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Geoelectromagnetic measurements across the southern Senegal basin (West Africa)

Michel Ritz and Jacques Vassal

Orstom, BP 1386, Dakar (Senegal)

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Magnetotelluric and differential geomagnetic sounding surveys, consisting of nine soundings, were performed in 1984 along a 200-km profile across the southern Senegal basin. They were intended to obtain information concerning the resistivity structure of the crust and upper mantle and the distribution of the induced electric currents. Magnetotelluric data indicate that two-dimensional resistivity models are appropriate for the region. The zone above the basement is highly inhomogeneous in geoelectrical structure. Very conductive sediments (0.6–3 ohm m) appear in the Mesozoic–Cenozoic Senegal basin. These sediments lie at depths of up to 4500 m on the west end of the profile. Below this, a modest resistivity material (10–30 ohm m) extends to a maximum depth of about 3000 m. The material at depth on the east part of the traverse line is thought to be Palaeozoic sediments of the Bove basin. The depth of the magnetotelluric basement lies between about 250 m (in the east) and 4800 m (in the west). The crust is characterised by a drop in electrical resistivity at a depth of 15 km below the east part of the profile. Considering the total section, we observe a general trend towards lower resistivities at depths in excess of 100 km, the transition from 2000 ohm m to about 2 ohm m occurs in the depth range 100 to 175 km. An analysis of the geomagnetic variation field has identified a concentration of telluric current flow beneath the deep basin. It appears that the additional currents flowing in the striking direction of the Senegal basin are largely controlled by sedimentary rocks of high conductivity lying at depths less than 5 km. Model studies show that the local conductivity distribution is able to explain the currents circulating in the thick well-conducting sediments.

1. Introduction

In this paper, the third field operation, concerned with the study of the structure of electrical resistivity in the Senegal basin (Fig. 1) using both magnetotelluric (MT) and differential geomagnetic sounding (DGS) techniques, is presented. Results of the earlier studies have already been published. Thus, two-dimensional (2-D) interpretations were successful in detailing the lithosphere resistivity structure beneath the central basin (Ritz, 1984; Ritz and Flicoteaux, 1985) and the northern basin (Ritz and Vassal, 1986), and in delineating a strong crustal inhomogeneity in electrical resistivity on the eastern margin of the deep basin. Moreover, as horizontal magnetic field observations were made simultaneously, it has been possible to map the flow of anomalous electric current associated with lateral variations of electrical resistivity, either in the well-conducting sediments of the basin, or the crust, or both. To complete the electromagnetic coverage in Senegal, we occupied a total of nine stations (Table I), distributed along an E–W traverse in the southern basin, by recording electric and magnetic signals in two period bands: 600 to 10 s for the short-period band and DC to 300 s period for the long-period band. Data were obtained using the field system and acquisition procedures developed at the Centre de Recherches Geophysiques in France (Mosnier and

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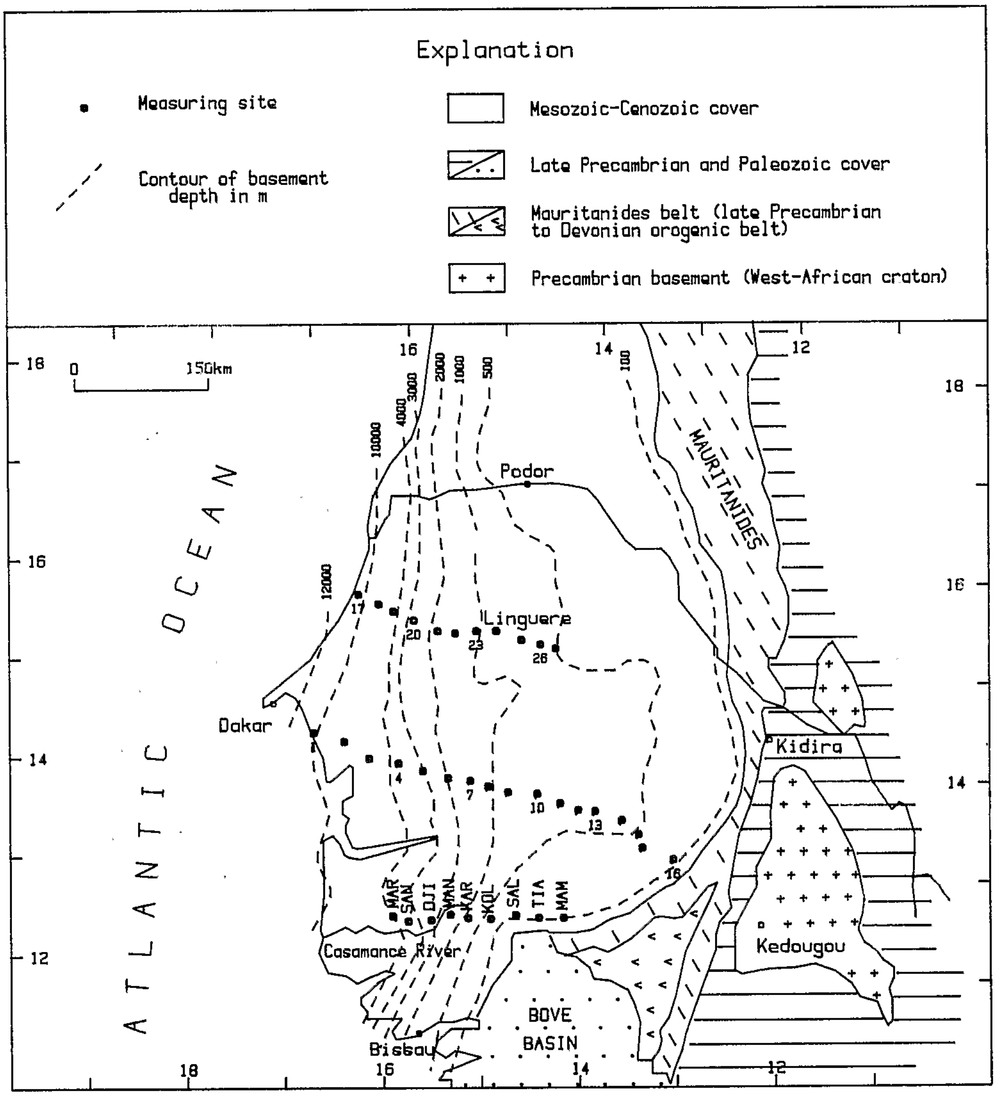

Fig. 1. Magnetotelluric and differential geomagnetic sounding locations in the Senegal basin. Data from sites 1 to 16 were interpreted by Ritz (1984) and results from sites 17 to 27 were presented by Ritz and Vassal (1986).

Yvetot, 1972). All soundings were performed using two remote magnetic references to provide an estimate of the anomalous geomagnetic variation field (Babour et al., 1976).

The basin is poorly known from its surface geology and the main knowledge of the region comes from drilling (De Spengler et al., 1966), electrical soundings (Mathiez and Huot, 1966), aeromagnetic profiles (BRP, 1956), gravity studies (Crenn and Rechenmann, 1965; Liger and Roussel, 1979; Liger, 1980; Roussel and Liger, 1983). From east to west, the Precambrian basement dips under the Mesozoic–Cenozoic Senegal basin. The western extension of the partly metamorphic basement under the sediment basin is only known within a certain depth range because of limitations in the geophysical methods used: the resistant basement, easily visible to the east, disappeared in

TABLE I

Location of the stations

Station name	Code name	Latitude N	Longitude W
Mampatim	MAM	12.88	14.33
Tiara	TIA	12.86	14.54
Salamata	SAL	12.86	14.78
Kolda	KOL	12.88	14.96
Karsia	KAR	12.83	15.16
Mankono-ba	MAN	12.87	15.38
Djinde	DJI	12.80	15.56
Sansamba	SAN	12.80	15.78
Marsassoum	MAR	12.82	15.97

the west from a zone between 15 and 15°30′W. In the Dakar region, the basin is probably covered with more than 10 000 m of post-Palaeozoic sediments. Figure 1 shows basement depth contours. In the southern part of the basin, the Mesozoic–Cenozoic sediments partially cover the Palaeozoic Bove basin. The structure within the Mesozoic–Cenozoic sediments has a dominantly northerly trend and the main structural trends are southeasterly in the Bove basin. A major contrast in electrical resistivity can be anticipated at the base of the sediments and basement depths may be mapped using MT techniques (Vozoff, 1972).

2. Results

As a first step all field data were plotted for a visual examination to select those that are free from obvious technical and recording noise, step functions and those that have a broad spectral range with a sufficient magnetically active signal level. Simultaneous records were compared to detect any gaps.

2.1. MT responses

The field tapes were analysed after standard procedures (Sims and Bostick, 1969; Thayer, 1975). Tensor apparent resistivity values were rotated to their principal directions corresponding to the structural strike (TE-mode) and perpendicular to it (TM-mode). Phases for each of the apparent resistivity components were also computed. Only in the case of one-dimensional (1-D) structures do both TE-mode and TM-mode give identical results. Selection was undertaken by using data with a predicted coherence greater than 0.9. At most of the stations the azimuthal rotation angle appears frequency independent with an approximately NNW–SSE orientation. The direction of the MT impedance tensor observed for sites SAN–MAR on the west end of the profile is undefined for periods less than 100 s. Such undefined rotation usually indicates sequences of essentially homogeneous sediments. At periods greater than 100 s, the rotation angle becomes well defined with an approximately NNW–SSE orientation. This direction as determined from the impedance tensor for sites MAM–MAR represents the dominant geologic strike within Mesozoic–Cenozoic sediments and suggests control of the electrical structure beneath the study area by the Senegal zone. Traditionally skew (Swift, 1967) is used as a dimensional indicator. For all nine stations the skew factor is less than 0.15 at all periods and this indicates that the geological structures beneath these sites can be described as one- or two-dimensional.

The apparent resistivity and phase data across the profile appear to fall into three distinct groups which are consistent with separating the sites according to locality, i.e., the eastern group including the shallow basin with MAM, TIA and SAL, the central group with KOL and KAR and, the western group covering the deep basin with MAN, DJI, SAN and MAR. Typical sounding curves are shown in the upper portion of Fig. 2, which gives the responses in the parallel-to-strike (TE-mode) and perpendicular-to-strike (TM-mode) directions, observed at sites TIA, KAR and MAR. The bars indicate the probable errors (90% confidence limits). Note that the directions parallel and perpendicular thus defined are parallel and perpendicular, respectively, to the average strike of the Senegal basin.

2.1.1. Eastern response, site TIA

The data from TIA are anisotropic in that the TE and TM estimates are dissimilar. The anisotropy ratio increases with increasing period for periods larger than 100 s. At periods below 100 s,

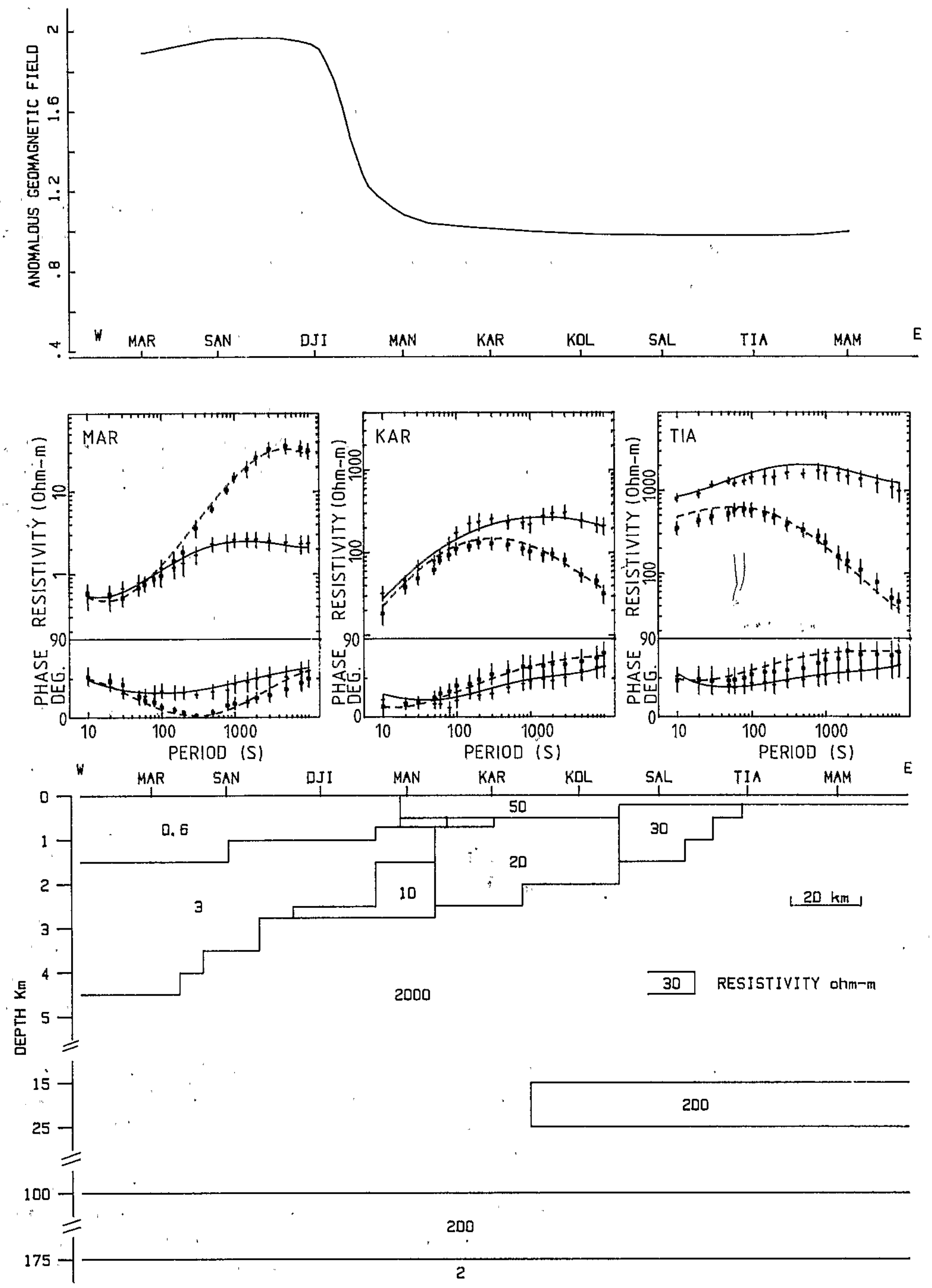

Fig. 2. Results of observation and calculation along a profile perpendicular to the electrical strike across the Senegal basin with the corresponding geoelectric structure below. In the upper part of the figure the computed MT data, generated for the direction parallel to strike (TE), are shown by dashed curves, and data for the direction perpendicular to strike (TM) are shown by solid curves. Calculated estimates are shown plotted through the measured values for three typical sites TIA, KAR and MAR. The amplitude of the anomalous horizontal geomagnetic field for the MT model is shown in the uppermost portion of the figure at 1000 s period.

the anisotropy ratio remains more or less constant. The TE apparent resistivity increases slightly with the period from 10 to 100 s and it decreases steeply for longer periods. The TM apparent resistivity reaches values close to 2000 ohm m between 100 and 1000 s. The period dependence of TM apparent resistivity is weaker than that of TE apparent resistivity. The phase of the TE response increases continuously with period from 45° to approximately 70°. The TM phase is close to 45° until about 300 s where it begins to gradually increase at the longest periods.

2.1.2. Central response, site KAR

In the 10–100 s range, site KAR exhibits apparent 1-D characteristics, in that the TE resistivities and phases and the corresponding TM values are very similar. In this period range, the apparent resistivities increase with the period and the phases remain more or less constant. The data in the period range from 100 to 10000 s show increasing divergent behaviour with increasing period between TE and TM resistivities and the corresponding phases. At 200 s period, the TE apparent resistivity is of the order of 150 ohm m. It decreases, with increasing period, to 30 ohm m at 10000 s. The TM apparent resistivity remains constant or decreases slightly (about 200 ohm m) in the 100–10000 s range. Both phases increase with period between 100 and 10000 s.

2.1.3. Western response, site MAR

The apparent resistivity and phase data at MAR are dramatically different from those recorded at stations outside the deep basin, represented here by KAR and TIA. We observe at site MAR fairly uniform but small values of apparent resistivity (0.5 ohm m) until about 30 s where they begin to gradually increase with period. The TE and TM responses are essentially equivalent diverging only at periods greater than 200 s, where the apparent resistivity estimates display increasing anisotropy with increasing period. For the short-period data, the shallow resistivity structure is dependent on depth only and the apparent resistivities may be interpreted by a 1-D model. The tendency for the responses to split into two different modes as periods rise above 200 s implies some effect from the basin sediments. For both estimates, the apparent resistivity values lie between 0.5 and 30 ohm m. The TM apparent resistivity at 10000 s is more than one order of magnitude smaller than the TE apparent resistivity.

2.2. DGS responses

The regional telluric current system is controlled by the electrical resistivity structure. Contrasts in the resistivity structure result in local variations in the density of telluric current flow and consequently in local variations in the geomagnetic variation field. The geomagnetic field of the electric currents which are induced additionally in the geoelectrical structure is superimposed locally to the large-scale geomagnetic field. Consequently, by subtracting the field observed at a reference station (assumed to be influenced only by the regional current system) from the fields observed at the remaining sites, the anomalous geomagnetic variation field due to the additional currents can be determined (Babour and Mosnier, 1977). Both local induction due to a nearby electrically conductive structure and the regional current channelling by a local conductor of currents generated by induction on a scale much larger than the region under investigation will cause an anomalous geomagnetic variation field (Dupis and Théra, 1982; Fischer, 1984).

Figure 3 shows the records of the geomagnetic variation field at three sites across the southern Senegal basin. Geomagnetic variations at SAL were chosen as the reference in calculations of the anomalous field across the basin. Figure 3 shows that the amplitude of the magnetic eastward (D) component is strongly enhanced at DJI above the deep basin, over a wide range of periods, indicating that the field at this station is influenced by lateral variations in the regional current flow. It first appears that these anomalous currents are induced in the thick well-conducting sediments of the basin in addition to the large-scale induced current system in the surrounding region. These results may be seen clearly from Fig. 4, where the distribution of anomalous telluric currents responsible for differential fields is plotted along the section for variations with the periods 800, 1800

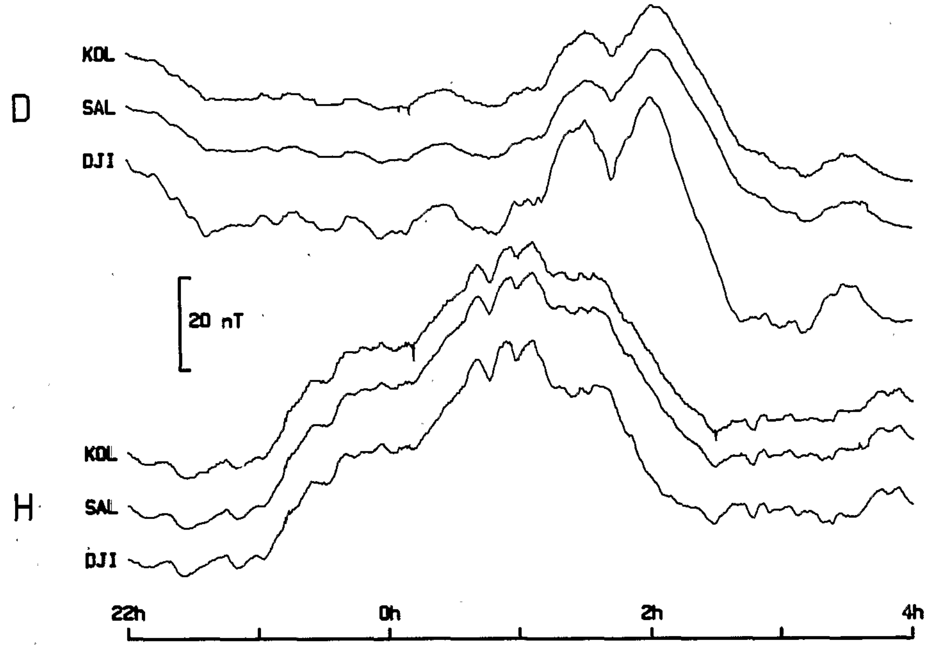

Fig. 3. Simultaneous records of horizontal geomagnetic variations between 2200 h on January 28, 1984 and 0400 h on January 29, 1984 from KOL, SAL and DJI. The sampling interval was 6 s.

and 5000 s. The vectors are at right angles to the anomalous field, giving the direction of additional current flow and their length gives the amplitude of the fields. On the basis of Fig. 4, we may distinguish at least two main parts along the profile, an eastern part including sites MAM–KAR where no anomalous horizontal fields (or very small in comparison with the length of vectors at western stations) are observed and a western part with sites MAN–MAR where the anomalous geomagnetic field is up to twice as large as the normal field at the reference site SAL. The obvious geological distinction of the anomalous zone is the thick blanket of Mesozoic–Cenozoic and Palaeozoic sediments. Anomalous stations appear to be very sensitive to the period in the range 800–5000 s. From east to west, at 800 s period the vector rotates northwards from an initial direction of 20° west (at MAN). At the two longer periods, there is a definite trend of decreasing vector amplitude with increasing period and our vectors are consistent in direction and point northwards except MAN, where the vector has a smaller amplitude and is directionally inconsistent with its immediate neighbour at station DJI. It is not clear whether this effect is related to the deepening of the basin westwards or is due to some additional local effect. The vectors at the three western stations (DJI, SAN and MAR) have the largest amplitude at 1800 s period and for periods longer than 1800 s there is a decrease in amplitude of the vector from east to west.

Finally, except at MAN for periods of 1800 s and above, all our vectors indicate that the additional telluric current flow direction is mainly towards the north, approximately parallel to the strike of the Senegal basin, suggesting that the induced telluric system is controlled by local geological structure. It is quite probable that current concentration westwards is due to electric currents flowing in the sediments of the Senegal basin parallel to the dominant geological trend. To the east the Precambrian basement is only thinly covered, it is likely to be highly resistant to telluric current flow which is deflected. Note that the strike of the telluric current system appears to be associated with the striking direction of the Senegal basin rather than the Bove basin strike.

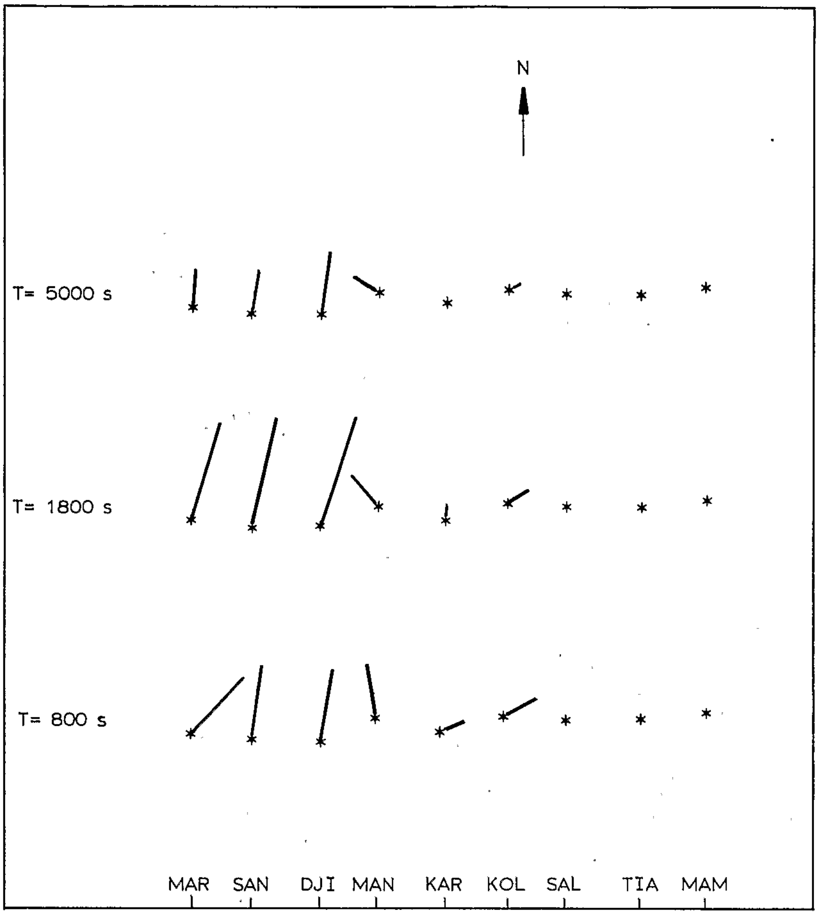

Fig. 4. The distribution of telluric current flow responsible for anomalous fields as a function of the period T at measuring sites. The length of the vector gives the amplitude of the anomalous geomagnetic field and its direction is perpendicular to that of the anomalous horizontal field. On the east end of the profile the additional currents vanish.

3. Interpretation

To provide some information on the resistivity distribution in the southern Senegal basin, we have made MT interpretations supposing that the anomalous fields in the west part of the profile are generated by lateral variations in conductivity and/or variation in depth of the basement within the basin (local induction). All responses were inverted by a 1-D scheme (Jupp and Vozoff, 1975), and the main features of these resulting models were used as a starting point to construct a simplified 2-D composite model. Repeated calculations from the initial model using the PW2D forward program (Wannamaker et al., 1985) for simulation of MT responses of 2-D resistivity structure resulted in a geoelectric model of the crust and upper mantle for the southern Senegal basin (lower part of Fig. 2). Computed apparent resistivity and phase versus period curves for this model are superimposed on the plots of values estimated from the field data (upper part of Fig. 2) from TIA, as representative of the eastern group; KAR, as representative of the central group and MAR, as representative of the western group (deep basin). The computed curves for this model are in general agreement with the TE and TM estimates. It should be emphasised that the above model is only one of a range of possible models that explain the data derived from our research. It is, however, the model that we prefer, after calculating a certain number of other configurations having varying resistivities and thicknesses. The result of the 2-D model-calculations is as follows.

3.1. Sedimentary sequence

The model shows a general decrease in near-surface resistivity from east to west. The thin surface layer of resistivity 50 ohm m between soundings MAM and MAN was not determined by the forward procedure but has been estimated with the help of DC resistivity soundings. The uppermost 50 ohm m material is correlated with Tertiary sediments, which may be completely or partially water-saturated. Within the deep basin, near-surface rocks have resistivities as low as 0.6 ohm m. Saline groundwater may cause lower resistivity than expected. Note that the Casamance river (close to the MT line) is saline up to 100–150 km inland. The mixing patterns between fresh and salt water are complex but a bulk resistivity of 0.6 ohm m is not unreasonable.

Underneath this 1000–1500-m thick conductive unit, a slightly more resistive unit exists that has a resistivity of 3 ohm m, its thickness reaches a maximum at sounding MAR of at least 3000 m. The 3 ohm m material was not detected at the sites east of MAN (margin of the deep basin). This sequence is probably related to Cretaceous rocks, apparently, with a large percentage of clays which significantly reduce the effective resistivity of the sequence. The layer of 10–30 ohm m within the range SAL–KOL–KAR–MAN–DJI is thought to be Palaeozoic sediments of the Bove basin. This zone grades from less conductive to the east to more conductive to the west and the maximum thickness of this layer is about 2000 m at sounding KAR. Underlying these low-resistivity sediments is a resistive unit (2000 ohm m) that can be followed across the entire profile. Both the resistivity of this layer, which increases drastically compared with the previous layer, and the large depth to its top (on the west end of the section), make it probable that these are basement rocks.

3.2. Deep crust and upper mantle

The model indicates a resistant crust (2000 ohm m), underlain by material of 200 ohm m beginning at a depth of approximately 15 km for the east part of the traverse. The insertion of the 200 ohm-m layer beneath the deep basin is poorly constrained in as much as the observed data fit an entire resistant crust nearly as well. The existence of this layer below the west part of the profile is therefore uncertain. This layer may represent the upper mantle or an anomalous layer in the lower crust. Garland (1975) showed that the top of the upper mantle was characterised by a drop in electrical resistivity (Moho discontinuity). However, if we accept the Latil-Brun and Flicoteaux (personal communication, 1986) depth to the Moho discontinuity of 40 km, the 200 ohm m layer probably represents an anomalous lower crust. Similar transition zones to more conductive material at lower depths have been found by many investigators using the MT, geomagnetic and controlled source magnetic induction experiments (see for example, Connerney et al., 1980). Regarding enhanced conductivities at a depth of 15 km or more, several theories exist: partial melting in the presence of a small quantity of water at relatively low temperatures (Wyllie, 1971), hydration processes (Hyndman and Hyndman, 1968), a combination of basic rock type and high pore fluid pressures (Lee et al., 1983). In our study area no measurement of the heat flow has been obtained and higher than normal temperatures cannot be ruled out as a possible mechanism for the enhanced lower crustal conductivities in the eastern Senegal basin. Because of the lack of additional corroborating evidence, based on other geophysical data, it seems impossible at this stage to arrive at a unique interpretation of this drop in electrical resistivity.

At depths greater than 25 km below the whole profile, the upper mantle resistivity decreases downward from 2000 ohm m material of about 75 km thickness through 200 ohm m material into a conductive medium of 2 ohm m at a depth of about 175 km. For the westerly sites, however, the 200 ohm m layer, which begins at about 100 km depth, is not a well-resolved feature of the model for our data set because of the obscuring effect of the thick low resistivity sediments. The presence of partial melting is an appealing proposal, in that it offers an explanation for conducting layers observed within the upper mantle at depths of about 150 km (Lilley et al., 1981).

4. Origin of the anomalous geomagnetic field

The MT results can be used to explain causes of the anomalous geomagnetic field in the west part of the profile. The shallow conductive unit between MAN and MAR on 2-D geoelectric model (lower part of Fig. 2) probably provides the main electrical conduit for the anomalous currents. The MT model was used to study the horizontal geomagnetic field anomalies which occurred across the boundaries of the MT interpretive cross-section. Computed values of the anomalous fields at each station, normalised with respect to the normal horizontal geomagnetic field at SAL, are plotted in the uppermost part of Fig. 2 at 1000 s period (the E along strike component of the 2-D model is used). Figure 2 shows that the magnetic induction in local structure is very strong within the range DJI–SAN–MAR, and the observed geomagnetic variation anomaly on the deep basin can be attributed to thick well-conducting sediments and subjected to regional electromagnetic induction. Note that telluric current flow in the sediments of the deep basin, which causes the geomagnetic variation anomaly, continues northwards (Ritz and Vassal, 1986).

5. Conclusions

An interpretation of the MT data, collected across the southern Senegal basin, gives a 2-D model that provides interesting results about the electrical nature of the crust and upper mantle. The results characterise the region as consisting of very conductive surficial sediments underlain by a resistant crust down to about 15 km. Beneath this zone, a more conductive layer (200 ohm m) exists in the east portion of the profile. In the depth range 100–175 km, resistivities decrease to less than 2 ohm m. The study of the geomagnetic variation field indicates the presence of a concentration of geoelectrical currents in the deep Senegal basin. The strike of the telluric current system corresponds remarkably with the main structural trend of the Mesozoic–Cenozoic sedimentary sequence. For the most part, the 2-D MT model explains the observed geomagnetic variation anomaly in the west end of the profile. The flow of current beneath this region is largely controlled by sedimentary rocks of high conductivity lying at depths less than 5 km.

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