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A magnetotelluric study in the Campidano Graben of Sardinia

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Abstract. The Campidano Graben is certainly one of the most striking geological features of Sardinia. Up till now there has been no general agreement as to the origin of the graben. As the adjacent andesitic rock formations and old extinct volcanoes suggest, volcanism has certainly played a role in the geological history of the graben. This is confirmed by data from a borehole which has been drilled in the search for oil in the southern part of the Campidano Graben. It has revealed an insulating layer of andesitic tuffs sandwiched between two sedimentary layers. The lower sediments are Eocene sandstones and clays from the nearby Cixerri valley, while the upper ones comprise formations of the Pliocene to the Upper Oligocene. All this rests on an old and resistive Paleozoic basement. Our soundings have indeed confirmed this alternance of resistive and conductive layers at depths in the range 0–10 km and also indicate the presence of a very good conductor at depths of 10–40 km or more. They have made it possible to propose a two-dimensional conductivity structure for the Campidano Graben.

Key words: Magnetotellurics in the Campidano Graben and Cixerri valley of Sardinia – Two-dimensional magnetotelluric modelling

Introduction

In Sardinia the Campidano Graben is, without question, one of the outstanding geological features of the island. So far, however, there is no consensus as to its origin. For some it is the result of middle Pliocene to Quaternary rifting (e.g., cf., Cherchi and Montadert, 1985), others see it as the remains of a subduction trench where the NE block plunged under the SW part. This suggestion stems from the geochemical character of the volcanism observed, composed of andesitic tuffs and pyroclastic lavas interspersed with ignimbrites (Cocozza and Jacobacci, 1975). But paleomagnetic data from the present to the Eocene indicate a counterclockwise rotation of Sardinia and Corsica (e.g., cf., Illies, 1975; Horner and Lowrie, 1981; Burrus, 1984). When Sardinia is rotated back to its Eocene position of 40–50 my ago, the Campidano Graben appears as a continuation of the Rhone Valley, which has been found to constitute a deep trench extending far below the present-day sea level (Hsü, 1983). However, some problems of chronology must be sorted out before this last suggestion can be accepted. As Burrus (1984) showed, the recent rotational phase of Sardinia occurred between 19 and 21 my ago, whereas some ot the sediments found in the Rhone gorge near Valence are as young as the Pliocene age (Hsü, 1983). More favourable to our hypothesis are the well-known and striking similarities of the Sardinian and Languedoc geological landscapes (e.g., cf., Gèze, 1957) and the often-observed NS orientation of all major adjacent geological lineations (e.g., cf., Knetsch, 1964) like the Rhine Graben, the Rhone Graben, and the Algerian and Libyan structures.

Our study of the Campidano Graben does not purport to settle the question of its geological origin. Our aim is to investigate the sediments and, possibly, other fill of the graben and to compare our MT and AMT data with the results obtained in the same area with other sounding methods. Our range of periods extends from 1 ms to 30 s and provides an ideal coverage of the graben structure from about 10 m to 20 km. Pedersen and Svennekjaer (1984, cf. also Finzi-Contini, 1982) have carried out an MT sounding along the axis of the Campidano Graben. Their period range stretches from around 0.1 s to around 10^3–10^4 s and is therefore in part complementary to ours. These longer periods are adequate to study the basement and upper mantle, but they are not suitable for revealing the sedimentary graben structure in detail. In the period range from 0.1 s to 10 s the data of Pedersen and Svennekjaer agree fairly well with ours, but at longer periods their apparent resistivity remains at rather unrealistically high values, implying resistivities of the order of 10^2–2×10^3 Ωm at depths of 100–500 km.

Experimental method

Our AMT sounding method has been described elsewhere (Fischer, 1982; Schnegg et al., 1983). We shall therefore limit our present description to a few additional details. The soundings were performed in two stages. First we collected about 60 samples with our AMT coils (ECA-CM 16, cf. Andrieux et al., 1974) to cover the periods from 1 ms to 0.3 s. Then 48 samples were taken with ECA-CM 11 E coils to cover the range from 0.1 s to 30 s. This insured a good overlap between the two ranges. Data collection, as well as deployment and recovery of the equipment, took about one and a half to two hours. In general, four soundings were performed each day.

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Table 1. Geographical situation of the MT sounding sites (longitude of Rome: 12° 27.14 E of Greenwich)

MT Station no.	Longitude W Rome	Latitude	Altitude (m)	Profile
1	3° 38.64	39° 22.15	73	PECA
2	3° 36.32	39° 22.89	45	PECA
3	3° 33.94	39° 23.22	32	PECA
4	3° 30.09	39° 21.80	24	PECA/PACA
5	3° 29.05	39° 22.89	41	PECA/PACA
6	3° 27.67	39° 23.09	51	PECA/PACA
7	3° 25.82	39° 23.31	63	PECA/PACA
8	3° 23.67	39° 24.95	93	PECA/PACA
9	3° 41.31	39° 21.55	160	PECA/PACA
10	3° 40.18	39° 21.46	84	PECA/PACA
11	3° 26.85	39° 20.12	30	PACA/PACI
12	3° 35.57	39° 26.79	40	PACA/PACI
13	3° 38.42	39° 22.80	84	PECA
14	3° 44.47	39° 16.65	80	PECI
15	3° 44.35	39° 16.05	89	PECI
16	3° 44.26	39° 15.78	98	PECI
17	3° 44.50	39° 17.97	106	PECI
18	3° 44.33	39° 17.36	84	PECI/PACI
19	3° 44.86	39° 19.55	154	PECI/PACI
20	3° 32.30	39° 18.70	13	PACI
21	3° 38.90	39° 19.08	76	PACI
22	3° 41.35	39° 31.66	64	PACA
23	3° 45.64	39° 35.72	50	PACA

PE = Perpendicular PA = Parallel CA = Campidano CI = Cixerri

The location of the sounding profiles is given in Table 1 and shown in Fig. 1, while Fig. 2 helps to situate these profiles with respect to the geological setting. Profiles 1 and 2 are across the Campidano Graben and across the Cixerri valley, respectively, whereas profiles 3 and 4 are along the strike directions of these two features. At the location of our profiles, the geological strikes are approximately N 45° W for the Campidano and N 90° E for the Cixerri. These two directions were therefore chosen from the start as principal directions, respectively for profiles 1 and 3 and profiles 2 and 4. It was thus not necessary to rotate the data mathematically afterwards. When the phases of the data are not too reliable, avoiding the mathematical rotation may be preferable (Schnegg et al., 1986). Note that the stations along profile 1 are not set exactly across the graben, but the measurement axes were nevertheless laid out according to the strike, i.e. x-axis along N 45° W and y-axis along N 45° E. The average strike direction of the Campidano is closer to N 35° W, but in the measurement area the choice of N 45° W is more appropriate.

Interpretation of the data from profiles 1 and 3

Our MT soundings over the central section of profile 1 consistently suggest a succession of five layers of alternatively high and low conductivity. Examples are given in Figs. 3 and 8. At periods below 0.1 s the data are isotropic, indicating that to depths and lateral distances of the order of 0.5 km the structure can be treated as one dimensional (1 D). With periods longer than 0.1 s, the 2D character of

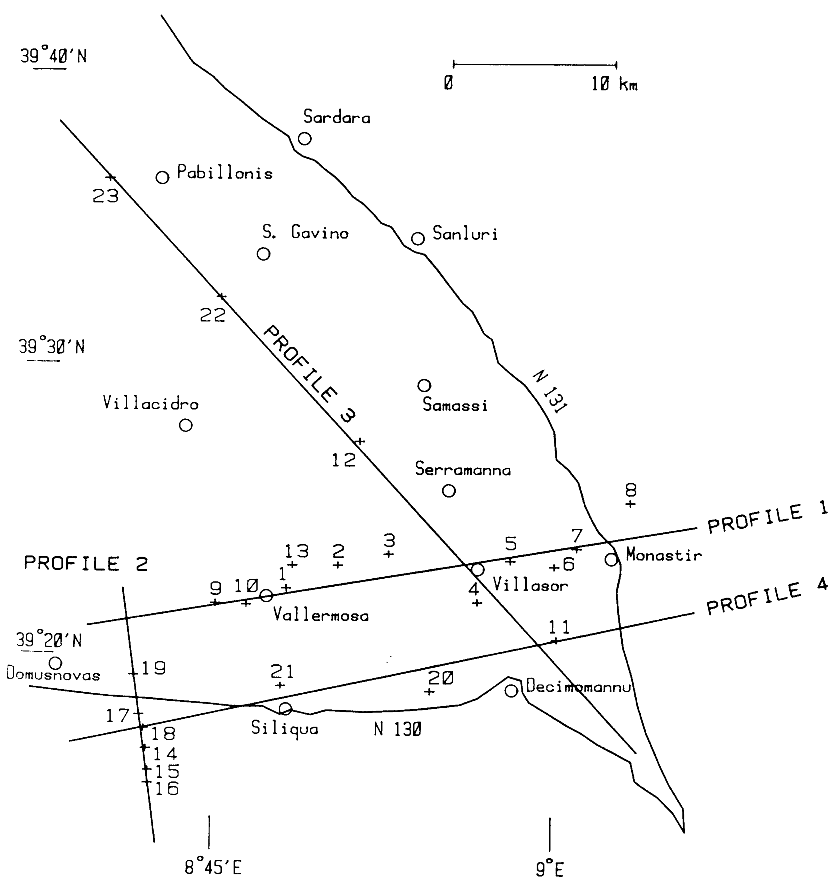

Fig. 1. Geographical situation of the 23 sounding sites and the 4 profiles. Station 4 is also the location of the Campidano 1 borehole, the lithology of which is given by Pala et al. (1982)

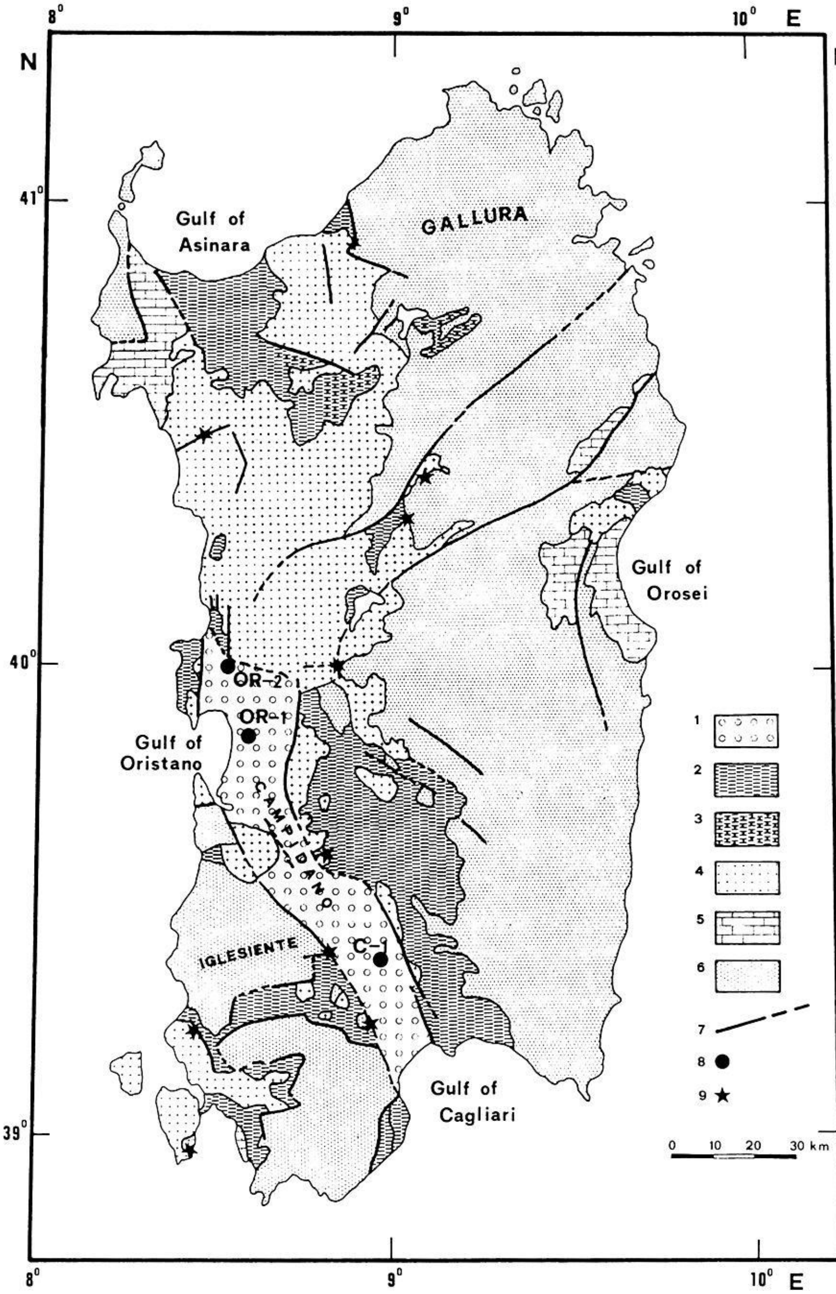

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Fig. 2. Geological sketch map of Sardinia. (1) Quaternary sediments, (2) Miocene deposits, (3) Miocene delta sand, (4) Tertiary basalt, andesite, rhyodacite, ignimbrite and tuff, (5) Mesozoic limestone and dolomite, (6) Paleozoic granitic-schistose basement, (7) fault, (8) borehole, (9) thermal spring (redrawn after Pala et al., 1977)

the graben structure is increasingly evident. For stations on the flanks or shoulders of the graben, Fig. 4 shows that anisotropy already begins at 10 ms; this means that the 2D character has become dominant. Furthermore, it is obvious that the resistivities over the graben shoulders are much higher than over its central part. Clearly the data over this profile must be interpreted in terms of a 2D structural model.

Schnegg et al. (1986) have recently shown that, for 2D structures which do not comprise highly insulating layers, the H-POL adjustment length can sometimes be very short. With this in mind an initial 2D model was constructed by smoothing the structure obtained through the juxtaposition of 1D/H-POL interpretations according to the modelling routine of Fischer and Le Quang (1981). The apparent resistivities alone were considered because our phase data in general seem somewhat less reliable. The response of this initial 2D model was computed with the finite-difference program of Brewitt-Taylor and Weaver (1976), including some recent improvements by Weaver et al. (1985). The 2D model was then gradually modified with a view to improving the fit of its H-POL response with the H-POL field data. Once satisfactory accord was achieved for H-POL we found that the E-POL response of the model already fitted the E-POL field data reasonably well. Only small modifications of the model were then required to achieve the same degree of concordance between model responses and field data for both E and H polarizations. The final model is shown in Fig. 5 and its responses at various periods are compared in Fig. 6 with the original field data. The agreement can be termed very good, as model and field values of apparent resistivity generally remain within a factor of two of each other.

Figure 7 is a smoothed version of Fig. 5, adapted to

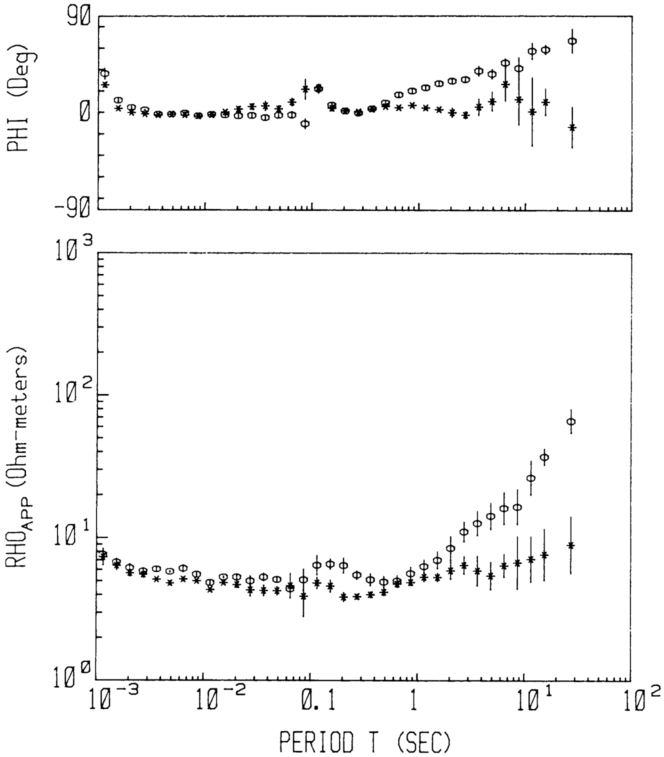


Fig. 3. Magnetotelluric sounding data obtained at station 6, inside the Campidano Graben. The *stars* refer to the H-POL geometry and the *circles* to E-POL. These data indicate a structure with at least four layers with, beginning at the top, alternately low-high-low-high resistivities. Here the graben sediments are highly conducting and only the H-POL phase gives some indication of the presence of a deep conductor. The *vertical bars* give a measure of the statistical uncertainty of each data point. The phase T is given as deviation from the 45° uniform half-space limit, i.e. PHI = 45° − ψ

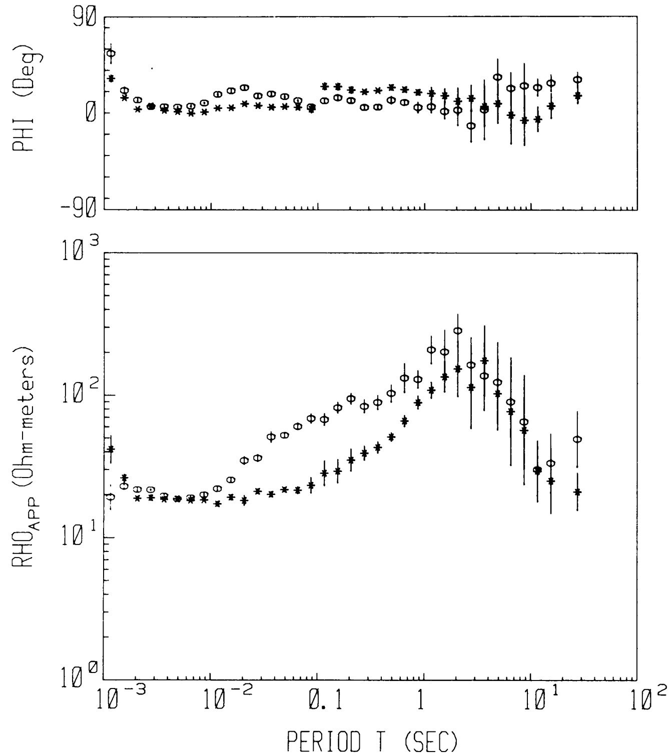


Fig. 4. Magnetotelluric data obtained at station 10, on the western shoulder of the Campidano Graben. The *stars* refer to the H-POL configuration, the *circles* to E-POL. The E-POL data clearly suggest five layers of alternatively low and high resistivities. The *vertical bars* are a measure of the statistical uncertainty of each data point. The phase T is given as deviation from the 45° uniform half-space limit, i.e. PHI = 45° − ψ

the geological setting of the Campidano Graben. The lithological interpretation is in perfect accord with the data obtained at the Campidano 1 drill hole (Pala et al., 1982), located almost exactly at our site 4, as well as with the resistivities derived by Marchisio and Ranieri (1982) from Schlumberger and dipole-dipole resistivity soundings [also see Marchisio et al. (1982)]. The 15- and 4-Ωm material corresponds to the four sedimentary formations of various alluvial deposits, silts and clays, down to 1,162 m, followed by about 400 m of vulcanitic andesites, ignimbrites and pyroclastic lavas (our 400-Ωm formation), underlain first by 120 m of Eocene sediments of the Cixerri formation (10Ωm) and followed by the resistive 400Ωm of the Paleozoic basement.

The transition to a good deep conductor at lower crust or mantle depths is confirmed by all our data, but the exact form of the transition to the mantle cannot be considered as resolved by the present measurements. For the moment the two conductive horsts rising to within about 10 km of the surface must be looked upon as conjectural. Good data to periods longer than 30 s will be required to confirm their existence. If they do exist, these two horsts, placed symmetrically with respect to the graben axis, could perhaps provide the basis for an explanation of the origin of the Campidano. All we can say with certainty, so far, is that our data suggest a good conductor at depths in the range 10–40 km. As we said in the Introduction, there is no indication of its presence in the data of Pedersen and Svennekjaer (1984), but their high apparent resistivities of 10^2–2×10^3 Ωm at periods of 10^3 s must be considered as highly doubtful. Also see the doctoral thesis by Svennekjaer (1982).

A few other features of our model are worth mentioning. The eastern part of the graben is apparently more conducting than its western side and the graben wall seems to dip much more abruptly on the east than on the west. On the western shoulder the metamorphic rocks crop to the surface. Indeed, at site 9 it was difficult to bury the electrodes or introduce the coil spikes into the rocky ground. On the eastern shoulder, on the contrary, there is a sedimentary cover a few metres thick. Our site 8 was in the middle of a vineyard. Our model indeed comprises a top layer 7 m thick of 3-Ωm material over the 400-Ωm basement rocks, but this cannot be shown with the range of our logarithmic scale.

For the stations along profile 3, i.e. along the axis of the Campidano Graben, we only made a 1 D interpretation of the H-POL data. This confirmed the gravimetric evidence (Balia et al., 1984) that the graben floor is undulating and at Villasor it is dipping toward the NW. We find the basement at a depth of about 1,700 m at station 4. At station 12 we are unable to see any increase in resistivity down to

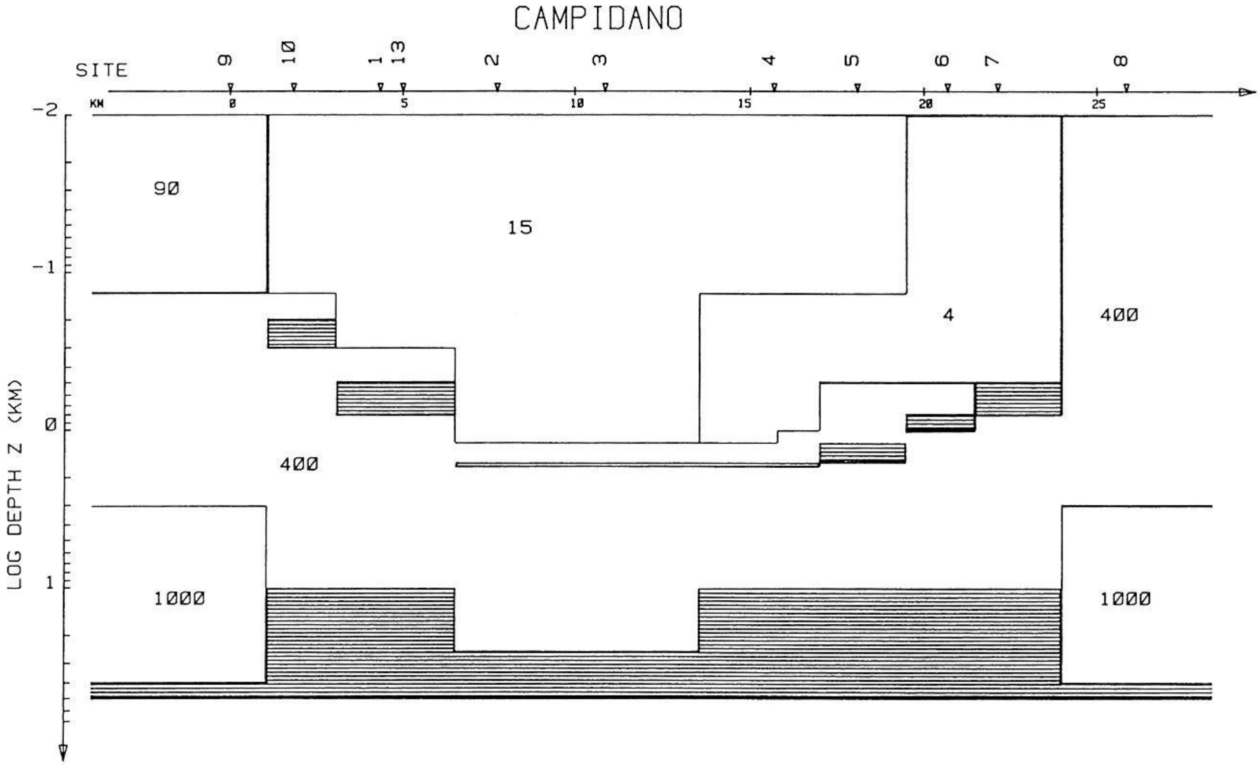


Fig. 5. Two-dimensional model proposed for the Campidano Graben structure along profile 1 (cf. Fig. 1). The model responses of apparent resistivity are given in Fig. 6, together with the observed values at the periods of 10 and 100 ms, and 1 and 10 s. Note that the vertical depth scale is logarithmic. The horizontally striped areas of the Cixerri formation have a resistivity of 10 Ωm; on the right-hand side of this model they seem contiguous with the upper sediments. The lowermost conductor has also been given a resistivity of 10 Ωm. The model is cut off at a depth of 50 km with a perfect conductor, to reduce computer time

about 2,800 m, whereas at stations 22 and 23 our data place the basement level at a depth of around 2,400 m.

Station 11 does not seem to fit into this pattern. We believe that this station is over an extinct but buried volcano. The data are very isotropic and suggest a transition to a 500-Ωm resistor at a depth of only 275 m. As we shall see, stations 20 and 21, which are on the same profile 4 as station 11, are also odd, probably for the same reasons.

On the uniqueness of our graben model

As is well known, the inverse geophysical problem is generally non-unique. Obviously, this also applies to the 2D model of Fig. 5. A fit as good – or probably even better, since our model is the result of a few trials only and is therefore in no way optimal – as the one shown in Fig. 6 could have been achieved by an infinite variety of other models. Indeed, we were able to obtain an excellent agreement with a much simpler model comprising, in broad terms, only three formations (Fischer et al., 1986). However, the Campidano geology is quite well known already and, as has been shown for example by Fischer and Le Quang (1982), any prior geological knowledge must be taken into consideration to restrict the family of possible models. At the same time it is imperative to look for models with as few parameters as are compatible with the prior knowledge and with the data. In 1D interpretations, for example, Fischer and Le Quang (1982) have argued that this means working with as few layers as possible.

In the southern part of the Campidano Graben, a structure comprising five layers of alternatingly high and low conductivity is required by the known lithology revealed through the Campidano 1 borehole. As Figs. 3 and 8 demonstrate, our data systematically suggest these five alternating formations, but the second resistive layer is rather thin and sandwiched between two good conductors. It is thus not surprising if this layer does not appear prominently in the field data of Fig. 3. Station 13, which will be used as base station in a telluric survey of the same profile, provides a similar example. It is clear that the H-POL data of Fig. 8 could have been interpreted almost equally well with only three layers rather than with five. Since all our soundings on profile 1 suggest five layers and since this agrees with the known lithology from the Campidano 1 borehole at our site 4, the family of permitted models is strongly reduced. While an unlimited number of small variations of the Fig. 5 model are certainly possible, the broad outlines of this model can, however, be considered as unique.

Interpretation of the data from profiles 2 and 4

The data from stations 14–19 on profile 2 across the Cixerri valley were interpreted in a manner similar to those of profile 1, except that here it was usually sufficient to postulate three layers only. This is also in accord with the known geology (Pala et al., 1977). Station 9 from the first profile was projected onto profile 2 to provide one site on the northern shoulder of the valley.

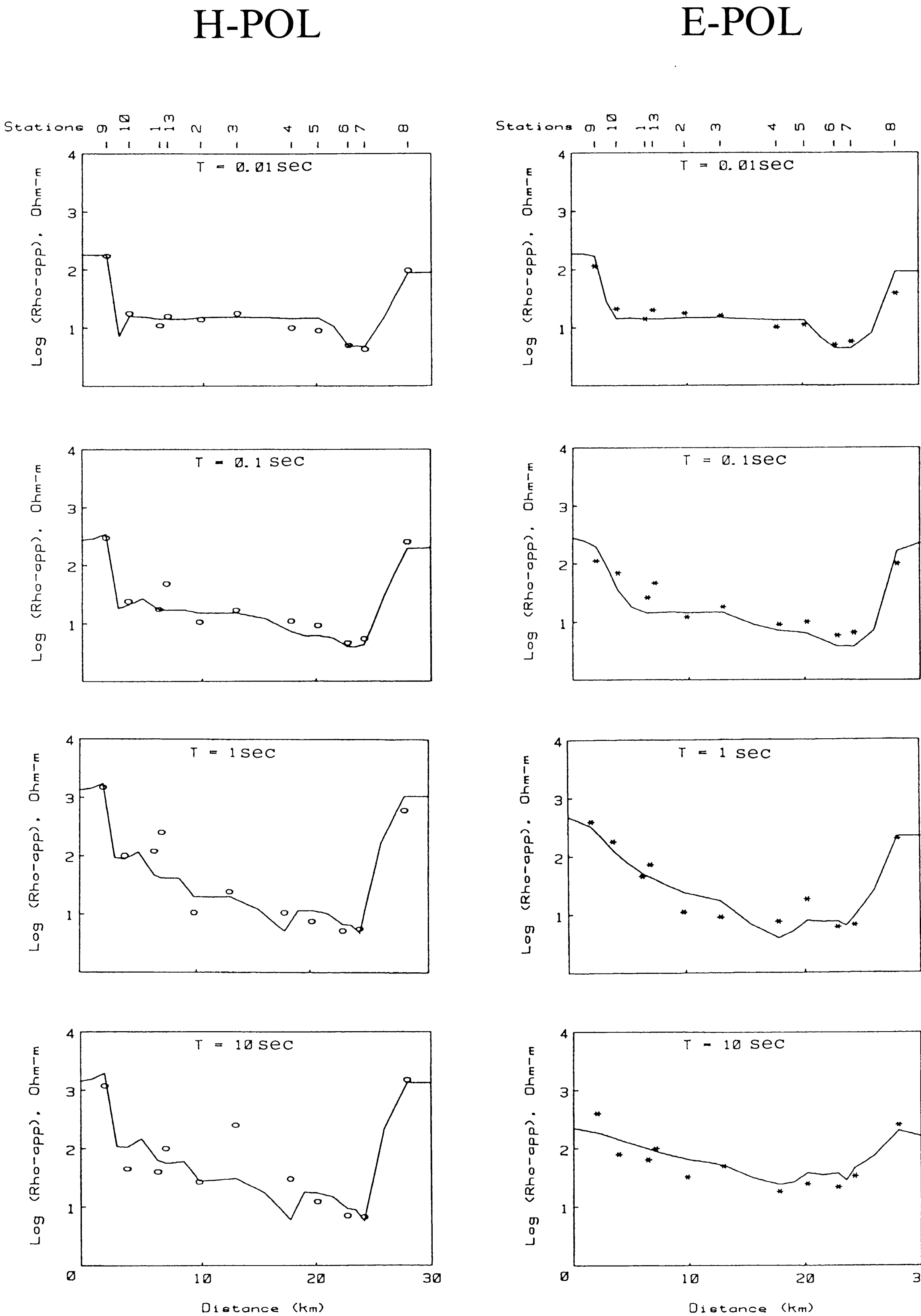


Fig. 6. Comparison of measured apparent resistivities ρ_a (*dots*) with the computed response from the Fig. 5 model (*curve*) at periods of 10 and 100 ms, and 1 and 10 s. The agreement is remarkably good. The standard deviation for log ρ_a is 0.276, corresponding to an average resistivity ratio of only 1.89. This ratio in fact rarely exceeds the value of 3

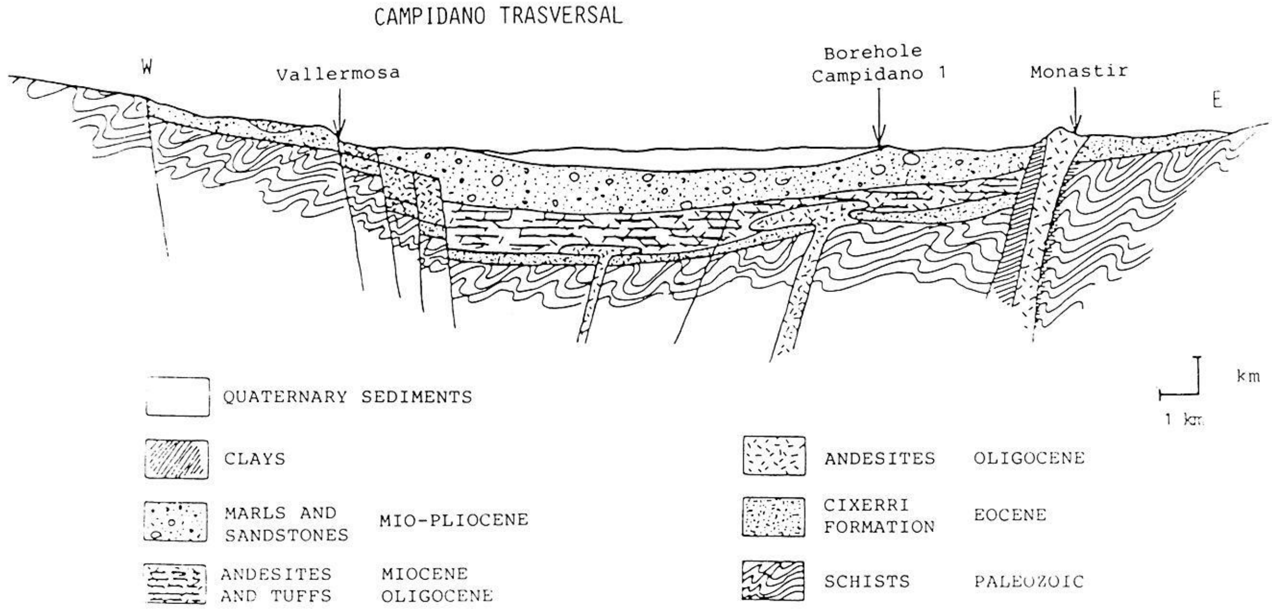
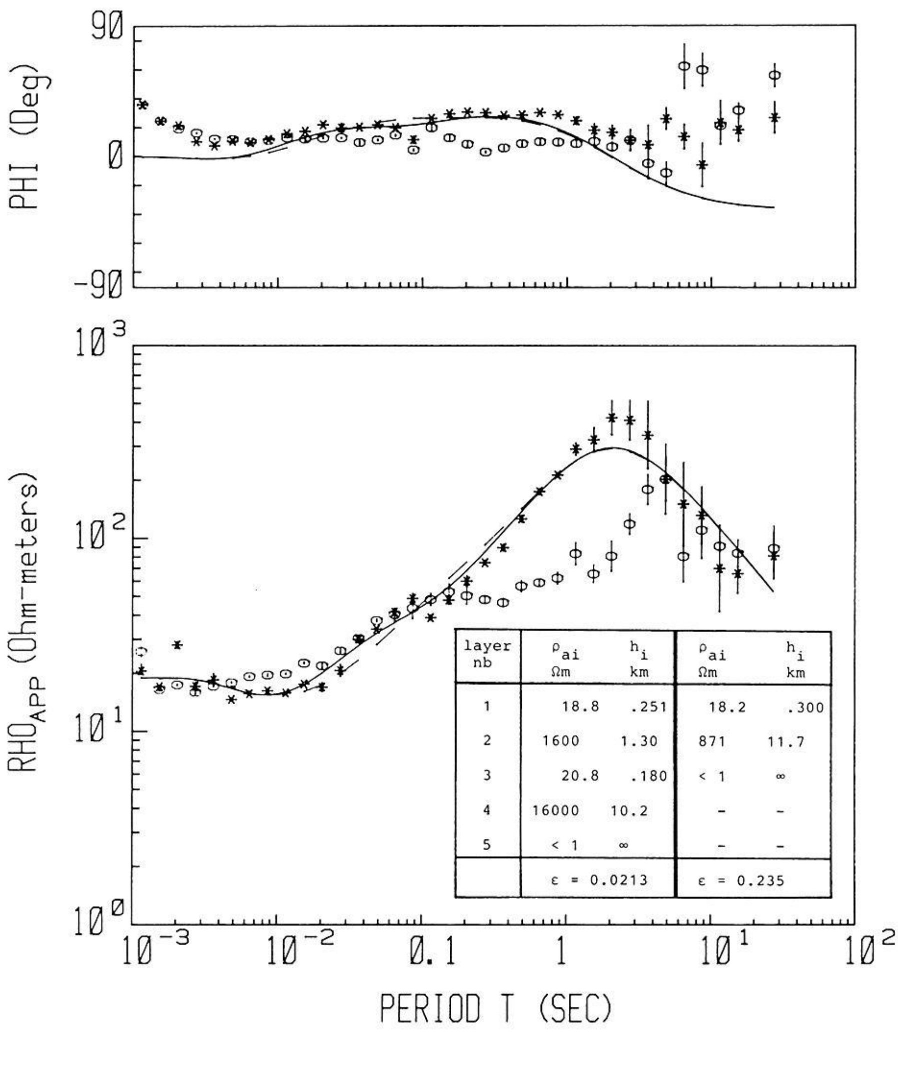


Fig. 7. Geological structure of the Campidano Graben as inferred from our Fig. 5 model, together with the lithological information from the Campidano 1 borehole at the site of our station 4 (cf. Pala et al., 1982). Here the depth scale is linear



layer nb	ρ_{ai} Ωm	h_i km	ρ_{ai} Ωm	h_i km
1	18.8	.251	18.2	.300
2	1600	1.30	871	11.7
3	20.8	.180	< 1	∞
4	16000	10.2	-	-
5	< 1	∞	-	-
	ε = 0.0213		ε = 0.235	

Fig. 8. MT data at station 13 which will be used as base station for a telluric survey of the same profile 1. The *full curve* corresponds to a 1D/H-POL model with five layers (standard deviation for log ρ_a of $\varepsilon_\rho = 0.0213$); the *dashed curve* refers to a 3-layer model ($\varepsilon_\rho = 0.0235$). Only the apparent resistivity was modelled. Around 10^{-3} s and in the range 1–10 s the natural signals are weak and the phase data become unreliable. But this station is close to the graben border and is thus more anisotropic than station 6 (cf. Fig. 3)

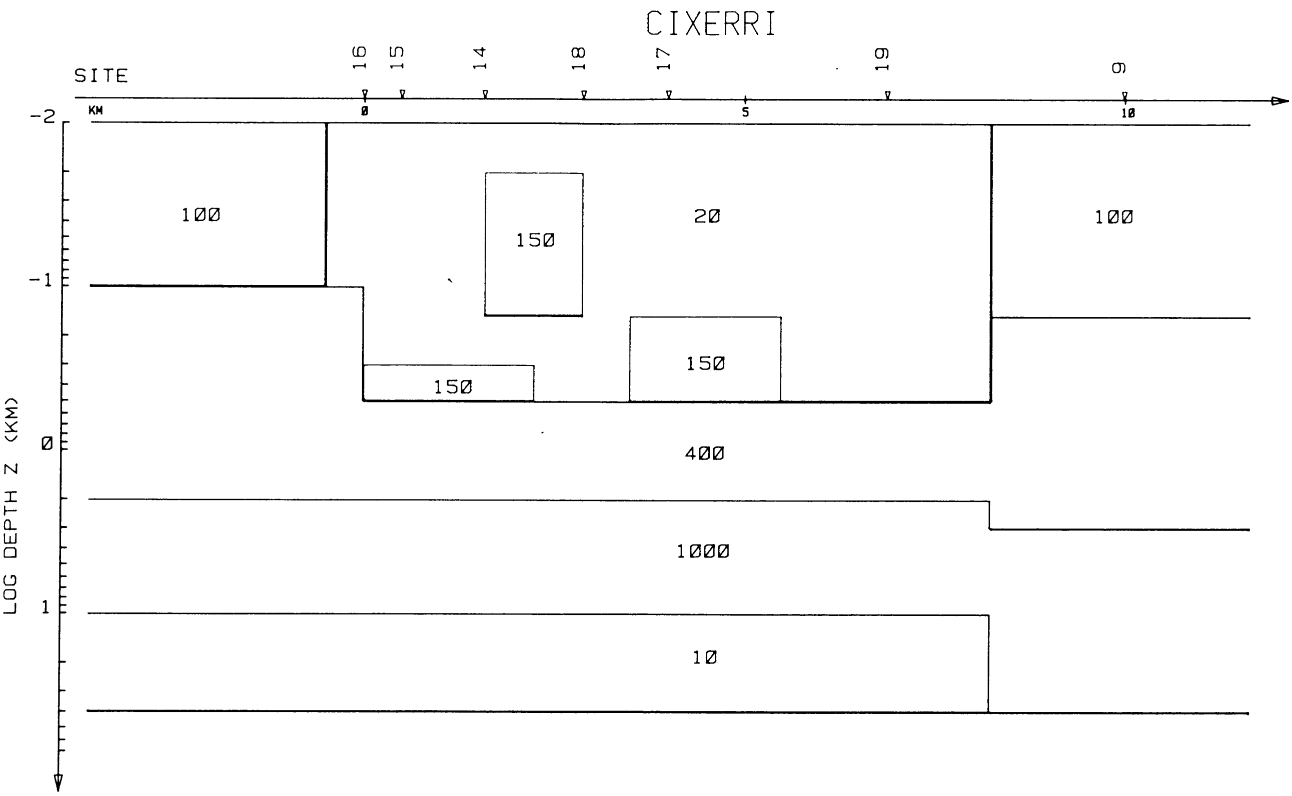


Fig. 9. Two-dimensional model proposed for the Cixerri valley along profile 2 (cf. Fig. 1). Note the logarithmic depth scale. Station 18 is over an old lava outcrop, which explains the higher surface resistivity. The model is cut off at a depth of 50 km with a perfect conductor, to limit computer time. The standard deviation between measured and computed values of log ρ_a at 10 and 100 ms, and 1 and 10 s is $\varepsilon = 0.341$, which corresponds to a resistivity ratio of 2.19

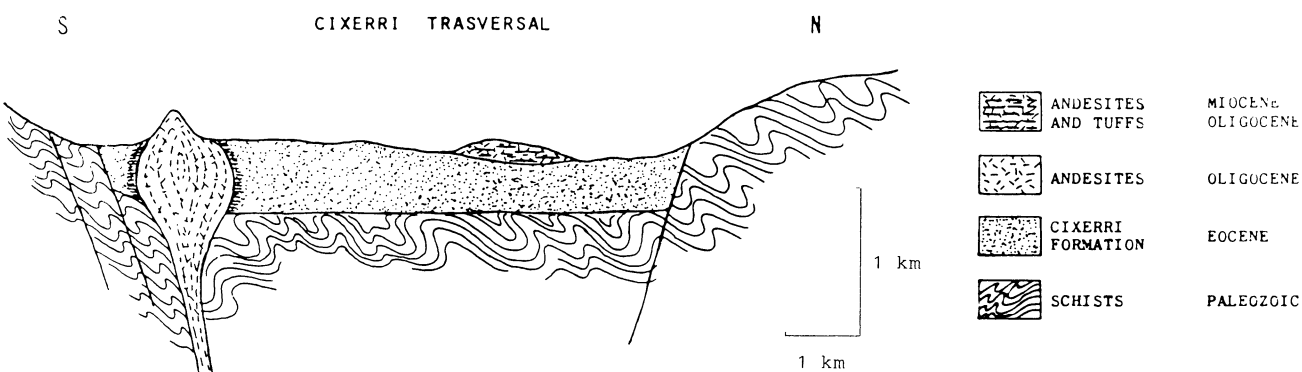


Fig. 10. Geological structure of the Cixerri valley as inferred from our Fig. 9 model and prior geological information (Pala et al, 1977). Here the depth scale is linear, with a vertical exaggeration of 2

An initial 2D conductivity model was again derived from the juxtaposition of 1D inversions of the original H-POL data. The model was gradually improved to insure a better fit first with the H-POL field data, and then also with the E-POL data. The final model is shown in Fig. 9, with a smoothed version according to the known geological elements given in Fig. 10. The most striking feature of these profiles is the presence of a resistive outcrop of metamorphic rocks, actually visible at the site of station 18. They correspond to an extinct volcanic diapir. In fact, the southern part of the Cixerri valley is strewn with extinct volcanoes of Oligocene to Lower Miocene age which often rise above the level of the valley sediments, as for example the Castello d'Acquafredda south of Siliqua (cf. Fig. 1). It is not surprising, therefore, if our stations 21, 20 and 11 all suggest high resistors at depth which are shallower than the actual basement level. If this level is at 500 m at profile 2 and at about 1,700 m at station 4, our soundings at stations 21, 20 and 11, which are all fairly isotropic, indicate resistive formations at depths of 840 m, 435 m and 275 m, respectively. We believe that many more closely spaced soundings would be required in that area to determine this complicated buried topography. This more complex buried structure also leads to more frequent deviations from an ideally 2D structure on profile 2 than on profile 1 and accounts for the somewhat greater standard deviation ($\varepsilon = 0.341$ on profile 2, as against $\varepsilon = 0.276$ on profile 1).

Conclusions

Our MT study of the structure of the Campidano Graben has confirmed the lithological information provided by the Campidano 1 borehole. Above the resistive Paleozoic valley basement, whose central depth is in the range 1,500–2,000 m, we find a first conducting layer corresponding to the sediments of the Cixerri formation of Eocene age. This is followed by a resistor, attributed to the vulcanitic andesites and ignimbrites which were deposited during the Oligocene – Lower Miocene period of great volcanic activity in SW Sardinia. The younger upper sediments are not individually resolvable by the MT method, since they are all of low resistivities, in the range 4–15 Ωm.

The present study further indicates that the sediments are appreciably more conducting on the eastern flank of profile 1. On this side, the graben shoulder seems to dip more steeply than on the western border. Along its axis from SE to NW the Campidano Graben appears to deepen rapidly from Decimomannu to the latitude of Villacidro and then rises again toward Pabillonis. At the southern end of profile 3, and indeed all along profile 4, there seems to be an accumulation of extinct volcanoes, some of which reach above the level of the valley; but the great majority are probably buried under the sediments and create a rather rugged hidden topography along the south side of the Cixerri valley.

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