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Physics and Chemistry of the Earth 31 (2006) 198–203

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Magnetolelluric data collection and analysis in the SES sensitive site of Ioannina area (Greece)

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Accepted 6 February 2006
Available online 16 May 2006

Abstract

Two independent magnetotelluric sounding (MTS) studies in Ioannina (NW Greece) area have been reported. Their conclusions, however, differ essentially. To proceed in the correct understanding of the geoelectrical structure in that area, additional detailed observations in several sites were made. The analysis of the new data proves that the conclusion of Pham et al. [Pham, V.N., Boyer, D., Le Mouel, J.L., Chouliaras, G., Stavrakakis, G.N., 1999. Electromagnetic signals generated in the solid Earth by digital transmission of radio-waves as a plausible source for some so-called "seismic electric signals". Phys. Earth Planet. Int. 114, 141–163] claiming a globally high resistivity structure in the area does not hold. Moreover the present analysis strengthens the model that the main geoelectrical structure of Ioannina area (being considered along a regional profile of the NE–SW direction) is characterized by a high resistive formation in the upper crust, but inside it a set of narrow conductors (elongated in the NW–SE direction) exists. These conductors provide support for the possibility that seismic electric signals emitted from distances of the order of 100 km can be recorded at the Ioannina SES sensitive site.

Keywords: Magnetotelluric sounding; Principal directions; Conductivity structure; Seismic electric signal

1. Introduction

The study of Ioannina area (Northwestern Greece) has attracted much interest, because several publications of the VAN group reported that it is sensitive to the recording of seismic electric signals (SES). The latter are low frequency ($\leqslant 1$ Hz) signals that have been found in Greece (e.g., Varotsos and Alexopoulos, 1984; Varotsos et al., 1993) and Japan (e.g., Uyeda et al., 2000) to precede earthquakes (EQs) by a lead time ranging from several hours to a few months. It has been suggested (Varotsos and Alexopoulos, 1986; Varotsos et al., 1993) that a measuring site is sensitive to the SES collection, if it is located close to the upper end of a highly conductive channel and the focal area of the impending EQ lies in the vicinity of the lower part of this channel. This model is supported from both numerical simulations (Sarlis et al., 1999) and analytical results (Varotsos et al., 2000). Aiming at clarifying whether this model is applicable to the case of Ioannina SES sensitive station (hereafter IOA; it is located at the site labelled PER in Fig. 1, and shown as dipoles B in the inset), Solid State Physics Institute, Greece (SEPI), proceeded to an investigation of the geoelectrical structure of the area by means of magnetotelluric sounding (MTS) studies (Makris et al., 1997; Eftaxias et al., 2002). These studies revealed a tentative model for the geoelectrical structure of the area (Eftaxias et al., 2002), which lends support to the aforementioned explanation of the SES sensitivity in IOA.

In an independent MTS study by Pham et al. (1999), an opposite conclusion, however, was reached: "our broad

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doi:10.1016/j.pce.2006.02.016

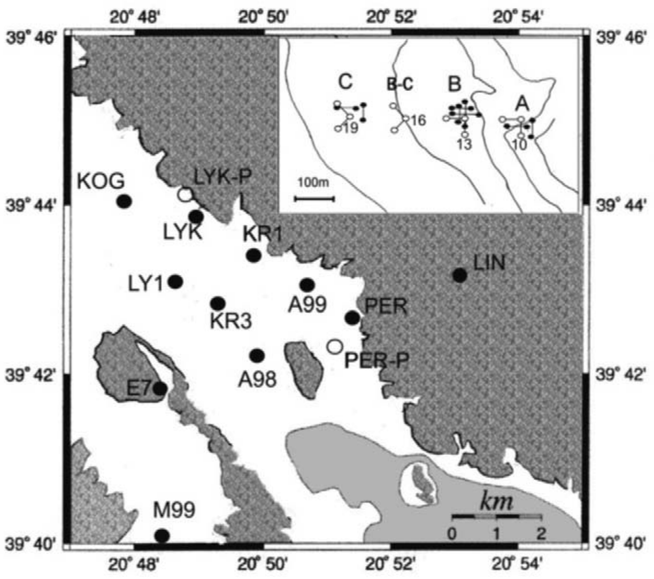

Fig. 1. Location of MTS sites in the Ioannina region on a simplified geological map. White: recent and old alluvium. Shaded: Mesozoic and Palaeogene limestone. Grey: Ioannina lake. (●): MTS observations sites of SEPI. (○): the two sites for which MTS results were presented in Pham et al. (1999). In the upper right inset, a more detailed plan of the short dipoles in and around PER station is given together with four dipoles pairs of our detailed profile, sites 10–21.

band MT sounding results at PER…clearly show that…there is no conductive path in the crust beneath the IOA''. It is the main object of this paper to shed light on this disagreement.

2. MT data of Pham et al. (1999)

Pham et al. (1999) presented MTS curves at two sites: PER-P and LYK-P (Fig. 1). They write (see pp. 159 and 160): ''The signals recorded at the PER station are very noisy…. Nevertheless, selecting the least noisy data, we have been able to derive two MT sounding curves along two principal directions 40–45°N and 130–135°N, using the classical tensorial MT processing''. The same was reported for LYK station. The main feature of the MTS curves presented in Pham et al. (1999) is the absence of strong MT field anisotropy: the curves along the principal directions almost coincide (Fig. 2) for diapason of periods 0.01–200 s. But do these curves really correspond to the principal directions?

It is well known that the MT processing gives the impedance tensor and hence the MT sounding curves only along the measurement lines directions. In order to obtain MT curves along the principal directions, a special analysis of the impedance tensor (consisting of 4 complex numbers) should be done. Although it is commonly accepted to indicate the method of the tensor analysis used (e.g., Swift's rotation (Swift, 1967), eigenstate analysis of Eggers (1982), Mohr circle analysis or others), Pham et al. (1999) do not mention such a method. Thus, their statement that they ''have been able to derive two MT sounding curves along the two principal directions'' is not appropriately documented. It seems that what they actually derived are two (only amplitude) MT curves along a priori selected measurement lines, as will be further supported below by the analysis of extensive MT data.

The polarization diagrams of the electric field for the PER-P station have been presented by Pham et al. (1999) for several periods, two of which are presented in Fig. 3. For the longest periods 20–50 s, a linear polarization (although not very strong) can be clearly seen in the direction approximately 55° from the N. A rough estimation of the ratio of the principal impedances yields a number between 3 and 5, which corresponds to a difference more than one order of magnitude in the apparent resistivity. Thus, the polarization diagrams presented by Pham et al. (1999) contradict their aforementioned claim that their MTS curves (Fig. 2, left) have been constructed along the two principal directions.

3. MT data of SEPI

Our observations (Makris et al., 1997; Eftaxias et al., 2002) have been made at 42 sites around IOA area by the

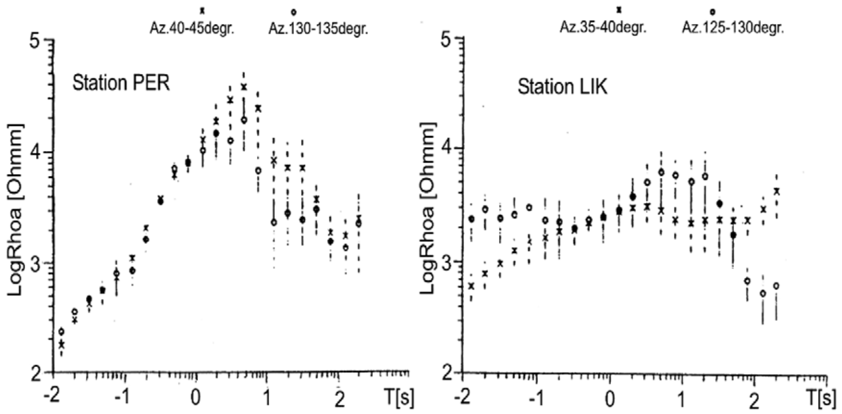

Fig. 2. MTS curves which according to Pham et al. (1999) correspond to the two principal directions at PER-P and LYK-P stations. Full and dashed vertical bars represent the standard deviation for these two directions.

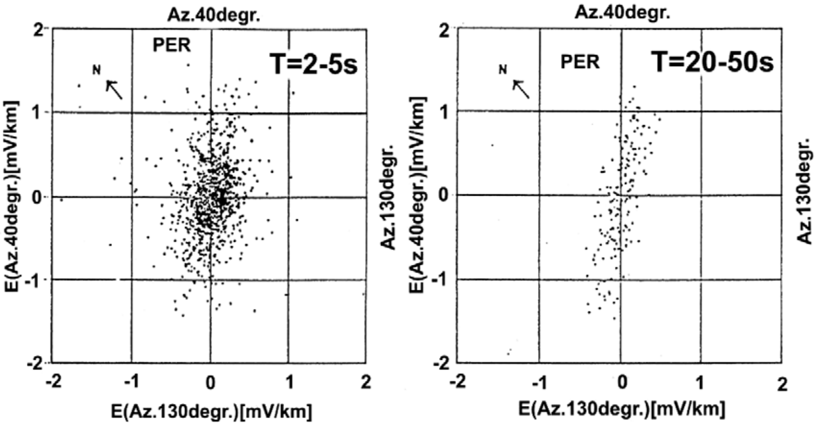

Fig. 3. Polarization diagrams of the electric field at the station PER-P for two period intervals (Pham et al., 1999).

EMI MT-1 system using remote reference technique. Bahr's (Bahr, 1988) and eigenstate Egger's analyses (Eggers, 1982) have been applied by Makris et al. (1997) to the four sites A, B, C and B–C of PER station (Fig. 1, inset). Swift rotation (Swift, 1967), Groom–Bailey and Mohr circles analyses have been applied to the data of 42 MTS sites (Balasis et al., 2002; Eftaxias et al., 2002). Different methods yield stable parameters of the regional MT structure (for long periods 50–1000 s): regional strike of maximal impedance is 50 ± 5°, of minimal 140 ± 5° from N clockwise with a stable ratio of the maximal apparent resistivity to the minimal one as high as 2–4 orders of magnitude. In Fig. 4 we present the MTS curves along the principal directions for the 11 sites located around of (and close to) the observation sites of Pham et al. (1999) (see Fig. 1). At the shortest periods (0.01–0.05 s), the amplitude curves for different directions almost coincide. At longer periods the curves along the principal directions (determined by Swift rotation in every site) strongly diverge in a way *similar* for all sites, which manifests the regional nature of the divergence. The minimal curves (referred as E-polarization) turn out to be more sensitive to local conductors. Being in different positions in respect to these conductors, different sites have no identical minimal curves; they can be subdivided into two groups, as shown by the broken lines in the right part of Fig. 4.

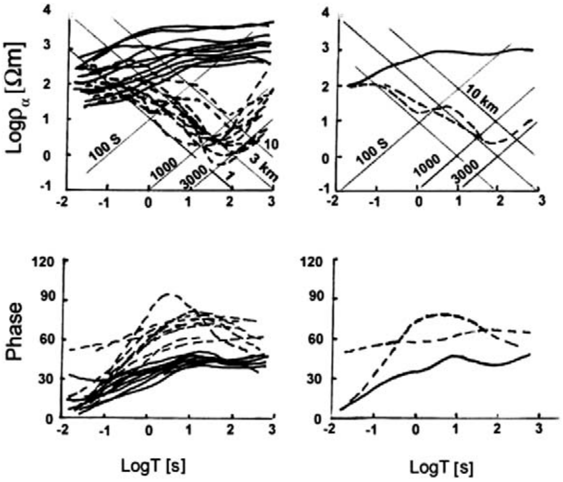

Fig. 4. Left: maximal (solid lines) and minimal (dashed lines) MTS curves of SEPI at 11 sites of Ioannina region (Fig. 1, full circles). The azimuth of maximum curve measured from N clockwise varies from 40° to 77° (on the average 60°). Right: the mean curves of those depicted in the left panel; the minimal curves are subdivided into two groups. The so called "h" and "S" lines are also drawn.

Synchronous polarisation diagrams of the magnetic and electric fields have been also presented by Uyeshima et al. (1998), for the area B of PER station (Fig. 1, inset). Their electric field diagrams exhibit strong linear polarization for the MT as well as for the lightning signals. Analogous diagrams for the nearby sites A, B and C (see Fig. 1, inset) have been published by Makris et al. (1997) for the period's interval 10–500 s. Very strong linear polarization of the electric field was observed in all three sites A, B and C, but the azimuth of the polarization varies: i.e., 87° in A, 58° in B and 82° in C. Such a variability of principal directions at sites separated by few hundreds meters can be solely explained by local inhomogeneities which impose additional (to regional strike) rotation.

4. Detailed profile of SEPI close to Ioannina station

In order to study further the local peculiarities of the MT field and the related geoelectrical structure in the area of PER station, SEPI also made a detailed continuous MT survey along a 600 m profile between the areas A and C (twelve measuring sites marked by the numbers 10–21). In the first 6 sites (numbers 10–15), the measurements were made in the directions NS and EW. In the sites numbered 16–21 (which, compared to the first six ones, are closer to the measuring site PER-P) the electric dipoles (50 m long) and the magnetic sensors had been rotated at 45° and hence had almost the same orientation with the measuring dipoles of Pham et al. (1999). Measuring the MT field preferably at the night time and applying remote reference

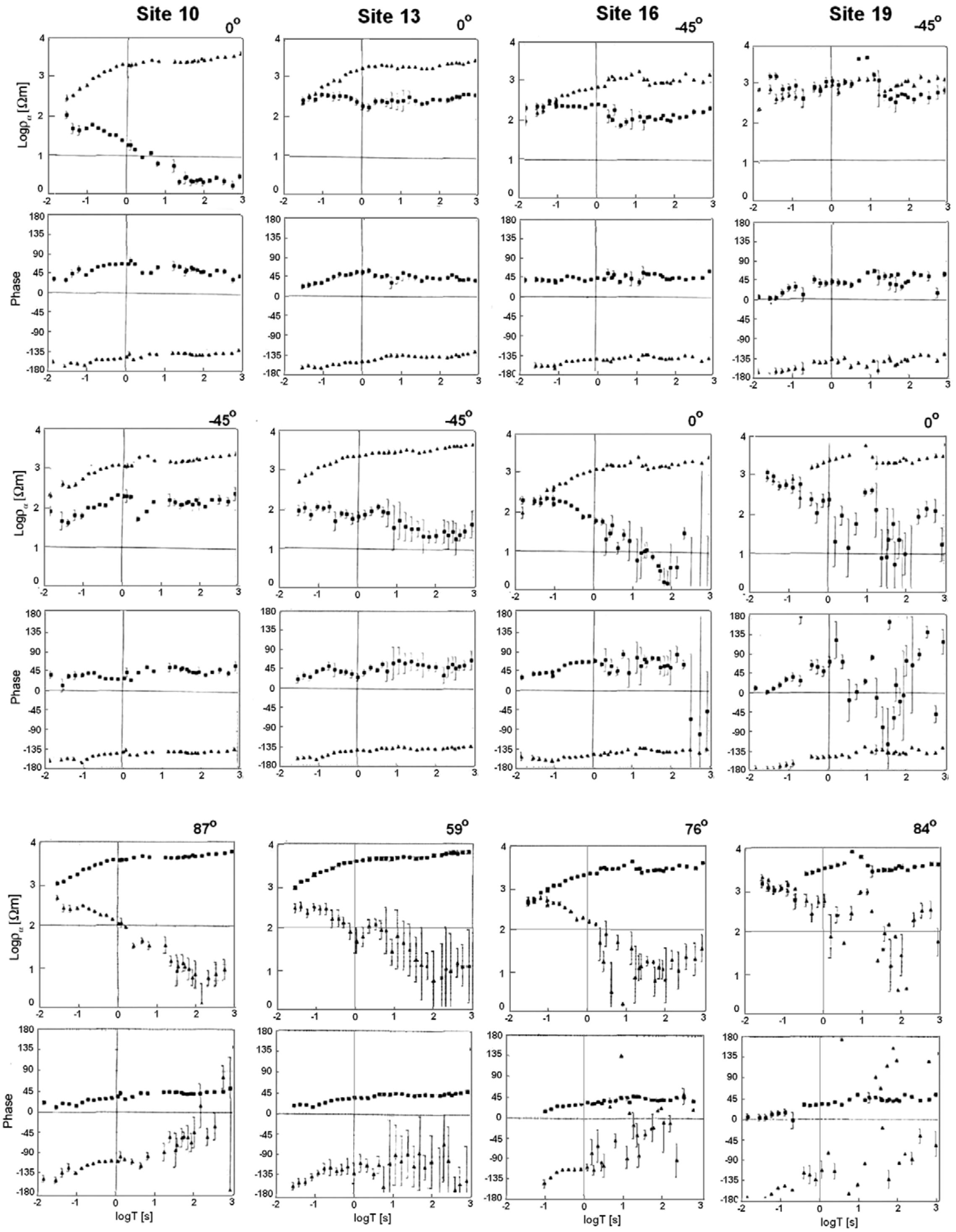

Fig. 5. Examples of MTS curves at four sites of the short profile in PER-station. Three panels are presented. The upper panel shows the observed curves, i.e., along the measurement directions. (The first and the second line correspond to the apparent resistivity ρ_{xy}, ρ_{yx} and the phases φ_{xy}, φ_{yx}, respectively.) The azimuth of one of the measuring dipoles is marked on the upper right of each graph. The middle panel presents the MTS curves rotated by 45° in respect to the original ones given in the upper channel (cf. the third and the fourth line correspond to ρ and φ, respectively.) The lower panel depicts the MTS curves rotated to the maximal/minimal apparent resistivity at long periods 100–1000 s. In the upper right of every graph, the azimuth of the maximal curve measured from N clockwise is given. The vertical bars represent the statistical error of the results; note the small error in the observed curves and the large error in the minimal curves after rotation. (Phase of *yx* is presented with the shift of 180° to give the space for great scatter of the results after rotation.) Squares or *xy* component, triangles – for *yx* one.

technique for processing, satisfactory results along the measurement directions were obtained (upper panel in Fig. 5): error 5–10% for the apparent resistivity and a few degrees for the impedance phase. The variation of the MTS curves along the profile is rather smooth, which confirms the reliability of data. In Fig. 5 (in order not to overload it) we present only 4 MTS out of 12. In the middle panel of this figure, we present the results when the axes have been rotated by 45° from the measurement directions. Thus, one can see MTS curves: (i) along NS- and EW-direction in the upper panel for the sites 10 and 13 and in the middle panel for the sites 16 and 19 and (ii) along NE–SW and SE–NW directions in the middle panel for the sites 10 and 13 and in the upper panel for the sites 16 and 19. Finally, in the lower panel of Fig. 5, we present the MTS curves rotated to maximal divergence at the long periods 100–1000 s. These can be considered as the MTS curves along the two principal directions. Their inspection shows that at long periods, all apparent resistivity curves diverge up to 3–4 orders of magnitude (while the curves of Pham et al., 1999 at nearby site PER-P do not show such a feature). The same behaviour is inherent for *all* 12 MTS curves of our short profile, as well as for the 11 MTS presented in Fig. 4 and the additional 40 MTS curves in Ioannina area, described in Eftaxias et al. (2002). Could the MTS curves behaviour at the sites PER-P and LYK-P (see Figs. 1 and 2) studied by Pham et al. (1999) be essentially different? Of course, they could not, because the divergence of MTS curves at the long periods is a regional effect imposed to all MTS in the area. Thus, we conclude that the MTS curves presented in Pham et al. (1999) cannot be the "curves along the two principal directions", as they claim. We also note that Pham et al. (1999) did not present phase curves (probably due to the large errors), although it is well known that for the impedance tensor analysis (including the determination of the principal directions) all tensor components (modulus and phases both off-diagonal and diagonal terms – 8 numbers altogether) are needed.

5. Discussion

A possible explanation for the behaviour of MTS curves presented by Pham et al. (1999) becomes clear from a further inspection of Fig. 5. The apparent resistivity curves measured at the site 19 along the azimuth −45° (and at the site 10 rotated to the azimuth −45°) do not diverge, because this azimuth turns out to be approximately in the middle between the true principal directions. In this case, having strong MT anisotropy, the two curves presented in each site are essentially the projections of the same maximal curve, because the contribution of the minimal curve is negligible. This also explains the large error in the determination of the minimal curve as follows: let us see Fig. 5 again. All MTS curves constructed along the measurement directions (upper panel) are characterized by small errors. After rotation, the maximal apparent resistivity (and corresponding phase) retains small error, but the minimal one exhibits very large error, which can make MTS curves construction not reliable. For the site 10 we have a favourable exception. The measurement directions turn out to deviate only by 3° from the principal directions. After rotating to this direction (at 3°), the errors became several times larger, but nevertheless they are sufficiently small for a reliable drawing of the minimal curves and the consequent interpretation in terms of narrow 3D conductors elongated in the NW–SE direction (see Eftaxias et al., 2002). The main points of the latter interpretation as well as the main characteristics of the geoelectrical structure of Ioannina area (i.e., a high resistive formation in the upper crust and, inside it, a set of narrow conductors elongated in the NW–SE direction) can be found in the recent review by Varotsos (2005).

We finally shortly comment on the claim of Pham et al. (1999) that "digital transmitters" of radio waves may be a plausible source for some SESs. The following point alone (Sarlis et al., 1999) invalidates this Pham et al.'s claim. During the period of Pham et al.'s data collection. i.e., June 1997, both they and we recorded a number of electrical disturbances. However, they were all recognized by our group (through the four criteria published by Varotsos and Lazaridou (1991)) as "artificial noise" and hence no earthquake prediction was issued. Additional reasons that invalidate Pham et al.'s claims have been summarized in Varotsos (2005) (see p. 174 and references therein). Among others, we report here that when employing the natural time domain analysis suggested by Varotsos et al. (2002) one can immediately distinguish (Varotsos et al., 2003a,b) true SESs from signals emitted from artificial sources.

6. Conclusion

The claim of Pham et al. (1999) that their "broad band MT sounding results at PER . . . clearly show that . . . there is no conductive path in the crust beneath the IOA" is not supported neither from their own data (if properly analysed) nor from an appreciably more extensive data set and detailed analysis of our group. The analysis shows that the main geoelectrical structure of Ioannina area (being considered along a regional profile of the NE–SW direction) is characterised by a high resistive formation in the upper crust with a set of narrow conductors elongated in NW–SE direction inserted in it. These conductors provide support for the model stating that seismic electric signals coming from epicentral distances of around 100–200 km can give detectable electric field values (i.e., a few mV/km) – mainly due to edge effects (Varotsos, 2005) at IOA sensitive site.

Acknowledgement

We thank Drs. J. Makris and N. Bogris who participated in field works and data processing.

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