:11 | 39.27N 23.04E | 14.0 | 6.4 | (58° 41° -128°) & (283° 58° -62°) |
| 10/07/80 19:39 | 39.31N 22.92E | 10.0 | 5.5 | (79° 31° -123°) & (296° 64° -72°) |
| 11/08/80 09:16 | 39.27N 22.66E | 17.0 | 4.8 | (225° 47° -124°) & (90° 53° -59°) |
| 30/04/85 18:14 | 39.25N 22.79E | 19.0 | 5.6 | (281° 43° -72°) & (77° 50° -106°) |

Focal mechanism solutions for the major shocks of the 1980 sequence have also been given by several authors (Fig. 6). The solutions derived by Papazachos et al (1983, Nos 1, 2 & 3) indicate normal faulting of ENE-WSW orientation generated by a uniquely NNW-SSE extensional stress field. Drakopoulos and Delibasis (1982, No 4) on the other hand, suggest normal faulting in the WNW-ESE direction due to NNE-SSW extensional stress field (solution exists for the largest, M6.4 shock only). Finally, Galanopoulos and Delibasis (1983, Nos 5 & 6) propose focal mechanisms due to a NE-SW extension with oriented NW-SE fault planes. Notably, Papazachos et al are the only authors to suggest a uniquely consistent NNW-SSE oriented extensional field generating the sequence; all other investigators (including Taymaz et al, 1991) point towards a more complex stress field being responsible for the M6.4 shock.

A respectable number of authors propose different mechanisms for the main shocks of the 1980 sequence. Papazachos et al (1983) attribute the sequence to a single continuous, almost purely normal to slightly sinistral fault of ENE-WSW orientation along the northern coast of Pagasitikos Gulf, dipping to the SSE, their contention possibly being that this interpretation is consistent with the southerly dipping, E-W to WNW-ESE surface ruptures observed on west end of seismogenic volume (in the area of N. Angkhialos). Taymaz et al (1991) working with the same CMT focal mechanisms used herein, share this opinion on the same grounds. An interpretation based on Case B above (earthquakes occurring in two simutaneously activated faults) would, at first, appear to contradict the direct evidence from surface ruptures. Note however, that there's neither direct or indirect evidence (e.g. a tsounami), that the M6.4 main shock of 02:11 which occurred at (39.27N, 23.04E), produced any surface ruptures in its epicentral area, although it probably should, considering this event's e epicentral location, distance form the coast and depth. The surface ruptures were observed only at Nea Angkhialos, in the epicentral area of the M6.0 event of 02:35, which occurred at the opposite end of the acti-

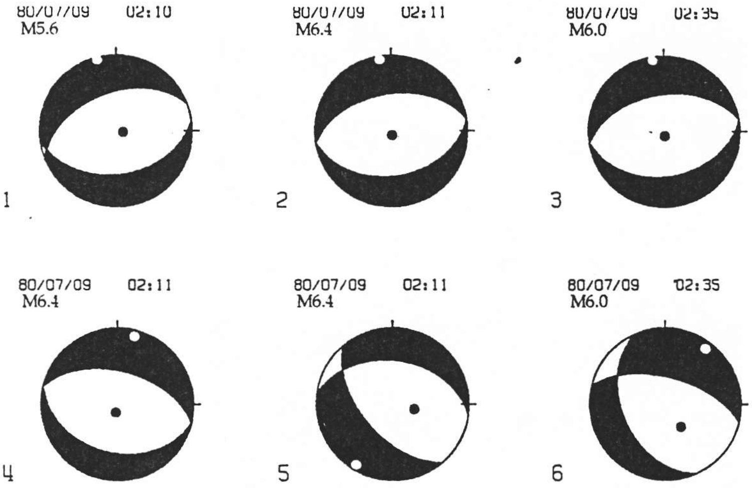


Figure 6. Fault plane solutions of the two main events in the sequence of 1980, as derived by Papazachos et al (1,2 & 3), Drakopoulos & Delibasis (4) and Galanopoulos & Delibasis (5,6).

vated volume (39.23N, 22.59E) within Area A of Fig. 5a and for which a CMT solution does not exist. Considering also that the two largest events have similar magnitudes it is likely that they both represent main shocks in two different albeit simultaneously activated faults or fault segments, as per Case B above. Nevertheless, this interpretation is still not free of problems: Considering the azimuth and dip of the assumed NW-SE fault plane, we may determine that its surface expression should be expected approximately at the position of the dashed thick grey line in Figure 5b; there is insufficient physical evidence for its existence, or they are obscured by several tens of meters of water and fresh sediment.

*The 1985 event.* The CMT solution of this event clearly indicates normal faulting in the general E-W direction. Considering the recent seismic history as well as the more active faulting structures of its immediate epicentral area, the southerly dipping plane (azimuth 77°, dip 50°) should probably be taken to be the fault plane. Then, this would show a small dextral slip component. It should be noted however and in foresight, that due to the very location of this event, *either plane would be acceptable* as the fault plane by the geotectonic model proposed herein. This event was followed by a short sequence which is not presented for the lack of space. At any rate, this would appear to be of low value for sound inference.

## Discussion - Conclusions.

In summarising the results and arguments presented above we conclude that:

* The interpretation of the geotectonics in SE Thessaly based on the assumption that deformation takes place by almost pure N-S extension in a single E-W oriented plane contradicts both the MT data and our 1992 experiment results and will therefore have to be rejected.

* The interpretation of the geotectonics in SE Thessaly based on the assumption that deformation takes place in two simultaneously active tectonic directions comprising a system undergoing shearing in two conjugate planes is consistent with the MT data, the CMT solutions of the 1980 sequence main shocks, the CMT solution of the 1985 event and our 1992 experiment results. This interpretation is therefore preferred and will be elaborated forthwith.

The CMT focal mechanisms of the large (M>5) earthquakes since 1980 indicate either normal, sinistral faulting in NW-SE planes dipping to NNE, or normal to slightly dextral faulting in E-W to WSW-ENE planes dipping to SSE. The focal mechanisms of microearthquakes collected during the summer 1992 experiment indicate simultaneous activity in two dirrections with normal to oblique-slip sinistral faulting in NW-SE to WNW-ESE fault planes and normal faulting in E-W to WSW-ENE planes. In both cases, the P-T plane of no shear undergoes an identical rotation from NNW-SSE in the southeast of the study area, to NNE-SSW in the central parts, to NNW-SSE in the northwest.

More scrutiny into the stress field is possible from the determination of the P and T axes azimuths (φ) and dips (δ) for the CMT mechanisms and likewise for the 1992 data using composite focal plane solutions constructed from all the available events in areas A-D. These are summarized in Table 2, where it can be seen that the T-axis has approximately N-S direction throughout and the rotation is mainly due to changes in the orientation of the P-axis. Moreover, the properties of the P-axis indicates that at least 30-40% of the total compressive stress acts on the horizontal plane and more than 60% of this, i.e. approximatelly 25% of the total compressive stress comprises its E-W component. Such a stress field appears capable of producing deformation by shearing and considering that we have observed simultaneous seismic activity in two directions, this would be shearing in two conjugate planes.

Table 2: The P and T axes azimuths and dips per area (from composite solutions) and per each CMT solution.

| AREA | P-axis (φ°/δ°) | T-axis (φ°/δ°) | CMT | P-axis (φ°/δ°) | T-axis (φ°/δ°) |
|---|---|---|---|---|---|
| A | 193 / 80 | 174 / 80 | 09/07/80 02:11 | 243 / 70 | 353 / 9 |
| B | 70 / 68 | 175 / 13 | 10/07/80 19:39 | 238 / 65 | 12 / 17 |
| C | 65 / 71 | 180 / 7 | 11/08/80 09:16 | 61 / 65 | 158 / 3 |
| D | 266 / 21 | 11 / 33 | 30/04/85 18:14 | 283 / 77 | 178 / 3 |

The existence of NW-SE to WNW-ESE geoelectric structures due to faulting has been detected at lower crustal depths by the MT surveys. These could also be attributed to a stress field generating N-S to NNE-SSW extension and NW-SE to WNW-ESE shear (fault) planes which facilitate the infiltration of water and development of high conductivity parallel to their direction. The MT data also identify an elongate conductive zone of WNW-ESE orientation at depths, 10-15 km, which appears to control induction processes at intermediate crustal depths and possibly comprises a transition between the upper and lower crust. The origin of this zone is believed to be closely related to the deformation of the investigated area : it is apparently generated by the stress field. Moreover, and inasmuch as it has been indicated that contemporary active normal faulting in SE Thessaly is listric, it appears that this conductor constitutes a domain within which the flexure of the fault planes increases to sub-horizontal and they diffuse into a shear zone comprising a transition between a brittle, deforming upper crust and a relatively undisturbed, flowing lower Also note that significant earthquake activity does not occur at depths greater than 15km. The lower crust is clearly associated with NW-SE trending conductive geoelectric structures which could also be attributed to shearing due to the aforementioned contemporary stress field at depth.

The above lines of MT and seismotectonic evidence would appear to be consistent with the geotectonic model presented in Figure 7. The conjugate (fault) planes are represented with thick grey lines. The angle between the two planes is of the order of 30° as should be expected in a sheared a system with moderate-high internal friction. The configuration of the stress field is such that:

- The E-W plane experiences almost pure N-S extension and expresses normal faulting with a small dextral component.
- The NW-SE plane absorbs most of the horizontal compressive stress and expresses normal, oblique-slip faulting with sinistral slip.

In this way, the entire deforming system should experience dextral block rotation about the vertical axis, with little or no mass translation. Since we find no apparent evidence of internal rotation, we assume that the deformation is homogeneous.

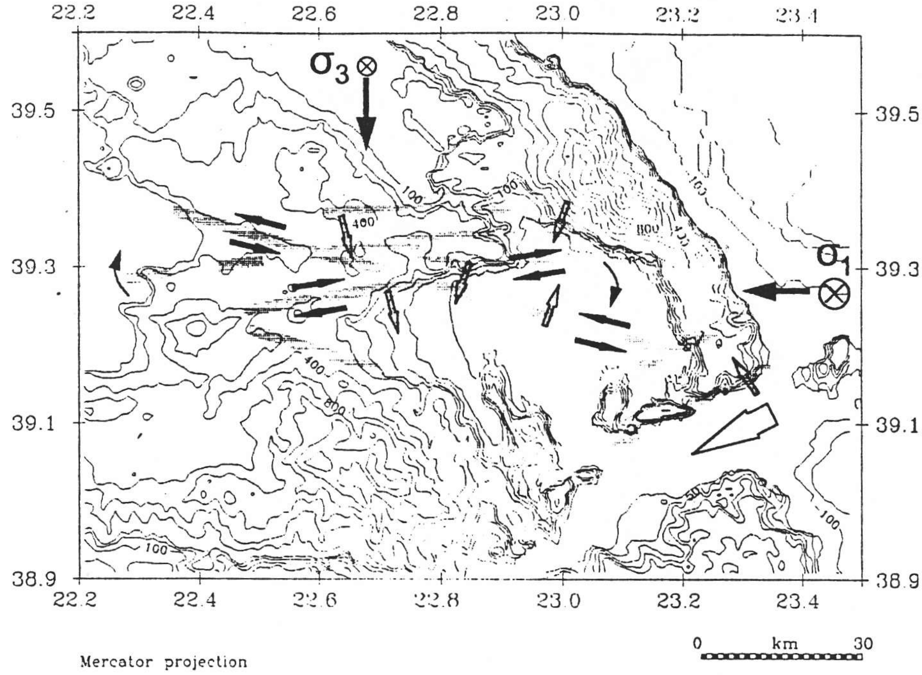


FIGURE 7. A geotectonic model for SE Thessaly. Thick grey lines indicate faults or faulting zones either directly detected (continuous) or inferred (dashed). Grey filled arrows indicate the observed direction of the P-T plane, pointing from P to T.

The proposed geotectonic model of SE Thessaly is but an updated version of the ideas first presented by Tzanis et al (1994), which, having been constructed on the basis of an incomplete data did show a number of shortcomings which, we believe, were extensively amended herein. Note also that the proposed model has certain differences, but produces the same effect with the block model of distributed deformation by faulting, proposed by Taymaz et al, (1991) and Jackson and McKenzie, (1986), because it predicts that the greater part of deformation is taken up by sinistral slip in NW-SE planes, leading to dextral block rotation with little or no mass translation.

It is also important to note that the proposed model fits neatly into, and practically explains all the geomorphological characteristics of the area, with special reference to those included between 39.1N and 39.4N.

The geotectonic model of SE Thessaly derived herein, albeit in advanced stage should still be perceived as a general framework and will certainly require refinement and augmentation in the future, when additional deep EM, seismological and other geophysical 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 far more complex that previously thought to be.

As a concluding remark, note that in this paper we combined MT and Seismotectonic data to derive a geotectonic model for SE Thessaly. In fact, it was the MT data and its persistent detection of NW-SE conductive directions, that initiated the scrutiny into the 1980-85 seismological data and the more meticulous analysis of the 1992 records. We believe that this work present a fine example that the two lines of research can be an essential combination in the analysis of geologically active domains, because in such cases their very foundations depend directly on the configuration and the properties of the stress field.

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