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IMPROVEMENT OF MT SOUNDINGS THROUGH COMBINATION WITH TDEM SOUNDINGS

MT Sondajlarının, TDEM Sondajlarıyla Birleştirilerek Geliştirilmesi

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ABSTRACT

One major problem in the interpretation ot magnetotelluric (MT) data is to identify the smooth apparent resistivity curve when the actual sounding curves are distorted by small and large scale lateral resistivity discontinuities and by cultural noise. Time-domain electromagnetic (TDEM) soundings at the same MT sites, carried out with the central loop mode, make a significant contribution by identifying the most representative high-frequency part of an MT curve. The combination of TDEM and MT methods is an efficient way to overcome problems due to cultural noise, shallow resistivity discontinuities which produce a frequency-independent shift of the MT curve (static shift), and larger scale discontinuities which cause frequency-dependent splitting of the two orthogonal (E and H mode) MT curves.

ÖZET

Manyetotellurik (MT) verilerin yorumunda en büyük sorunlardan biri, sondaj eğrilerinin küçük veya büyük yanal özdirenç süreksizlikleri ve kültürel gürültü ile bozulduklarında gerçek görünür özdirenç eğrisini saptamaktır. Bir lupun merkezinde alınan Zaman Bölgesi (TDEM) elektromanyetik ölçümleri, MT eğrisinin yüksek-frekans bölümünün tanınmasına büyük katkı sağlar. TDEM ve MT yöntemlerinin birlikte kullanımı, kültürel gürültü, MT eğrisinde frekans-bağımsız kaymaya (static-shift) neden olan sığ özdirenç süreksizlikleri ve iki ortogonal MT (E ve H modları) eğrisinin birbirinden frekans-bağımsız olarak ayrılmasına neden olan büyük ölçekli özdirenç süreksizlikleri sorunlarının yenilmesinde etkin bir yoldur.

INDRODUCTION

In recent years the magnetotelluric (MT) method has been increasingly utilized as an alternative to D.C. resistivity or even to seismic reflection methods in the exploration of oil and geothermal fields.

A number of factors concur to the increasing demand for MT surveys. They include:

— cost effectiveness in volcanic-covered "no reflection" areas;
— ability to detect conductors at great depths; since these are often seismically undetectable low velocity layers, synthesis with reflection data can be very important;
— the adtitional information about geoelectrical structures which can be extracted from MT soundings, including the degree of departure from the ideal 1-D conditions, the azimuthal variation of electrical properties at different penetration depths, etc.
— the lack of environmental damages produced during the survey, in contrast to explosions, vibrations, long cable spreads used by seismic reflection surveys.

This is becoming very important in some western European countries where exploration is made within cultivated land or in areas under environment protection laws;

— the portability and ease of use of state-of-the art MT equipment even in locations with difficult access;
— the development of very compact and powerful portable computers, which permit data processing and preliminary interpretation in the field;

The use of MT method in complex situations requires increasingly sophisticated data acquisition, processing and interpretation. Two major problems need to be overcome to achieve meaningful interpretations:

— the occurrence of coherent noise which hides the signal at frequencies higher than 10 Hz. It is produced by human activities and it becomes a major disturbing effect in locations close to

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densely inhabited areas;

— the distortion of 1-D MT curves produced by shallow lateral variation in conductivity, due either to rough topography or to geological heterogeneity.

In this paper we want to show how the combination with time domain electromagnetic soundings (TDEM) can help to overcome these problems, providing the optimum apparent resistivity curve for interpretation.

MT AND TDEM DATA ACQUISITION

The MT method consists of the computation and interpretation of the transfer function (Z) relating the time variations of the electrical (E) and geomagnetic (H) natural fields on the surface of the Earth. Z is a tensor (the impedance tensor), whose horizontal components form a 2x2 complex matrix. The elements of the matrix are related to the average resistivity of the layer penetrated by the electromagnetic wave of a given frequency.

Computation of the single matrix elements allow to determine apparent resistivities along two perpendicular directions. When the resistivity distribution within the Earth is 1-D there is no variation of apparent resistivity with direction. When the resistivity distribution is 2-D, it is necessary to choose a coordinate system as resistivity will change with direction. The usually chosen coordinate system has one axis parallel to geological strike and the other perpendicular to it. Two apparent resistivity curves are obtained: one is normally called E-mode, and the other H-mode. A third curve can be obtained from the Zxx and Zyy elements of the impedance matrix. It is not dependent on direction and it is therefore called invariant apparent resistivity curve.

An MT sounding consists typically of the measurement of the time variations of two horizontal components of the electrical field and of the three components (two horizontals and the vertical) of the magnetic field over a frequency range from 200 to 0.005 Hz. The typical MT lay-out is shown in Fig. 1. The electric dipoles have a length of 100-200 m. The magnetic sensors are high sensitivity induction coils. Advanced real-time PC-based acquisition systems allow electric and magnetic signals to be amplified, filtered, processed and finally stored in the field.

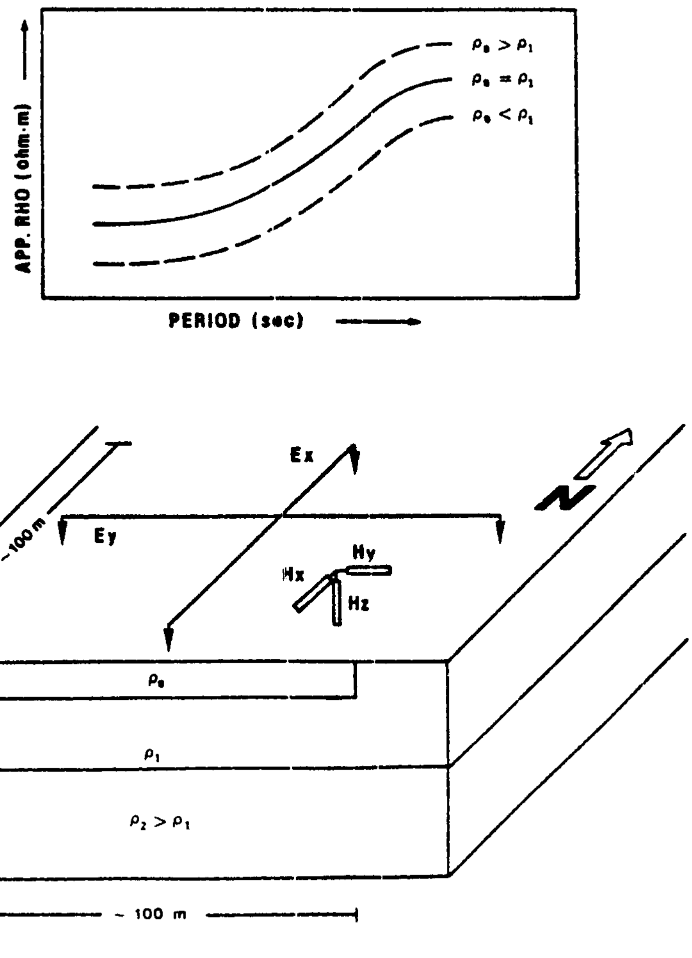

Fig. 1. Lay-out of a 5-component MT sounding. The upper part of the figure shows the static shift due to a thin three dimensional inhomogeneity underlying the sounding site.

Şekil 1. Beş-bileşkeli MT sondajı ölçüm düzeni. Şeklin alt bölümünde, sondaj noktasının altında uzanan üç boyutlu bir sürekizlik nedeniyle oluşan statik-kayma görülmektedir.

Unlike MT method, the TDEM soundings utilize an artificial source of electromagnetic waves. A typical lay-out of a concentric loop TDEM sounding consists (Fig. 2) of a 200-300 m square loop driven by a transmitter which emits signal pulses at fixed repetition rates (tipically 2.5 or 25 Hz) and a small centrally located receiving coil. The primary magnetic field induced by the emitting coil propagates inside the Earth. The flow of energy downward has a typical "smoke rings" structure (Nabighian, 1979). When the energy flow meets an electrical conductor, high intensity eddy currents will be generated. These will produce a secondary magnetic field, whose vertical component will be detected by the receiving coil. The signals are fed into a multichannel processor where the decay with time of the received signal is measured. The occurrence of a conductive layer will decrease the decay rate of the signal.

Consequently, TDEM apparent resistivities are obtained as a function of decay time of the signal (see Fig. 3), whereas MT apparent resistivities are obtained as a function of period of the electromagnetic wave oscillation (see Fig. 4). In order to merge the two data sets, it is

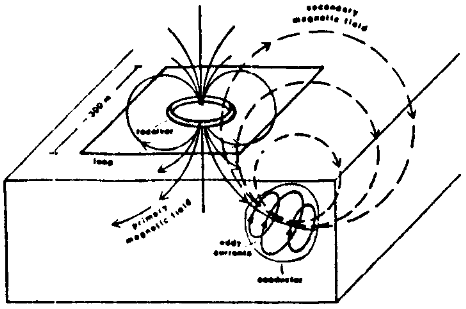

Fig. 2. Lay-out of central loop TDEM sounding. The patterns of primary and secondary magnetic fields are shown.

Şekil 2. Merkezi-lup TDEM sondajı ölçü düzeni. Birincil ve ikincil manyetik alan çizgileri gösterilmiştir.

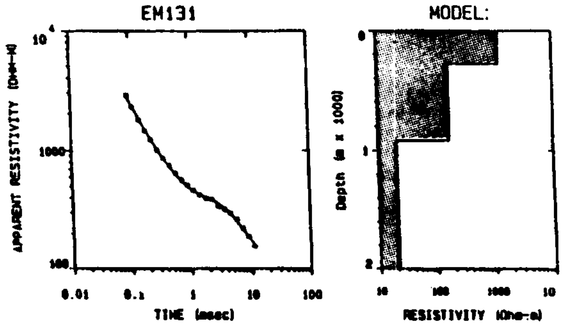

Fig. 3. TDEM apparent resistivity curve and corresponding 3-layer model,(• measured values; — calculated values).

Şekil 3. TDEM görünür özdirenç eğrisi ve ona karşılık gelen 3-katman modeli. O ölçülen değerler, — hesaplanan değerler.

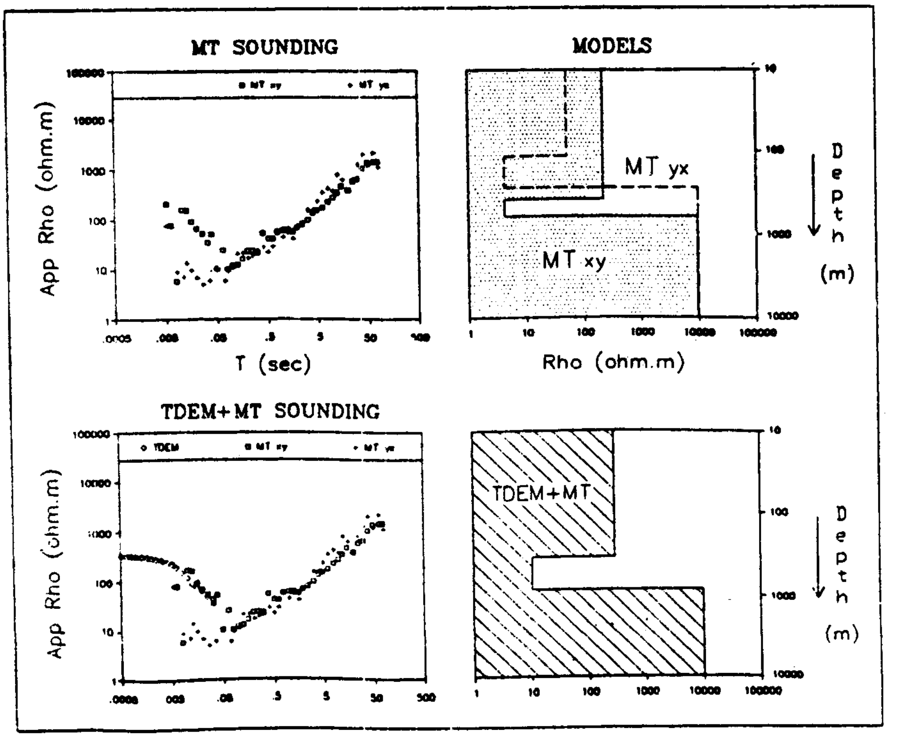

Fig. 4. Apparent resistivity curves and corresponding 1D inversion models from MT and TDEM data collected in a Southern Italy volcanic area. Upper part: MT sounding. Lower part: Combined TDEM-MT sounding.

Şekil 4. Güney İtalya'da volkanik bölgede ölçülen MT ve TDEM görünür özdirenç eğrileri ve 1 boyutlu değerlendirme modelleri. Üst bölüm: MT sondajı. Alt bölüm: TDEM+MT sondajlarının birlikte değerlendirilmesi.

necessary to transform TDEM apparent resistivity as a function of period. The method we have used was suggested by M. Stark, Unocal Co. It is based upon consideration of MT and TDEM penetration depths and a study of synthetic data to calculate the factor relating TDEM decay time to MT period.

HIGH FREQUENCY NOISE IN MT SOUNDINGS

When MT soundings are carried out in inhabited areas, one of the main problems is the occurence of coherent noise at frequencies above a few Hz. This noise has well defined peaks corresponding to the frequency of the local electric power (50 or 60 Hz) and its multiples. However, it often appears as a complicated fine structure signal which distorts strongly the high frequency part of the MT apparent resistivity curve, sometimes causing a split of the E-mode and H-mode curves. This structure of the noise makes simple analog filtering ineffective.

An example of this is shown in Fig. 4. It refers to a MT sounding carried out in a Southern Italy volcanic region, where pervasive cultural noise disturbed the apparent resistivity curves at periods shorter than 0.1 sec. The good quality of the data for periods longer than 0.1 could not be exploited conveniently because of the ambiguity of data at high frequencies. The combination with a TDEM sounding carried out in the same site permitted the unequivocal definition of the high frequency part of the apparent resistivity curve and thus the definition of the best curve to be used for modelling.

EFFECTS OF LATERAL RESISTIVITY VARIATIONS

MT aparent resistivity curves obtained over an horizontally layered (1-D) Earth are smooth, do not have any split between E and H modes, and are readily inverted without further manipulation. In general an MT apparent resistivity curve can be viewed as a 1-D curve which is perturbed to some degree by lateral variations of the geoelectrical characteristics of the Earth. A basic step in the interpretation of the curve is the recognition and removal of the disturbing effects due to lateral variations. Therefore an impressive amount of research work was dedicated to the classification and evaluation of these effects. This work was mainly carried out at the Moscow State University and was summarized by Berdichevsky and Dmitriev (1976) and Rokytiansky (1982). They calculated 2-D forward models for a great number of situations. An example is reported in Fig.5, where the effect of a resistive slab of thickness h and length 2L is evaluated for MT sites along a profile departing from the center of the slab (d = 0). At a distance greater than twice the half length of the slab (d = 2) apparent resistivity curves are 1-D. At shorter distances the presence of the slab affects clearly the high frequency part of the apparent resistivity curve. The effect attenuates as a function of frequency.

Deep lateral inhomogeneities affect mainly the low frequency part of the apparent resistiviy curve (Fig. 6). Modifications of MT curves produced by a shallow inhomogeneity, represented by a topographic step, are schematically shown in Fig. 7. MT soundings located at distances much greater than the size of the step give rise to smooth and unsplit apparent resistivity curves, which are typical of 1-D situation. As the sounding site approaches the step (soundings MT2 and MT5) apparent resistivity curves of E and H modes start to split at long periods.

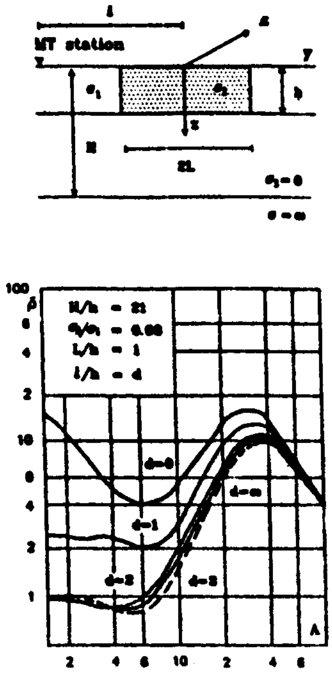

Fig. 5. Effect on apparent resistivity curves due to a shallow inhomogeneity.

Şekil 5. Homojen ortam içinde sığ süreksizliğin görünür özdirenç eğrisine etkisi.

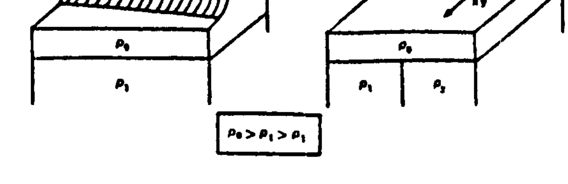

Fig. 6. Left: frequency-independent (static) shift produced by a shallow discontinuity;
Right: frequency-dependent effect of a deep discontinuity.

Şekil 6. Solda; sığ süreksizlikçe oluşturulan frekans-bağımsız kayma; Sağda; derin süreksizliğin frekans-bağımlı etkisi.

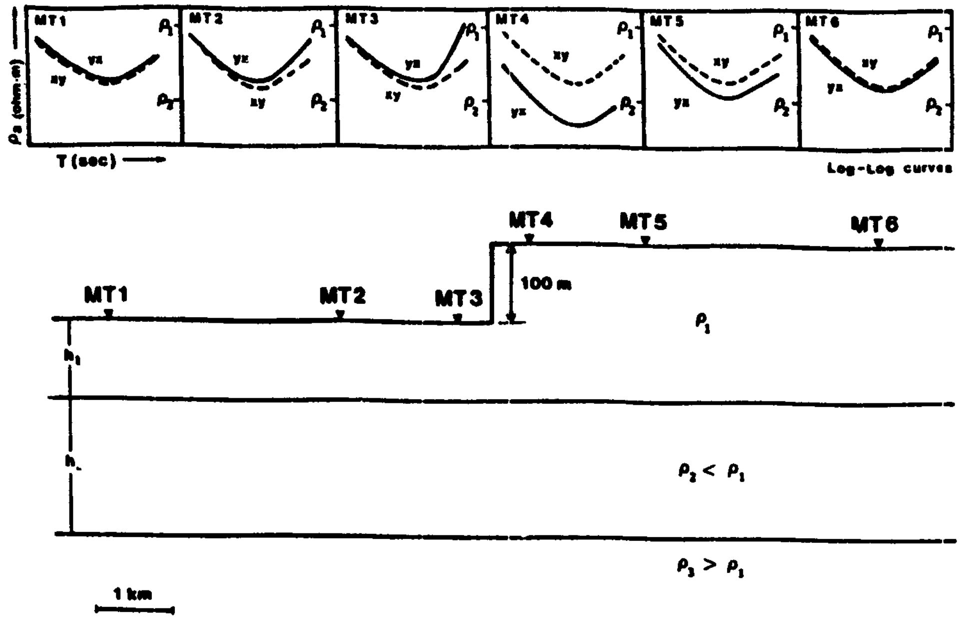

Fig. 7. MT resistivity curves at different distances from a topographic step on a horizontally-layered Earth. (from Z-axis, Modelling and interpretation of magnetotelluric data).

Şekil 7. Yatay-katmanlı yer üzerindeki bir topoğrafik atımdan değişik uzaklıklardaki MT özdirenç eğrileri (Z-ekseninden, MT verisinin yorumu ve modellenmesi).

The distortion source is at a great distance in comparison with its size, so the degree of distortion of the curves is still frequency dependent. When the soundings are located near the topographic step, the two modes are clearly split and the degree of splitting is not frequency dependent. The considerable alteration of apparent resistivities at 10 Hz produced by topography is further illustrated in Fig. 8. The same type of frequency independent curve distortion occurs when a thin geoelectric inhomogneitiy directly underlies the measurement site (Fig. 1). This class of frequency independent curve distortion is called "static shift". The removal of static shift is a necessary step before modelling.

STATIC SHIFT CORRECTION

Sternberg et al. (1982, 1985) and Andrieux et al. (1984) suggested the use of TDEM central loop soundings to correct MT soundings for static shift. The static offset is mainly caused by the electric field variations that the anomalous body produces. Determination of the apparent resistivity by measurements involving only the magnetic field are an effective way to by-pass the problem. TDEM soundings provide us with just this kind of measurement. In order to reach the objective, it is necessary that a sufficient overlap exists in terms of skin depth between TDEM and MT soundings.

In the following we present some examples of successful applications of the method. They are relative to a survey carried out as part of a geothermal exploration project. In some soundings a parallel upward offset of the E-mode with respect to the H-mode curve was observed. In this situation the MT invariant curve could be assumed

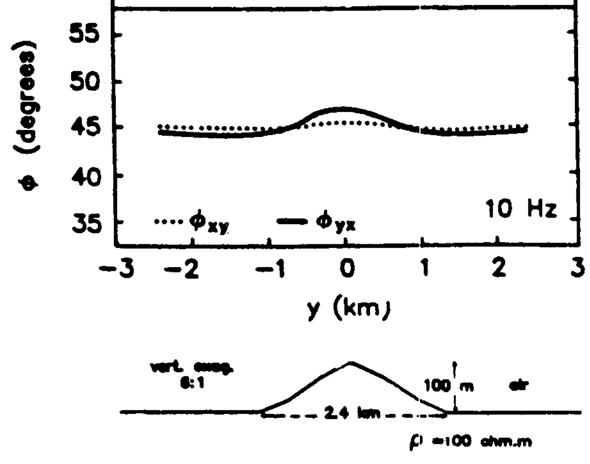

Fig. 8. Variation of apparent resistivity at a fixed frequency (10 Hz) along a profile crossing a topographic feature on an electrically uniform Earth (from Wannamaker et al., 1986).

Şekil 8 Tekdüze ortamda topoğrafik bir yapı boyunca sabit frekansta (10 Hz) görünür özdirencin değişimi (Wannamaker ve diğ. 1986).

to be the best approximation to the unshifted curve. The results of a TDEM sounding carried out at the same location showed that TDEM resistivities (i.e. resistivities determined using only the magnetic field) are higher than corresponding MT apparent resistivities. The two curves run parallel (Fig. 9). It is clear that this was a static shift effect, so that a parallel upward shifting of the curves is all that is needed to compensate for the effect and to allow 1-D modelling of the soundings.

Such a correction was a necessary preliminary step to have an inversion model consistent with both MT and TDEM data and to correlate resistivity-depth functions obtained at different sites.

In order to reduce ambiguities introduced by an arbitrary subdivision into discrete layers, correlations were made using the Bostick method of inversion. The example reported in Fig. 10 shows the much better definition of conductive areas obtained by correlating results from TDEM + MT data.

DEALING WITH DEEP LATERAL DISCONTINUITIES

As shown in section 4, deep lateral electrical discontinuities produce frequency dependent disturbance of MT apparent resistivity curves. When the discontinuity starts close to the surface, as in Fig. 5, it produces as spliting of the E and H modes a high frequency. In this case the combination with results from TDEM soundings allows selection and modelling of the most representative curve.

An example of this situation comes from an MT survey carried out on a volcanic covered prospect in Southern Italy. None of the 40 MT soundings showed evidence of static shift, indicating a quite homogeneous situation in the shallow subsurface.

Many of the soundings showed a splitting of E and H modes, mainly at high frequency, partly due to problems of cultural noise and partly due at deep lateral geoelectrical discontinuities. TDEM central loop soundings were carried out at the same MT sites. In most cases TDEM apparent resistivities fit quite clearly one of the two MT modes (Fig. 11). The combined TDEM and MT curves were inverted using 1-D MT programs. Results of inversion were then compared with Bouguer anomalies along selected profiles in order to reconstruct the morphology of the top of resistive, high density basement formed by carbonate rocks of Mesozoic age (Fig. 12).

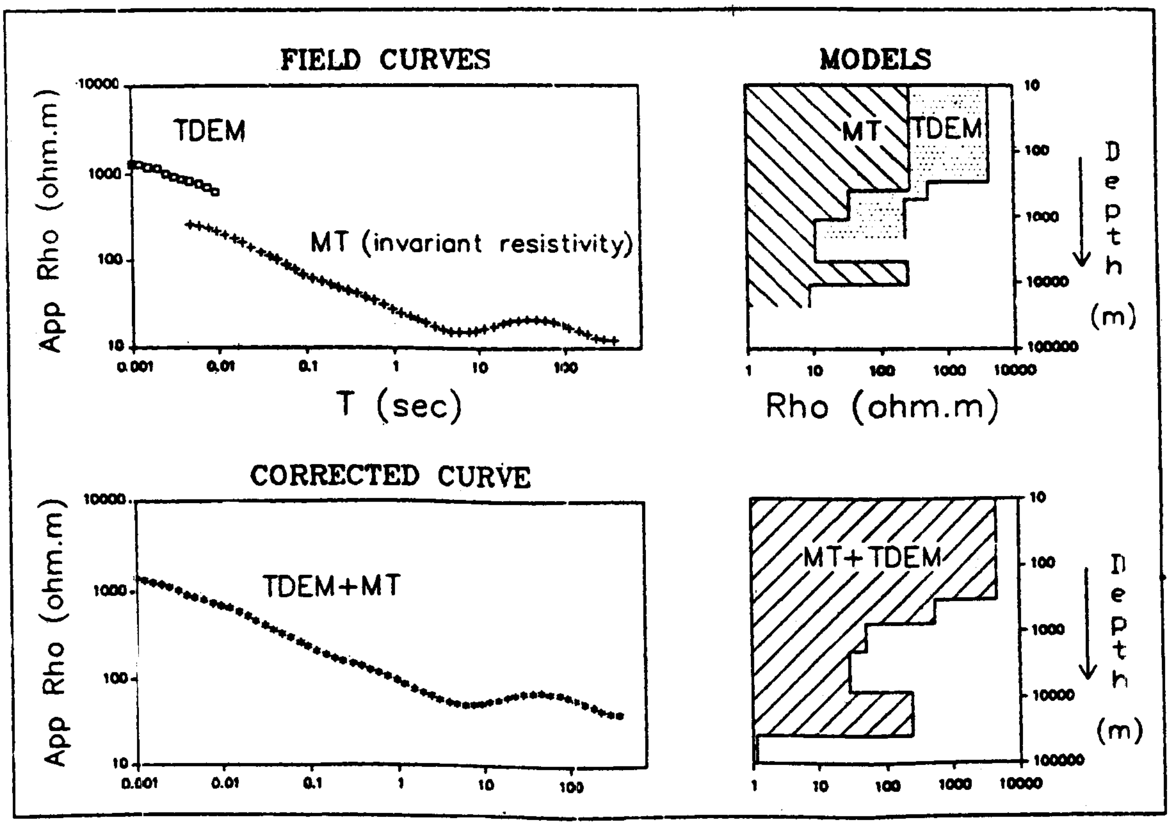

Fig. 9. Static shift correction of an MT invariant resistivity curve using TDEM data.

Şekil 9. TDEM verisi kullanılarak MT özdirenç eğrisinin de statik-kayma düzeltmesi.

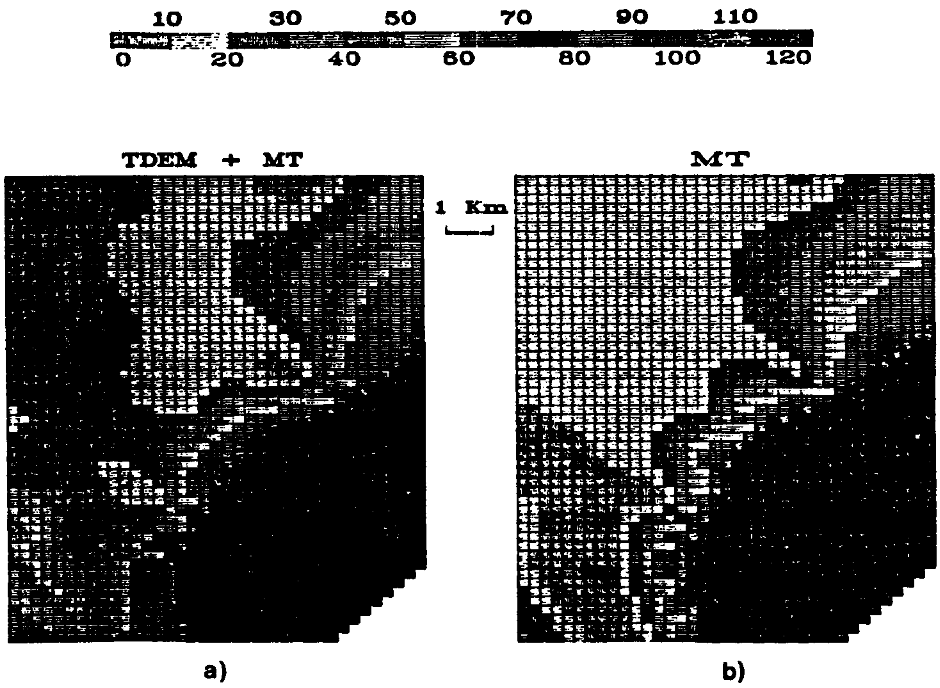

Fig. 10. Example of resistivity maps (3000 m depth) obtained from Bostick inversion of a) Combined TDEM + MT and b) MT soundings showing evidences of static shift.

Şekil 10. Bostick dönüşümü ile elde edilen (3000 m derinlik) özdirenç haritaları örneği. a) TDEM+MT birlikte ve b) statik kayma gösteren MT sondajlarıyla.

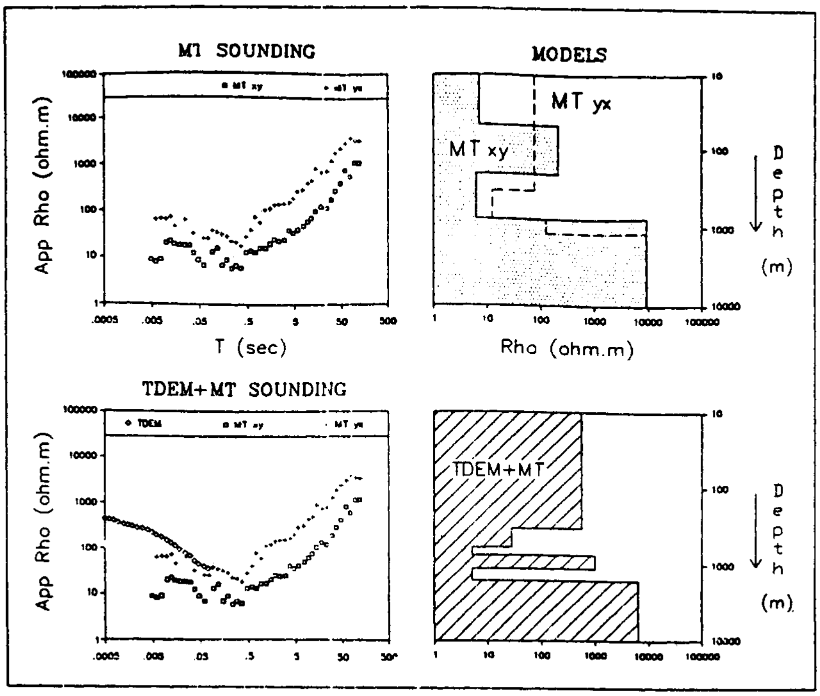

Fig. 11. Split E-mode and H-mode MT curves from Southern Italy (volcanic area). TDEM data closely match the upper MT curve.

Şekil 11. Güney İtalya (volkanik bölge) MT eğrilerinde E ve H modlarındaki ayrılma. TDEM verisi, üst MT eğrisine daha yakın olarak çakışmaktadır.

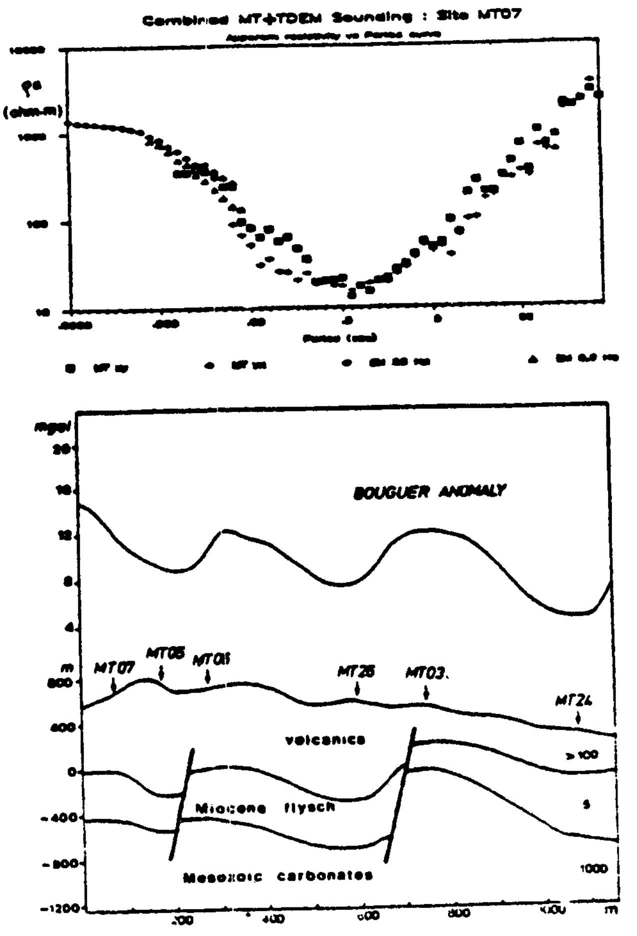

Fig. 12. Interpreted cross-section from MT, TDEM and gravity data collected in Southern Italy.

CONCLUSIONS

The application of central loop TDEM soundings enhances the utiliy of MT soundings when:

a) the definition of the high frequency part of MT apparent resistivity curves is masked by a high level of cultural noise;

b) there are static shift effects due to very local, shallow topographic and/or geological inhomogeneities;

c) where the occurrence of shallow discontinuities causes, a high frequency splitting of E and H mode curves.

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