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Magnetotellurics and Seismotectonics in the Analysis of Active Domains: An Essential Combination?

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Abstract. The geoelectric structural trends *(GST)* derived from the spatial analysis (rotation/decomposition) of MT and GDS data in the vicinity of active deformation zones, exhibit remarkable correlation with seismotectonic trends and nodal planes of earthquake mechanism solutions, in practically all the cases we have examined in Greece and abroad. In the upper crust of an active domain, the *GST* may be explained in terms of conductors formed by water infiltrating through fault planes and related discontinuities, aligned microcracks and anastomosing shear zones. If this interpretation is correct, the *GST* should be good indicators of the corresponding trends and location of active faulting. In this context, the spatial analysis of geoelectromagnetic data is important in constraining the geometry of active faulting and hence, the modes of deformation. Two characteristic examples are presented and discussed from the island of Milos, Greece, located in the Hellenic Volcanic Arc and experiencing extensional tectonics and the island of Terceira, the Azores, simultaneously experiencing normal and strike-slip faulting.

1 Introduction.

During several years of (published or unpublished) Magnetotelluric (MT) and seismotectonic (ST) studies of tectonically active domains in Greece and abroad, we have accumulated a number of examples in which geoelectric structural trends derived from the spatial analysis (rotation / decomposition) of MT and Geomagnetic Deep Sounding (GDS) correlate remarkably well with nodal planes of earthquake focal mechanisms, ST trends and morphotectonic features. Moreover, we have made similar observations by studying the results of other investigators. In some cases, (e.g. Tzanis et al, 1994; this paper), the EM data returned some rather unexpected results, indicating geoelectric structural trends and, by inference, faulting, unconforming to existing views and theories of the active tectonic modes of an area. Subsequent scrutiny into the seismotectonics of these areas revealed that the geoelectric structural trends did indeed correlate with 20^{th} century active faulting and earthquake occurrence along these directions : deformation modes were more complex than they were thought to be. For instance, in the case reported by Tzanis et al (1994), both the EM and ST data fit better into the context of inhomogeneous deformation in conjugate planes (involving rotation), rather than inhomogeneous deformation along parallel planes as was thought to be the case.

In consequence of the above, we concluded that in areas of active crustal deformation, 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 crust, then it is simultaneously possible to improve understanding of the fundamental modes of crustal deformation. For instance, one expects that homogeneous deformation in parallel planes by dominantly normal or inverse faulting, should yield unique conductive directions because the planes of maximum shear are aligned. On the other hand, homogeneous or inhomogeneous deformation by shearing in conjugate planes would generate conductors related to the locally active faulting plane, as well as spatial changes in the conductive directions

We note that ST data are notorious for non-uniqueness and bias, and that EM (particularly the MT) data are often distorted by local effects and extraneous processes. In consequence, the feasibility of an associative interpretation of MT and ST data, albeit expanding on a rather simple physical basis as we discuss bellow, it has to be demonstrated with a series of careful case-studies and examples from different geotectonic environments. This being impossible in the limited space of the present paper, we will limit ourselves to providing two case studies demonstrating the concept and the usefulness of this approach, by directly comparing archetypal ST data (earthquake focal mechanism solutions) and their correspondence with MT and GDS data. We use MT/GDS data in the frequency range 100Hz - 100s, which are carefully winnowed to exclude cases of local galvanic distortion, but not the galvanic effects of regional 3-D structures. The spatial information of the MT Tensor Impedance (MTTI) is extracted with rotation of the experimental coordinate system until it coincides with a coordinate system(s) *intrinsic* to the geoelectric structure, using a standard rotation procedure (Groom and Bailey, 1989). The term *spatial*

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analysis is used to describe the process of rotation and mapping of the results.

2 A brief review of the physical basis for associative Magnetotelluric and Seismotectonic analysis.

Within the *schizosphere,* (brittle upper crust), active faults are usually associated with elongate conductors along their strike : Faulting generates permeable rock, either directly within the fault zone, (fault gouge, brecia and mylonite), or around it as a result of repeated cycles of loading / unloading and elasto-plastic deformation (formation of microcracks).

The presence of water in the immediate vicinity of the fault zone is so important, as to form the basis of a number of earthquake instability models (e.g. Lockner and Byerlee, 1995). Around the fault zone, tectonically induced permeability can be a result of micro- and meso-scale fracturing and crack interconnection. This is a consequence of volume dilatancy prior to earthquakes; meso- or macro scale cracks result from crack propagation and fusion by mutual interaction at times immediately preceding the earthquake.

Cracks may be either axial tensile cracks aligned parallel to the compressive normal stress (σ_1), or shear cracks parallel to the fault. The former are usually micro-structures, while the latter can be micro-, meso- or macro-scale : shear cracks propagate by the formation of axial tensile (micro)cracks at their tips and merge to form larger cracks when any two cracks expand to sizes greater that the critical radii of their mutual instabilities. In this way, shear cracks get self-organised according to their sizes and form a fractal set from the smallest to the largest (the fault). When interconnected, water diffusion through the sheared zone may create a conductive structure aligned with the fault(s). For thorough treatments of brittle deformation, crack-to-fault processes and volume dilatancy by microfracturing, the reader is referred to Scholz (1990) and Teisseyre (1995).

Healing processes are expected to close the cracks and reduce conductivity, unless they are kept open by continuous accumulation of deformation, either seismic or aseismic. Thus, the effect should be stronger near the fault zone and attenuate with distance. Moreover, the more extensive and pervasive the microfracturing, (more heavily deformed the material), the more conductive the rock may be. Conductivity is also expected to change with time, albeit by an unpredictable amount, responding to changes in the stress and strain rate (tectonic activity) as well as changes in water supply.

Fluid-filled cracks generated by lithostatic pressure are a pervasive feature of crystalline rocks at depth (e.g. Scholz, 1990); their existence actually forms the basis of the Extensive Dilatancy Anisotropy theory (e.g. Crampin et al, 1984 and references therein). Under steady-state conditions these cracks are isolated, however, when the rock is disturbed they may become interconnected by the processes described above and lower its resistivity

Cracks may also form under stress beneath the schizosphere, in the brittle-plastic transition, a broad zone in which deformation is semibrittle, comprising microscale plastic (dislocation gliding) and brittle processes and macroscopic ductile rheology. *Cataclastic flow,* is typical of the semibrittle behaviour within the brittle-plastic trasition, where it is a mixture of brittle-frictional and plastic deformation which produces dilatancy and has a strongly pressure dependent strength (e.g. Scholz, 1990). These processes occur concurrently with low grade metamorphism involving liquid phase (brines), which may increase the electrical conductivity when interconnected. 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 deep borehole (e.g. Kozlovsky, 1988) as well as the German KTB.

Geothermal (hydrothermal) areas and volcanic domains in the upper crust are particular environments deserving special attention. The electrical conductivity of near surface rocks arises from the fluid content of interconnected pore space (liquid fraction) and depends on the salinity of the pore fluids, the temperature and the presence or absence of clay minerals (e.g. Keller and Rapolla, 1976). Clay minerals may increase the salinity of pore fluids, (hence electrical conductivity), by several orders of magnitude. The liquid fraction will certainly increase in the neighbourhood of fluid circulation conduits, as also will the fraction of clay minerals due to hydrothermal alteration. In convective geothermal systems, especially those controlled by concurrent tectonic activity, fluid convection and circulation conduits are usually identified with the dominant active fault systems through which fluids are transported from the deep feeder reservoirs or heat sources. This is also true for all geological situations associated with active circulation of subterranean waters.

3 An example from the Hellenic Arc System, Greece.

The island of Milos in the Cyclades, Greece, belongs to the Hellenic Volcanic Arc (HVA), which is part of the Aegean Arc and Trench system marking the collision between the Eurasian and African plates (Fig. 1). Given its geotectonic situation and high enthalpy geothermal field, the island has been exhaustively studied in a series of Greek and European research programmes, having also been selected as a test site of European geothermal research. Detailed reviews and information on the results of these programmes can be found in *Geothermics, Special Issue, v18 No 4, 1989.* Within the HVA, the island exhibits the most important volcanism in terms of quantity, duration of activity (3.5-0.8 M.a.) and variety of volcanic products. The latter belong to the calc-alkaline suite characteristic of island arcs. Volcanic activity in Milos occurred through a series of different, frequently synchronous eruption centres without ever building a characteristic central edifice; most of its has been mainly pyroclastic and submarine, but the most recent eruption (0.1 M.a.) was subaerial and formed "tuff rings", surge deposits and lava flows, all of homogeneous rhyolitic composition. Due to its geotectonic situation, the island has experienced intense tectonic activity during the Pliocene and Quaternary, which continues until the present and has also controlled its volcanological evolution and geothermal system by creating a complex faulting pattern resulting in the formation of horsts and grabens. Detailed studies (see Fytikas, 1989 and references therein; Papanikolaou et. al., 1993 and references therein), distinguished a phase of NE-SW extension since the Pliocene, producing NW-SE normal faulting, and a phase of NW-SE extension during the Quaternary. According to Fytikas (1989), the last (NW-SE) extension phase and asso-

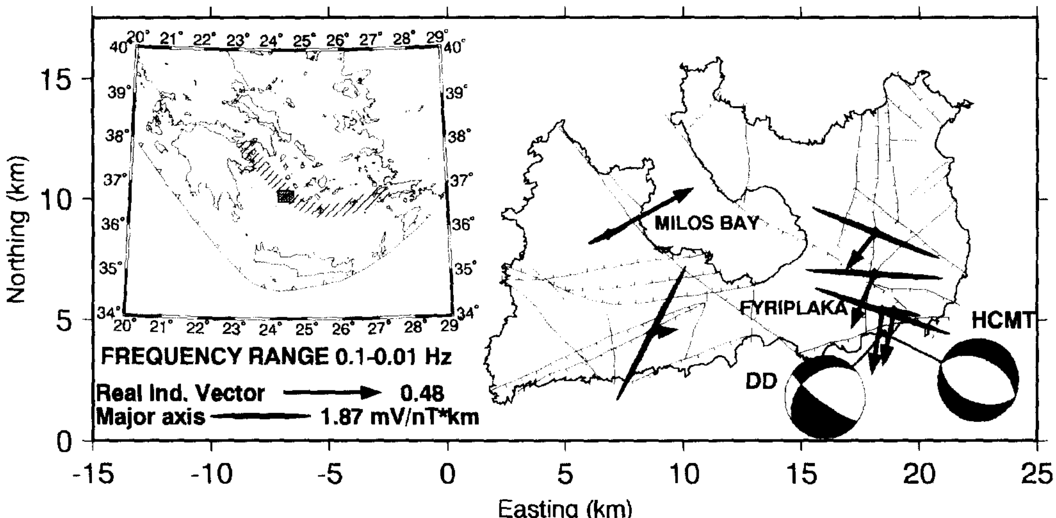

Fig. 1. The island of Milos and its most significant faulting structures according to Papanikolaou et al., (1993). Superimposed are the major axes of the observed impedance tensors and the real induction vectors averaged over the frequency range 0.1-0.01Hz, and the fault plane solutions by Harvard (HCMT) and Delibasis & Drakopoulos, 1993, (DD). The inset map shows the position of Milos (grey rectangle) in the Hellenic Volcanic Arc (hatched area). The toothed line indicates the front of the Aegean subduction system (Hellenic Trench).

ciated ENE-WSW faults are more frequent in the eastern part of Milos, especially at the places of recent and intense hydrothermal alteration and form a system of alternating horsts and grabens influencing the neotectonic evolution of the area, volcanic activity and the circulation of geothermal fluids. The NW-SE faults corresponding to Pliocene tectonic episodes are still active and, in combination with the Quaternary fault systems, have controlled the volcanism, tectonic structure and thermal regime of the area. On the other hand, Papanikolaou et al., (1993) assert that the major contemporary active faulting on the island occurs along the NW-SE normal faults, which have created the active tectonic graben structure that separates the Western and Eastern halves of Milos and which is "*characterised by the recently submerged morphology of the Bay of Milos in the NW and the most recent volcanic activity of the Fyriplaka crater to the SE*". The conclusions of these authors appear to be supported by most of the existing seismological observations. Present day tectonic activity has gradually declined in the western part of the island, while it is still intense in the central and eastern, expressed with continuous seismic activity.

Drakopoulos and Delibasis (1973) present a detailed report of previous seismicity and the 1971 volcanic earthquake swarm, however, the first well constrained data from local seismological arrays are reported by Ochmann et al., (1989) and Hirn et al., (1989), although it is only the former who put emphasis in reconstructing the seismotectonics of Milos. Their results clearly indicate a dominant NW-SE alignment of epicentres within the Milos Bay - Fyriplaka graben (Fig. 2 left). However, there is also some minor evidence of NE-SW alignments. The focal depths of these events vary between 5-10km, which is also consistent with Hirn et al., (1989). In addition, the fault plane solutions of the best quality events, (Fig. 2 right), all have NW-SE and NE-SW nodal planes and invariably indicate normal faulting. This is consistent with geological - tectonic evidence and may possibly indicate conjugation of the active faulting systems on the island. However, the analysis of the principal stresses deduced from the focal mechanisms clearly shows predominant NE-SW extension.

The most recent sizeable earthquake occurred on 05:37 of 3/20/1992 just off the S. coast of Milos, with M_s=5.3 and a focal depth of 11km. The Harvard CMT fault plane solution is presented in Fig. 1 and indicates pure normal faulting oriented at N293° and dipping approximately 45°, consistent with the strike of the Milos Bay - Fyriplaka graben. The solution is well constrained, but as always is the case, it cannot determine the actual fault plane, which may dip either to the NE or to the SW. Delibasis and Drakopoulos (1993), have produced a quite different mechanism, also shown in Fig. 1, using 19 first P-wave arrival polarities from neighbouring seismological stations. Their solution requires a substantial degree of oblique slip, either on a steep NW-SE normal fault, (N337° also consistent with the strike of the Milos Bay - Fyriplaka graben), or a NE-SW N52° low angle normal fault dipping NW. The main event was followed by an aftershock sequence lasting for approximately 10 days. Since no local networks were operating on the island at the time, aftershock location was based on data from the National Greek Network (with detectability threshold for events with $M_L > 3$) and was therefore poorly constrained, although the distribution of epicentres clearly shows a NW-SE elongation. Moreover, their frequency-magnitude statistics suggested a tectonic rather than volcanic origin. Based on such evidence, Delibasis and Drakopoulos (1993) consider the main shock to have ruptured a NW-SE normal fault, possibly one of the boundary faults of the Milos Bay - Fyriplaka graben.

Extensive MT surveys by different groups were performed as part of the European test site project, however it is only Hutton et al., (1989) who attempt to reconstruct the spatial properties of the electromagnetic field by mapping the major and minor impedance axes and the real induction vector. They present data in the frequency range 0.2-0.1 Hz which approximately correspond to the depths of the extensive and pervasive geothermal reservoir, and at frequencies lower 0.005 Hz, which correspond to lower crustal depths and hence convey strong re-

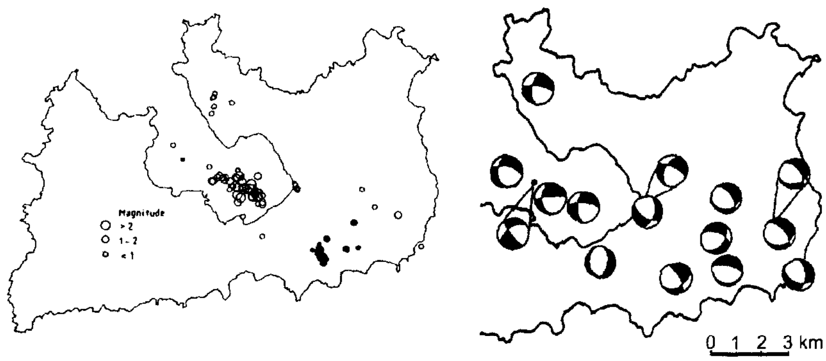

Fig. 2. Left: The best constrained earthquake locations (90 events) obtained by Ochmann et al (1993) during a few months of 1986 (solid circles) and 1987 (open circles). **Right:** The focal mechanisms of the better events of Fig. 2a, constructed with the first P-wave polarity method. Both figures are redrawn and modified from Ochmann et al. (1993).

gional influences. Their results clearly show a preferential NW-SE configuration of current flow. Moreover, their quantitative analysis shows an explicit NW-SE orientation of very good conductors at the central and eastern Milos which, presumably, include the geothermal reservoir (see their Fig. 8 and pertinent discussion). Such results have not been repeated by Haak et al., (1989) who, however, present images constructed with crude, approximate inverse mapping and not analytic inversions. Finally, Drews et al. (1989) have shown by thin sheet modelling that the effect of the surrounding sea is very small to significantly influence the results. Additional geophysical investigations included a detailed self-potential survey (Thanassoulas, 1989); modelling in terms of dipping planar structures yields a clear NW-SE orientation of the SP sources.

The MT work reported herein was conducted much later in collaboration with the French company GEOREX who carried out the field campaign and basic data processing. This programme was primarily targeted at researching and verifying the relationship between geoelectric structure and tectonics in the island and only a small number of soundings (6) were performed in the bandwidth 100Hz - 100s. Consistently with results of previous MT surveys, (e.g. Hutton et al., 1989), the data indicates a rather simple and conductive geoelectric structure with low lateral resistivity contrasts within the first 1-1.5km, where it is controlled by the geothermal system, especially at the eastern part of the island. At greater depths, roughly corresponding to frequencies lower than 1Hz (T>1s), multidimensional structural influences increase and the structure is apparently 2-D but no higher. The spatial properties of the MT and GDS data are shown in Fig. 1, respectively in the form of the major axis of the impedance rotation ellipse and the real induction vectors (Parkinson convention), averaged over the frequency interval 0.1-0.01 Hz and scaled with respect to the maximum. This interval corresponds to structure extending from 1.5-2 km down to several km and includes the domain where earthquakes nucleate in the area of Milos. The joint interpretation of MT and GDS data indicates a significant lateral resistivity interface of NW-SE orientation, such as to generate TE mode induction in the eastern part of the island and TM mode induction of the western part. The location of the interface appears to coincide with the western boundary fault of the Milos Bay - Fyriplaka graben.

The parallel NW-SE orientation of the *GST*, distribution of big and small earthquake loci and nodal planes of focal mechanism solutions may be correlated and interpreted in terms of the arguments proposed in section 1 above. Note that geothermal fluids are very rich in dissolved minerals which can easily precipitate and heal the faults, unless they are kept open by other natural forces, in our case active tectonics. Thus, the spatial distribution of seismicity provides an image of the geodynamic conditions, which also prepare the network of preferentially oriented fluid circulation conduits and diffusion paths that create massive, oriented conductive domains. In the case of Milos, it is apparent that the NW-SE oriented *GST* extend to the NE, beyond the eastern boundary fault of the Milos Bay - Fyriplaka graben, possibly indicating a similar preferential orientation of fluid circulation through active fractures. As is also evident from Hutton et al., (1989), the MT data could delineate active faulting in more detail, should more soundings have been available. The NE-SW faulting directions interpreted by many geologists to be the dominant contemporary trend, either they have not affected the older conductors as yet, or they comprise a set of secondary conjugate structures. It is also possible that these faults facilitate the discharge of thermal fluids to the surface and hydrothermal manifestations at the weak spots of their intersections with the dominant NW-SE trends, in which case they may give the impression of being more significant than they actually are.

4 An example from the Azores Archipelago, Portugal.

Terceira is a volcanic island of the Azores Archipelago, located near the triple junction between the Mid-Atlantic Ridge and the Azores-Gibraltar Ridge. It is part of a geologically very active region, exhibiting continuous seismicity and recent / contemporary volcanism associated with geothermal manifestations. The most outstanding regional tectonic structure reported on the island is the Terceira Ridge, which extends for over 600km, from the Gloria Fault to the Mid-Atlantic Ridge and comprises the boundary between the Eurasian and African plates (Fig. 3). The ridge is associated with NE-SW extension pulling apart the European and African plates and consequently; it has all the attributes of a secondary oceanic spreading centre associated with volcanic activity. In the Azores region, it can be followed along a NW-SE trending series of well aligned underwater volcanoes and sub-aereal structures. It intercepts Terceira and crosses it along a NNW-SSE course, then re-entering the sea and continuing its course to the NW through a series of submarine structures and volcanoes. A second apparent tectonic feature is the Central Rift system, a narrow (1-5 km) zone across the west half of the island, trending WNW-ESE and intersecting the Terceira Ridge in the central part of the island. Believed to be younger than the latter, it has

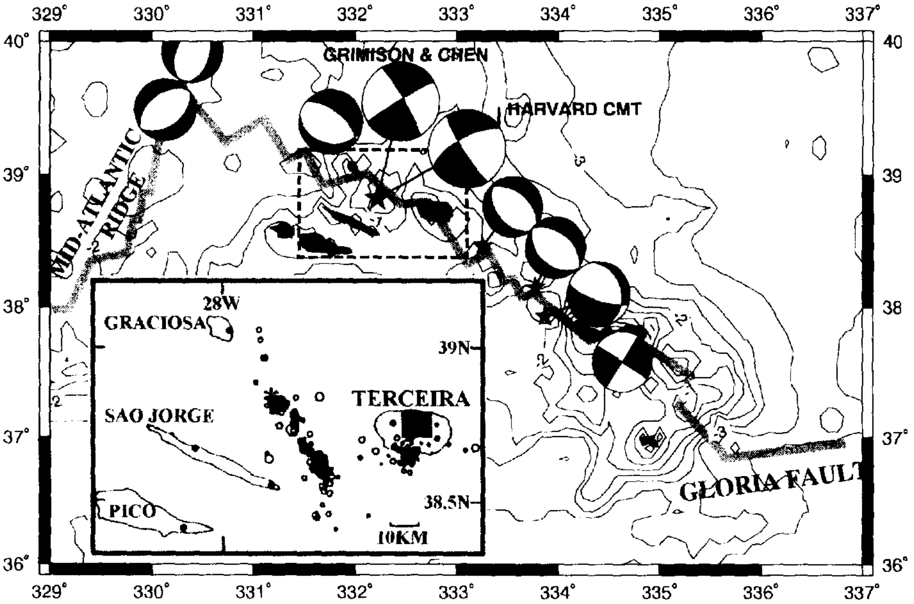

Fig. 3. Fault plane solutions and bathymetry along the Terceira Ridge (taken from the Harvard CMT catalogue, unless otherwise indicated on the map). The Terceira and Mid-Atlantic ridges and transform fault segments are outlined with the thick grey lines (after Searle, 1980). The inset map shows the aftershock locations of the 1-1-1980 earthquake (from Hirn et al, 1980). The solid grey rectangle in Terceira island (inset) indicates the magnetotelluric survey area.

been proposed by Searle (1980) to comprise the actual line separating the European and African plates. These two major NW-SE and WNW-ESE tectonic features respectively produce the two major systems of faults reported on the island. Other reported faulting features include ring and radial faults and caldera collapse faults, all typical of volcanic terrain.

We investigated the Harvard CMT focal mechanism solutions of the 10 major earthquakes since 1978, distributed almost along the entire length of the Terceira Ridge (Fig. 3). The tectonic regime of the Terceira Ridge is dominated by NE-SW (N37°E) extension. In most cases this field generates almost pure, low-angle normal faulting with rupture originating near the base of the crust (10-14 km). One important exception is the M6.7 earthquake of 1-1-1980, which was generated by predominantly strike-slip faulting. We provide two solutions of this event, one by Grimison and Chen (1988) and the other by Harvard, obtained with different algorithms for CMT inversion. The two solutions are very similar, but Grimison and Chen (1988) require strike-slip with a slight thrusting component, while the Harvard solution is strike-slip with a slight normal component. This earthquake is dissimilar to other events along the Terceira Ridge. This large event did not produce large aftershocks. Hirn et al (1980) reported a study of the aftershock sequence using a 8-station local network. A composite fault mechanism solution of these aftershocks was very similar to the main shock. The linear NNW-SSE distribution of the epicentres along a 40km stretch between Terceira, S. Jorge and Graciosa, (inset in Fig. 3), is parallel to one of the nodal planes in the focal mechanism. This led Hirn et al (1980), to suggest that the rupture took place by sinistral slip in this NNW-SSE striking plane. This interpretation is reasonable, but for Grimison and Chen, (1988), *"it does not fit into the general framework of the present-day plate motion along the boundary as a whole, or in the tectonic setting of the Azores in particular"*. Furthermore, *"left stepping ridges separated by short lineations which are sub-parallel to the small circles centred at the RM2 pole of Eurasia relative to Africa seem to characterise the bathymetry of the entire Azores Region (Searle, 1980)"*. The left-stepping can be seen in the thick grey line of Fig. 3, representing the Terceira Ridge. In order to relate the mechanism of the strike-slip event to the divergent nature of the ridge segments, the natural choice would be dextral slip on the NE-SW striking plane in a ridge - transform fault - ridge configuration (Grimison and Chen, 1988). It follows that the available data cannot determine the actual fault plane of this event.

A MT survey was conducted in Terceira during 1993, as part of a geothermal research programme targeting the Pico Alto Volcanic complex, in the Central-North part of the island, (Aumento, 1994; see inset in Fig. 3). As in the previous example, the spatial properties of the MT and GDS data are shown in Fig. 4, respectively in the form of the major axis of the impedance rotation ellipse and the real induction vectors (Parkinson convention), averaged over the frequency interval 10-1 Hz and scaled with respect to the maximum observed values. The spatial properties do not change significantly with frequency. Fig. 5 is an interpreted horizontal resistivity slice at 300m below mean sea level, constructed by interpolation from 1-D OCCAM inversion models. The general trends of the resistivity structure persist to the depth of 2000m below sea level. Superimposed on both Figures 4 and 5 is the observable rim of the Pico Alto caldera (hatched line) and the presently active fractures as identified by mapping of rare gas exhalation (Aumento, 1994).

The results of extensive investigations, (Anderson et al., 1982; Aumento, 1994; Tzanis, 1994), indicate that this active fracture system constitutes the network of conduits through which hot fluids circulate. Particularly important are the NE-SW faulting structures along the line Furnas do Enxorfre - Agualva, which have been determined to comprise the ascending branch of the convection cell. Independent, direct evidence in support of this interpretation are a definite SP lineament of ≥150mV/km extending in a NE direction between Furnas do Enxorfre and Agualva, (Anderson et al, 1982), and a very high radon emission lineament along the same direction (Aumento, 1994). The descending branches are similar active

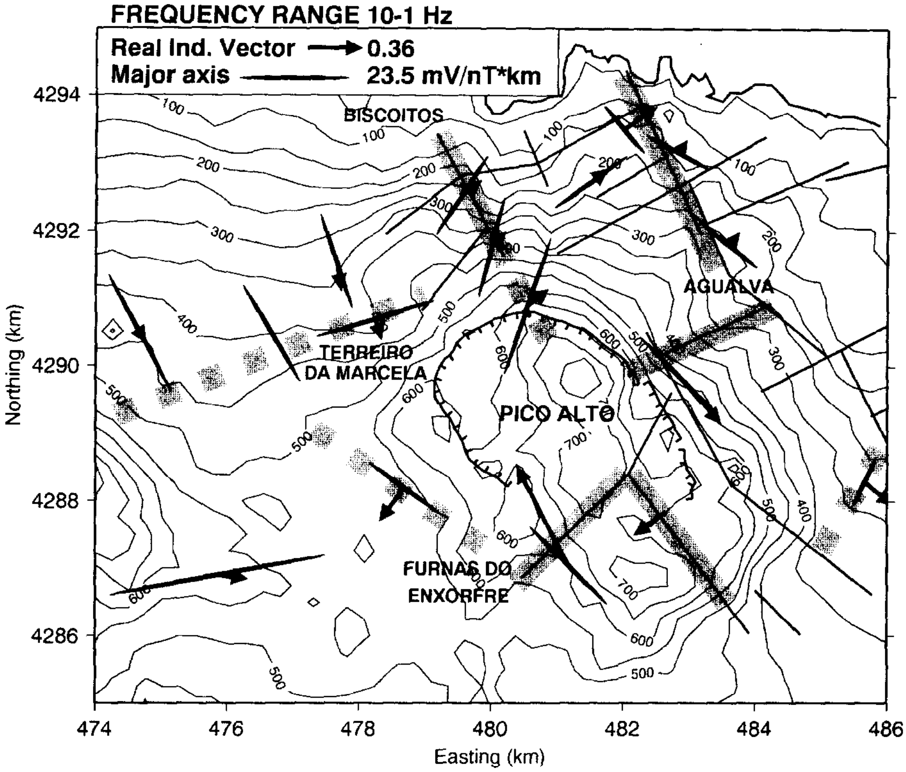

Fig. 4. Map showing the configuration of the impedance major axis and real induction vectors. The hatched line indicates the rim of the Pico Alto caldera; solid black lines mark the location of active fractures (Aumento, 1994); the thick grey line marks the position of elongate conductors as indicated by the MT and GDS data.

faulting structures to its NW and SE. Cold sea water invades through NE-SW and NW-SE fractures near the coast and mixes with the hot geothermal fluids; this is expected to generate a thick, electrically conductive formation of altered volcanic rocks, which can actually be seen in Fig. 5.

The detailed analysis of Tzanis, (1994), indicates a geoelectric structure with very low lateral resistivity contrasts within the first few hundreds of meters above and below sea level. Observe, for instance, that in Fig. 5 the range of resistivity is only 60 Ωm. Such a structure is expected to generate weak TE and TM responses observable only at short ranges around the interfaces producing them. Accordingly, the *GST* vary spatially but as can be clearly observed, they are almost always related to the strike of active fractures in their vicinity. The observable cases of such local / causal relationship are delineated with thick light-grey lines (Fig. 4). A characteristic example is the NNW-SSE fracture running between Biscoitos and Pico Alto and the apparently TM induction mode observed at the three MT sites lying immediately to its west. In addition, the *GST* indicate elongate conductors at places where rare gas exhalations have either not been mapped, or have not been detected. These are also delineated with dashed thick grey lines. A characteristic example is the one defined by TE mode induction at Terreiro da Marcela and TM mode induction at all sites to its NW.

Given the sparse distribution of soundings and the geoelectric structural peculiarities of the area, (volcanic island in the deep ocean), if studied independently, the spatial MT/GDS data would appear to provide inconsistent and confusing information. There's no obvious pattern to suggest some definite *GST*. Arguments involving extraneous effects (e.g. local distortion) would be very tempting in order to explain the apparent inconsistency. When, however, the EM MT/GDS spatial data is compared with rigorously and independently identified signatures of active faults (also serving as fluid circulation conduits), they can be clearly seen to adjust with respect to faulting structures in their vicinity. It follows that the 'inconsistency' was simply a result of the complex configuration of the faults and low resistivity contrasts producing mainly local/short range interactions, in combination with the sparse distribution of soundings. It turns out that if there was a higher density of soundings, the MT/GDS data could, in their own right, delineate and constrain the modes of active faulting.

It appears that the principal NNW-SSE trending structures of the Terceira Ridge interact with a system of NE-SW faults, which are apparently important in the contemporary tectonic and volcanological state of the island. Notably, the areas of both modern active volcanoes (Santa Barbara and Pico Alto) are characterised by a high spatial density and strong interaction between the two principal faulting systems (Aumento, 1994; Tzanis, 1994). The NE-SW direction of conductive *GST* is nearly identical to the NE-SW nodal plane of the 1-1-80 earthquake's focal mechanism solutions (Fig. 3). On the other hand, the NNW-SSE nodal plane is almost parallel to the Terceira Ridge system. Although the EM data cannot constrain the actual faulting plane of the 1-1-80 event, they provide direct evidence that both tectonic directions are simultaneously active. This requires inhomogeneous distributed deformation in a certainly more complex mode than previously appreciated. The precise nature of the deformation mode will have to be determined by future investigations. Judging from the currently available information, however, both faulting directions are

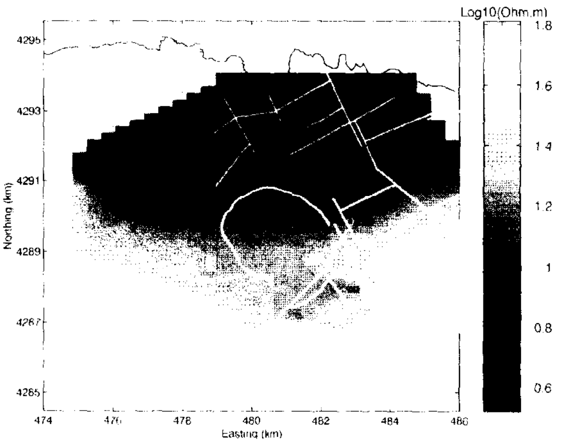

Fig. 5. Horizontal resistivity slice at 300m below sea level. Note the logarithmic resistivity scale. Circles indicate the locations of MT soundings. Straight lines indicate known active fractures (Aumento, 1994). The rim of Pico Alto Caldera is also superimposed.

equally capable of generating intermediate magnitude earthquakes. Therefore, both of them may have to be considered in future earthquake hazard assessment and mitigation studies in the Azores : this alone may be an important practical result of the associative interpretation of EM and Seismotectonic data.

5 Discussion

Although there's an arguably simple physical basis for establishing a relationship between EM induction and active faulting in active domains, the spatial information contained in the MT tensor impedance and the Magnetic Transfer Function is not commonly used in investigating the tectonic texture, while their correlation with seismological and seismotectonic data is very rarely attempted. Herein, we propose that MT/GDS data can provide essential information on the modes of active tectonics, and that their joint (associative) interpretation with seismotectonic data can be a very useful tool in the analysis of active domains. We provide two examples in support of our argument, which can be constrained and corroborated by independent hard evidence and data. A straightforward case from Milos (Greece) is used to demonstrate the concept while the second case from Terceira, (Azores, Portugal), may also be demonstration of its potential usefulness.

We note that Seismotectonic data is a direct consequence of active faulting, but reliable seismicity records and focal mechanisms exist only for second half of the 20th century. Earthquakes however, may nucleate in any fault within an active seismic zone, and only a small portion of the potential seismogenic faults have been activated during this period, the rest remaining quiescent. It follows that the correlation of reliable seismotectonic data with *GST* obtained at within the broader tectonic zone may provide an indication of the extent of active faulting systems, hence the extent of the potential seismogenic area.

References

Anderson, E., Usher, G. and Tearney, K., 1982: Gravity Survey, Geothermal Prospection - Ihla Terceira, Acores. Report, Geothermal Energy New Zealand Limited.

Aumento, F., 1994, TERGEOTER (Terceira Geothermal Project) : Identification and characterisation of a new, deep seated, high temperature geothermal; reservoir, Technical Report, Project JOU2-CT92-0114, DGXII, EU.

Crampin, S., Evans, R. and Atkinson, B.K., 1984. Earthquake prediction : a new physical basis, Geophysical Journal, 76, 147-156.

Delibasis, N.D. and Drakopoulos, J.C., 1993. The Milos island earthquake of March 20, 1992 and its tectonic significance, PAGEOPH, **141**, 43-58.

Drakopoulos, J., Delibasis, N., 1973. Volcanic-type micro-earthquake activity in Milos, Greece. *Annalli di Ceofisica*, **26**, 131-153.

Drews, C., Fuerch, N., Maurer, N. M., Musmann, G. and Weidelt, P., 1989. Active audiomagnetotellurics on Milos (Greece) for determination of electrical conductivity distribution and its correlation with geothermal anomalies, *Geothermics*, **18**, 507-519.

Fytikas, M., 1989, Updating of the geological and geothermal research on Milos island, *Geothermics*, **18**, 485-496.

Grimison, N.L. and Chen, W.P., 1988. Source mechanisms of four recent earthquakes along the Azores-Gibraltar plate boundary, Geophys. J. Int., 92, 391-401.

Groom, R.W. and Bailey, R.C., 1989. Decomposition of the magnetotelluric impedance tensor in the presence of local three-dimensional galvanic distortion. J. Geophys. Res., 94, 1913-1925.

Haak, V., Ritter, O. and Ritter, P., 1989. Mapping the geothermal anomaly on the island of Milos by magnetotellurics, *Geothermics*, **18**, 533-546.

Hirn, A., Haessler, H., Hoang Trong, P., Wittlinger, G. and Mendes Victor, L.A., 1980. Aftershock sequence of the January 1st 1980 earthquake and present-day tectonics in the Azores, Geophys. Res. Lett., 7, 501-504.

Hirn, A., Sachpazi, M.and Nercessian, A., 1989. Elements for a model of the geothermal field of Milos from seismological data, *Geothermics*, **18**, 579-595.

Hutton, V.R.S., Galanopoulos, D., Dawes G.J.K. and Pickup, G. E., 1989. A high resolution magnetotelluric survey of the Milos geothermal prospect, *Geothermics*, **18**, 521-532.

Keller, G.V. and Rapolla, A., (1974). Electrical methods in volcanic and geothermal environments. In Civetta, L., Gasparini, P., Luongo, G. and Rapolla, A. (editors), 'Physical Volcanology', Elsevier series Developments in Solid Earth Geophysics 6.

Kozlovsky, Ye.A., 1984. The world's deepest well, Scientific American, **251**, 106-112.

Lockner, D.A. and Byerlee, J.D., 1995. An earthquake instability model based on faults containing high fluid-pressure compartments, in Wang, R. and Aki, K., (Eds), Mechanics Problems in Geodynamics, Part I, (Pageoph Topical Volumes), Birkhaeuser, 717-146.

Ochmann, N., Hollnack, D., and Wohlenberg, J. Seismological exploration of the Milos geothermal reservoir, Greece, *Geothermics*, **18**, 563-577

Papanikolaou, D., Lekkas, E., Syskakis, D. and Adamopoulou, E., 1993. Correlation of Neotectonic structures with the geodynamic activity in Milos during the earthquakes of March 1992, *Bull. Geol. Soc. Greece*. XXVIII/3, 413-428.

Scholz, C.H., 1990, The Mechanics of Earthquakes and Faulting, Cambridge University Press.

Searle, R., 1980. Tectonic pattern of the Azores spreading centre and triple junction, Earth and Planet. Sci. Lett., 51, 415-434.

Teisseyre, R., (Ed), 1995. Theory of earthquake premonitory and fracture processes, Polish Scientific Publishers, 237-245.

Thanasoulas, C. P., 1989. Application of the self potential technique over the Milos geothermal test site, *Geothermics*, **18**, 497-505.

Tzanis, A., 1994. A Magnetotelluric reconnaissance survey of Pico Alto geothermal prospect (Terceira island, The Azores, Portugal), Technical report, Idrogeo S.R.L., Via Mercato Vecchio, 1, 34124 Trieste, Italia.

Tzanis, A., Ziazia, M., Kementzetzidou, D. and Makropoulos, K., 1994. A model of contemporary tectonics in SE Thessaly, Greece, as derived from Magnetotelluric, GDS and Seismotectonic investigations. *Proceedings, XXIV ESC Gen. Assembly*, Athens, Greece, **v1**, 419-431.