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Inhomogeneous Structure of the Senegal Lithosphere From Deep Magnetotelluric Soundings

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Data from 23 magnetotelluric sites were used to determine electrical conductivities within the crust and upper mantle in Senegal (West Africa) along a profile about 600 km long. Data have been obtained in a variety of tectonic zones: the West African craton (stable since 1850 ± 250 m.y.), the West African mobile belt (with ages in the range of 350–650 m.y.), and the Senegal sedimentary basin. An earth model is derived from two-dimensional modeling. The model shows several heterogeneities extending deep in the lithosphere and, perhaps more deeply, in the asthenosphere, to a depth of about 460 km. At the stations in the western part of the basin the average resistivity is anomalously low (20–30 ohm m) down to about 10 km. The basin anomaly in the upper crust is assumed to mark an initial rift zone; it may reveal a pattern of crustal weakness in this area. Beneath this zone, the resisitivity is in the range of 1000–3000 ohm m down to at least 300 km. In the eastern basin the resistivity is decreasing in the depth range of 20–30 km, and the top of the ultimate mantle conductor is at a depth of 300 km. At the sites in the marginal part of the West African craton, conductive layers can be recognized in the depth range of 30–40 and 80–100 km. The resistivity drops to 10 ohm m at a depth of about 460 km. The model in this region is compared with available geological and geophysical information, and an attempt is made to explain some of the observed discontinuities by plate tectonics. It is suggested that the major discontinuity which separates the basin and the mobile belt and extends to about 460 km depth could be interpreted as marking a Precambrian subduction slab dipping eastward. In the West African craton a low resistivity has been determined for a depth range of 130–150 km. The upper 130 km were found to have the rather high resistivities of 1000–3000 ohm m. A sharp rise in conductivity occurs at a depth of about 460 km beneath the craton. In contrast, a surprising feature in the Kedougou region (in the craton) is that the major portion of the lower crust is conductive. The existence of a Birrimian geosynclinal pair in eastern Senegal consisting of a eugeosynclinal marine andesitic volcanic trough, particularly volcanics with ophiolite affinity, and a miogeosynclinal sedimentary sequence could characterize a modern plate tectonic phase dominated by widespread ocean opening and continental collision. The conductive material in the lower crust might be explained by the buried ocean crust.

INTRODUCTION

During the years 1980–1982, 23 magnetotelluric soundings T) were carried out in Senegal along a profile across the enegal coastal basin, the West African mobile belt (Maurita- de) with ages in the range of 350–650 m.y. and the West frican craton (age of 1850 ± 250 m.y.). These sites are spaced 25- to 35-km intervals and extend for more than 600 km. T deep soundings up to 10,000 s have been carried out in ch tectonic province. The locations of the recording sites are own in Figure 1. The full station names, abbreviated station umes as used in Figure 1, and the station coordinates are ven in Table 1. This study has two main objectives.

1. I try to recognize where in the western part of the basin e boundary of tectonic structures linked to the opening of e Atlantic Ocean is located (problem of the boundary be- een oceanic and continental crusts). Generally, the available formation does not permit an unambiguous solution. Ac- rding to *Talwani et al.* [1978] the crust in this area was ither continental nor oceanic, but the western basin was derlain by "transitional crust." *Liger* [1980] and *Roussel d Liger* [1983] suggest an oceanic crust possibly located der the Dakar Peninsula. *Van der Linden* [1981] defines the undary of the attenuated African continental crust with the undary between the Jurassic quiet magnetic zone (JQMZ) d the marginal magnetic zone (offshore). At the other ex- me, *Rabinowitz* [1974] placed the ocean-continent boundary well within the Senegal basin and concluded that the basin fill prograted westward over oceanic basement over a distance of about 200 km.

2. I also try to see if structural differences extend deep in the lithosphere and, perhaps more deeply, in the asthenosphere between Phanerozoic and Precambrian Senegal. The presence of a low-resistivity layer at a depth of 30–40 km has been established in the mobile belt and its absence in the craton [*Ritz*, 1982*a*]. Several seismological studies have shown large lateral heterogeneities in the upper mantle between Precambrian continental regions and oceanic regions or continental regions with Phanerozoic orogenic histories [*Jordan*, 1975; *Okal and Anderson*, 1975; *Sipkin and Jordan*, 1976; *Dorbath et al.*, 1983]. Electromagnetic soundings also have been interpreted in terms of lateral variations in electrical conductivity at depths greater than 200 km [*Gough*, 1974; *Garland*, 1981; *Lilley et al.*, 1981*a*, *b*].

GEOLOGICAL AND GEOPHYSICAL FRAMEWORK

The area under study includes sections of three major tectonic provinces: the Senegal sedimentary basin, the Mauritanides orogenic belt, and the West African craton (from west to east).

The Senegal Sedimentary Basin

The Senegal coastal basin, situated on the western edge of western Africa, broadly extends to the boundaries of Senegal as it lies between the 10° and 21° northern parallels (Mauritania and Guinea Bissau). This basin was formed during the Jurassic period before the transgression of the Cretaceous time: then it extended to the Tertiary with a great subsidence

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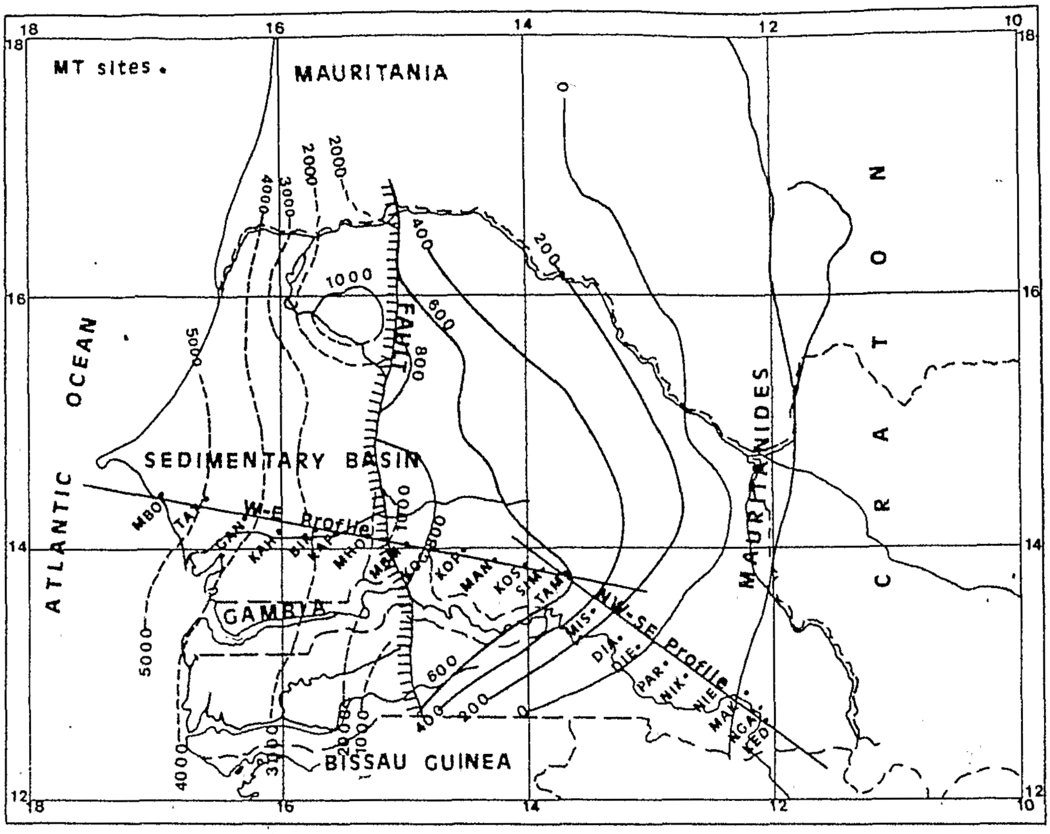


Fig. 1. Map of Senegal basin showing (1) locations of MT measuring sites, (2) the zone of N-S flexures and faults along longitude 15°W, and (3) solid lines: isobaths (in meters) of the top of the basement (dashed lines: unreliable isobaths).

ward the west [*Guetat*, 1981]. During this period, between 10 and 170 Ma, at the end of the different stages of rifting of e Trias, one witnesses the aperture of the Atlantic Ocean ith the formation of new oceanic crust [*Le Pichon and Fox*, 71]. The subsidence and the Mesozoic rifting of the West frican margin, responsible for the formation of the Senegal asin, was very likely accompanied by the intrusion of magatic material into predominantly coast-parallel fissures and fractures [*Van der Linden*, 1981]. The Jurassic is discerned under the form of thick limestones becoming sandy toward the east [*De Spengler et al.*, 1966]. Sedimentation is very active in the Cretaceous; in the western part of the basin (4000 m of Lower Cretaceous age), sediment is prominently placed. In the west the Cretaceous deposits are shales and limestones, whereas in the east, sandstones predominate. The difference in facies is effected along an ancient flexure line about 50 km east of Dakar [*Dillon and Sougy*, 1974]. A regression seems to have taken place at the end of the Maestrichtian period marked by more sandstoney deposits. It causes some deformations NS and NE-SW, and the fractures which accompany them are linked according to *De Spengler et al.* [1966] to some vertical movements of basement abutting on some systems of horsts and grabens. The important subsidence and accumulation of sediments are terminated by the beginning of Tertiary. From late Eocene through Miocene a major regression occurred affecting the coastal basin, the sea withdrawing from the east into the west [*Dillon and Sougy*, 1974; *Liger*, 1980]. At Dakar, volcanism occurred apparently during Miocene and Quaternary [*Hebrard et al.*, 1969].

Geophysical studies have been carried out in the Senegal basin: a gravity study, electrical soundings, drillings, and aeromagnetic profiling. The area between KAH and MBM, showing a strong gravity gradient, is interpreted in terms of thick mafic intrusions within the basement [*Liger*, 1980]. Many electrical studies on the Senegal basin, using Schlumberger array AMNB (AB electrode spacing to 6000 m) give us an idea of the thickness of the sedimentary series underneath the basement [*Compagnie Générale de Géophysique*, 1957]. However, the depth of the investigation is relatively shallow (~1000 m), and the resistive basement easily visible to the east is not

TABLE 1. MT Sites, Code Names, and Geographic Coordinates

Station Name	Code	Longitude W	Latitude N
Bour	MBO	16°57′	14°24′
attaguine	TAT	16°38′	14°24′
andiaye	GAN	16°18′	14°14′
ahone	KAH	16°02′	14°09′
irkelane	BIR	15°45′	14°08′
affrine	KAF	15°33′	14°06′
alème Hodar	MHO	14°18′	13°56′
baye Mbaye	MBM	15°	14°
oungheul	KOG	14°58′	13°59′
oumpentoun	KOP	14°33′	13°59′
alème Niani	MAN	14°18′	13°56′
oussanar	KOS	14°03′	13°52′
inthiou Malème	SIM	13°55′	13°05′
ambacounda	TAM	13°42′	13°48′
issira	MIS	13°30′	13°30′
ialakoto	DIA	13°15′	13°18′
iénoundiala	DIE	13°06′	13°13′
arc	PAR	12°55′	13°07′
iokolo Koba	NIK	12°44′	12°58′
iéménikè	NIE	12°37′	12°55′
ako	MAK	12°20′	12°51′
gari	NGA	12°15′	12°38′
édougou	KED	12°12′	12°36′

ached in the west from the meridian 15°W. Below the deep asin, the nature and depth of the basement are generally nknown. Figure 1 shows the unreliable isobaths of the top of ie basement.

he Mauritanides Orogenic Belt

In Senegal the Mauritanides folded chain divdes into two inges [*Bassot*, 1966, 1969): the easterly branch comprising ie Faleme, Bassaris, and Mali series and the western branch Koulountou chain) with the granitic inliers of Niokolo-Koba. etween the eastern and western branches lies the Youkounoun basin.

The Koulountou series comprises sericite schists and rhyotes with granite fragments along the contact of the Youounkou series and of the sedimentary basin. The Niokolo-oba granite is believed to be a basement to the Koulountou ries (age about 645 Ma). This series is a synclinorium; its istern side is cut by a fault which separates it from the Bassris series. The different elements of the series include white indstones, of a thickness of 300–500 m; red feldspathic sandones (approximately 2000 m); green argilites; and an acid olcanic complex (maybe from late Precambrian).

The Bassaris series represents a narrow belt trending SSW-NE; it is an anticlinorium which includes sericitoschists and eenschists. The series is slightly metamorphosed (greenschist cies metamorphism between 355 and 435 m.y. ago).

The Faleme series constitutes an immense synclinorium ing on the late Precambrian and on the basement rocks of ie Kedougou inlier. Toward the east, the basement rocks are eenschist facies and folded Birrimian pelites, graywackes lolly intruded by acid volcanism. Westerly the Falemian ineases in thickness and includes a thick basal sedimentary-olcanic sequence with spilites (~1000 m). This is overlain by litic sediments, graywackes, and, finally, red feldspathic ndstones. Pillow lavas and ultramafic rocks are also present *Bassot*, 1966].

An early geochronological study in this region confirms the olymetamorphic nature of the Mauritanides: an early Panfrican event, accompanied by intrusion of magmatic material to fractures and characterized by rests of old ultramafic rich rmations; an upper Ordovician tectonism (Caledonian oroeny) which provokes a first structuration of the belt being llowed by late Devonian movements (Hercynian orogeny) hich are responsible for the final form of the Mauritanides. or some authors the two late events may be due to collision fects on the margin of the West African plate [*Dia et al.*, 79].

The geophysical information about the Mauritanides are ite variable, and among the recent published works are ose by *Guetat* [1981] and *Dorbath et al.* [1983]. *Guetat* 981] uses gravity measures along several profiles in the auritanides (Figure 11). The belt of positive and negative avity anomalies is interpreted in terms of a westerly inclined ustal dislocation and a crust thickening in the Mauritanides. *orbath et al.* [1983] suggest that the mobile belt may have en formed in a similar manner to modern back arc basins of stern Pacific. Each basin would represent accumulation of eanic-type volcanics in the interior and arc-type volcanics at e margin of the basins.

he West African Craton

The craton consists of a Precambrian granitized basement iich was consolidated during the final Birrimian graniations at about 1850 ± 250 m.y. The Mako series is formed by a submarine eruptive complex with an ophiolitic tendency. Sedimentary layers, graywackes, and schists are interstratified with the ancient volcanic rocks. The Dialé and Dalèma series, situated farther east, appear to correspond to two parts of one formation separated by the granitic massif of Saraya. They are characterized by the predominance of flysch facies. The metamorphism is very weak. Various granitizations with ages of 2000 to 2100 m.y. affect the series. The three formations have certain characteristics of geosynclines [*Bassot*, 1966; *Bessoles*, 1977].

MAGNETOTELLURIC DATA AND PROCEDURES

The MT stations in this paper are listed in Table 1 and are shown in Figures 1 and 2. Results for sites PAR, NIK, NIE, and MAK were presented by *Ritz* [1982*a*] covering the period range from 20 to 300 s. Interpretation for stations KAH, BIR, KAF, MHO, MBM, and KOG have been discussed elsewhere for the period band from 10 to 1000 s [*Ritz*, 1984]. For all sites a low-frequency band of 0.001–0.1 Hz was used, and long-period MT data up to 10,000 s were also collected at MBO, MHO, SIM, NIK, and MAK. The equipment used has been described in a previous article [*Ritz*, 1982*a*]. Measurements were made during 1 week for the short-period soundings simultaneously with MT recording at SIM. For long-period investigations the maximum period of continuous operation was limited to about 4 or 5 days during an interval of 2 or 3 weeks. For this study, data were sampled at 3-s intervals for the period band 10–1000 s and at 60-s intervals for long-period data.

Reduction of these data followed the methods described by *Sims and Bostick* [1969]. Following *Madden and Nelson* [1964], the spectral estimates were used to determine the surface impedance tensor, the elements of which relate the components of E to those of H via the equation

$$\begin{vmatrix} E_x \\ E_y \end{vmatrix} = \begin{vmatrix} z_{xx} & z_{xy} \\ z_{yx} & z_{yy} \end{vmatrix} \begin{vmatrix} H_x \\ H_y \end{vmatrix}$$

In this equation the components are a function of period and may be complex.

The MT impedance tensor was then rotated into the principal coordinates which, if the structure is reasonably two dimensional, should be aligned parallel and perpendicular to the structural strike [*Thayer*, 1975]. Finally, apparent resistivities ρ_{ij} in units of ohm meters and phases ϕ_{ij} were calculated from the equation

$$\rho_{ij} = 0.2T|Z_{ij}|^2$$

and

$$\phi_{ij} = \tan^{-1} \frac{I_m Z_{ij}}{R_e Z_{ij}}$$

where T is the period in seconds, and z_{ij} an off-diagonal element of the rotated impedance tensor. It is assumed that the source field is uniform. The 90% confidence limits for apparent resistivity and phase were also computed. The ratio of diagonal to nondiagonal terms following the rotation is a measure of the two dimensionality of the medium (skew parameter defined by *Swift* [1967]). It tends to zero for one- or two-dimensional earth structure. Large ratios are a measure of strong three dimensionality.

For the sites taken as a whole the degree of skew is low until about 500 s (≤ 0.3), where it begins to increase to nearly

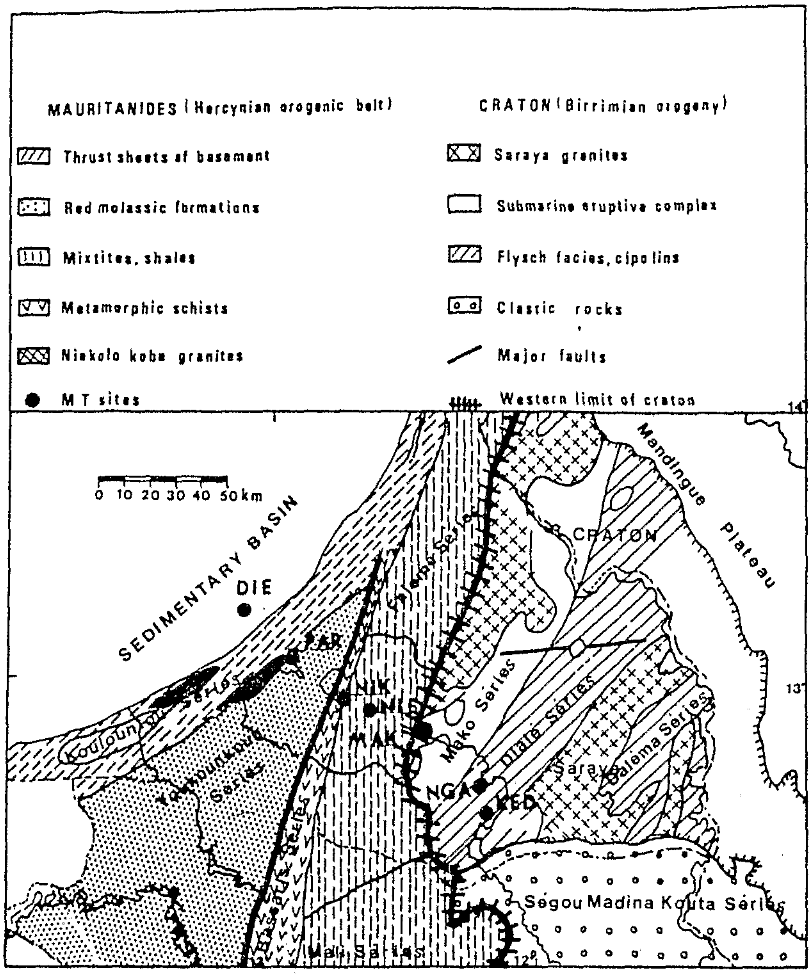


Fig. 2. Schematic tectonic map of Mauritanides and West African craton with MT sounding points (dots).

; at the longest periods for the stations situated on the ecambrian shield. The results of the data processing are the parent resistivity curves ρ_M (major) and ρ_m (minor) associ-ed with the respective phases ϕ_M and ϕ_m in the directions of incipal axes. These parameters are shown in Figures 3 to 6 · the short-period data; the long data up to 10,000 s are own in Figure 7 with the errors bars which represent the indard deviation from the average value. (A lack of bars licates confidence limits less than the size of the plotting nbol.) The azimuth of the major impedance axis is nearly variant over all the period bands analyzed at all sites. The erage major resistivity axes at each site for the short-period nd are shown in Table 2. It can be seen that the axes are ented nearly north-south in the basin for BIR, KAF, MHO, BM, and KOG but are more east-west oriented for sites to ; east. In the mobile belt and craton the directions of the ijor axes are more complicated and change markedly be-een sites and can be related to local contacts or fracture nes in the exposed rocks. The first nine sites in Table 1 have very low anisotropy at short periods; the anisotropy grad-ily increases for the longer periods (Figure 7). The major parent resistivity curves at MBO and MHO reach values s than 300 ohm m at 10,000 s. Generally, both curves at se sites have low error bars (not represented). For stations ther east on the basin the apparent resistivity curves display reasing anisotropy with increasing period, and the maxi-m apparent resistivities are higher. The scatter is larger in the minor curve. In reality, the MT curves in the basin may be separated into two groups: in the first group the plots for the first nine sites where the scatter is low in the minor and major curves and the apparent resistivity less than 100 ohm m in the range of 10–1000 s and in the second group the plots for KOP, MAN, KOS, SIM, TAM, MIS, and DIA where the major apparent resistivity is higher (approximately one or two orders of magnitude).

The most noticeable feature of the resistivity curves for the remaining sites (mobile belt and craton) is the very high degree of anisotropy. The ρ_M curves reach values greater than 10^4 ohm m except for two sites (NIE and KED). The ρ_m curves display considerable scatter: the scatter is lesser in the major curve, and in fact, the phases are not well resolved. The probable explanation for the scatter in the minor curve is a strong polarization of the electric field. The telluric field was found to be highly polarized at most sites, in directions which markedly changed between sites, because of the complex geological structure [*Ritz*, 1982*a*].

INTERPRETATION

The sounding curves of the first group, where anisotropy is low and the skew less than 0.1, may be fitted to layered models according to an inversion modeling scheme [*Jupp and Vozoff*, 1975]. For the other sites the value of the skew is low for periods less than 500 s, and the apparent resistivity curves show anisotropy, some more than others. At longer periods

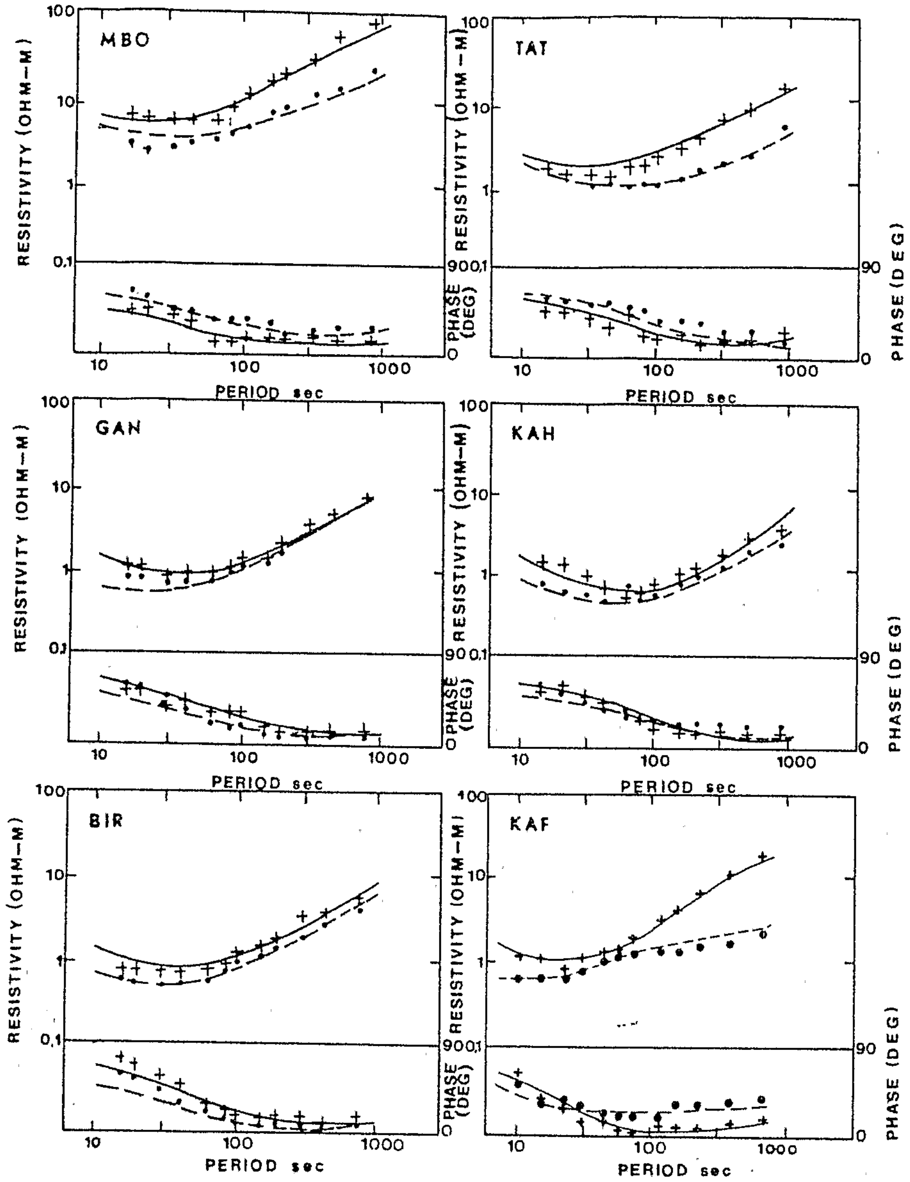


Fig. 3. Apparent resistivities (ρ_M and ρ_m) and phases (ϕ_M and ϕ_m) computed from the nondiagonal elements of the rotated impedance tensor for the period band from 10 to 1000 s (stations MBO, TAT, GAN, KAH, BIR, and KAF). The solid lines are theoretical resistivity and phase curves computed for the two-dimensional models in Figures 9 and 10.

e anisotropy and the skew become larger, and the resistivity ucture along the Precambrian profile is probably very com- cated. Although the parameters used in the short-period nd have a two-dimensional character, the possibility of elec- c current channeling cannot be ignored, and the problem is e of three-dimensional induction over a very wide area *ailey et al.*, 1974; *Park et al.*, 1983]. For all the sites the unding curves, were approximated by one-dimensional odels for the component of the electric field parallel to the ike of the discontinuity [*Ritz*, 1984]. Interpretation of MT rves in terms of layered models is not always a satisfactory ocedure, particularly when there is a reason to expect lateral nomogeneities in the geoelectrical structure. The models, de- rmined on the basis of these curves, differ from each other. ese one-dimensional models may only be regarded as first proximation. With the above reservations in mind, it was cided to employ two-dimensional modeling techniques to ovide some information on conductivity structure.

The objective of two-dimensional modeling is then to convert these starting models into a model representative of the geoelectric structure which fits the observed data well for the two modes of polarization of the electric field. The starting two-dimensional models use geophysical and geological data as a constraint (fracture tectonics, the varying thickness of surface sediments, gravity and magnetic data, etc). *Fournier and Metzger* [1969] have shown that the coast effect at MBO is insignificant, and thus in the two-dimensional modeling, it has been assumed that the basin structure extends 60 km west of MBO. The surface layer was not determined by the forward procedure but is included to model the known sediments for the top 1000 m.

Computations of particular two-dimensional models were then carried out, following the methods of *Rijo* [1977] and *Stodt* [1978]. Thirty models were investigated, each one at several different periods (10, 30, 100, 300, and 1000 s) in order to obtain the best fit for the experimental data. The computed

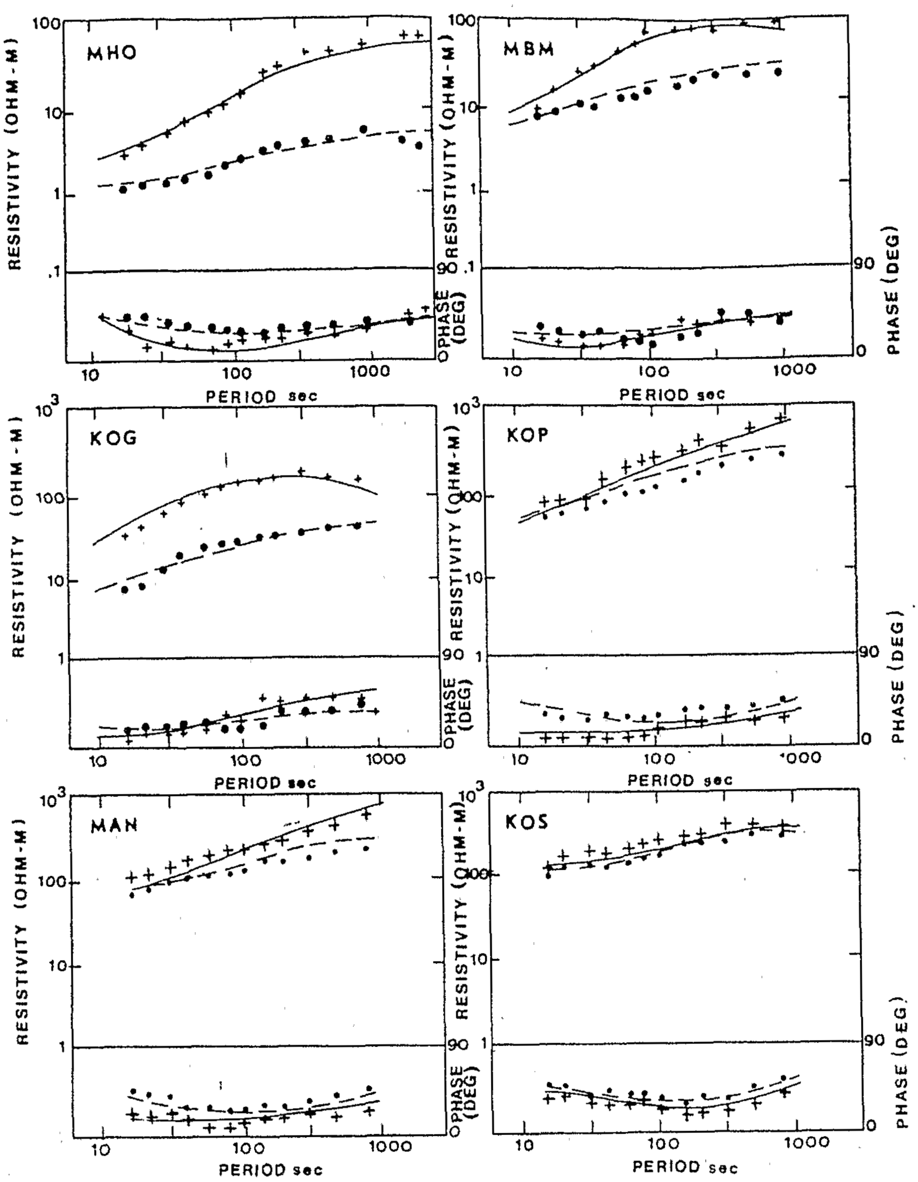


Fig. 4. Same as Figure 3 for sites MHO, MBM, KOG, KOP, MAN, and KOS.

esponses of the final model are shown in Figures 3–8 with the bserved apparent resistivities and phases at each site (connuous lines). In general, for the sites in the basin the agreeient is good for both the major and the minor curves. Howver, in the shield it was not always possible to fit the minor xis resistivity because it had low amplitude and high scatter. or PAR, NIK, NIE, MAK, NGA, and KED the strong fluciations in the phases did not allow a reasonable interpretaon, and so they are not presented in this paper. Figure 9 iows the west-east resulting resistivity cross section across ie Senegal basin, derived from two-dimensional MT modling, and Figure 10 shows a northwest-southeast cross section cross the east part of the basin, the mobile belt (Mauritaides) and West African craton. Although the twoimensional resistivity models illustrated in Figure 9 and 10 ive results which approximately correspond to the field reilts, the uniqueness of these models cannot be guaranteed ecause of the number of assumptions involved. Several iodels with an uniform crustal conductivity in the Senegal asin were unsuccessful at predicting the observed apparent sistivities and phases [*Ritz*, 1984]. We have classified the regions of Senegal on the basis of these two-dimensional numerical models and then considered the geologic and tectonic significance of four cross sections.

Region 1: The Deep Basin

This area is located between the Atlantic coast on the west and extends as far as the zone of N-S flexures and faults along longitude 15°W (MBO, TAT, GAN, KAH, BIR, KAF, MHO, MBM, and KOG). The uppermost low resistivity layer of 15 ohm m with a thickness of about 700 m corresponds to Quaternary sediments. The second sedimentary layer dips from east to west, 2000 m at MHO and more than 5000 m at MBO; this thickening of the deep basin is in agreement with the isobath map of the top of the basement (Figure 1). Resistivities are very low: between about 0.5 and 5 ohm m. This layer corresponds to Infra-Maastrichtian formation (Cretaceous), and the most likely explanation is that there is highly interstitial saline water in this area. An important discovery is the presence of a conductive layer of about 20–30 ohm m below the deep basin and which extends at a depth of 10 km. The resistive layer (~ 1000 ohm m) below is interpreted as crystalline basement.

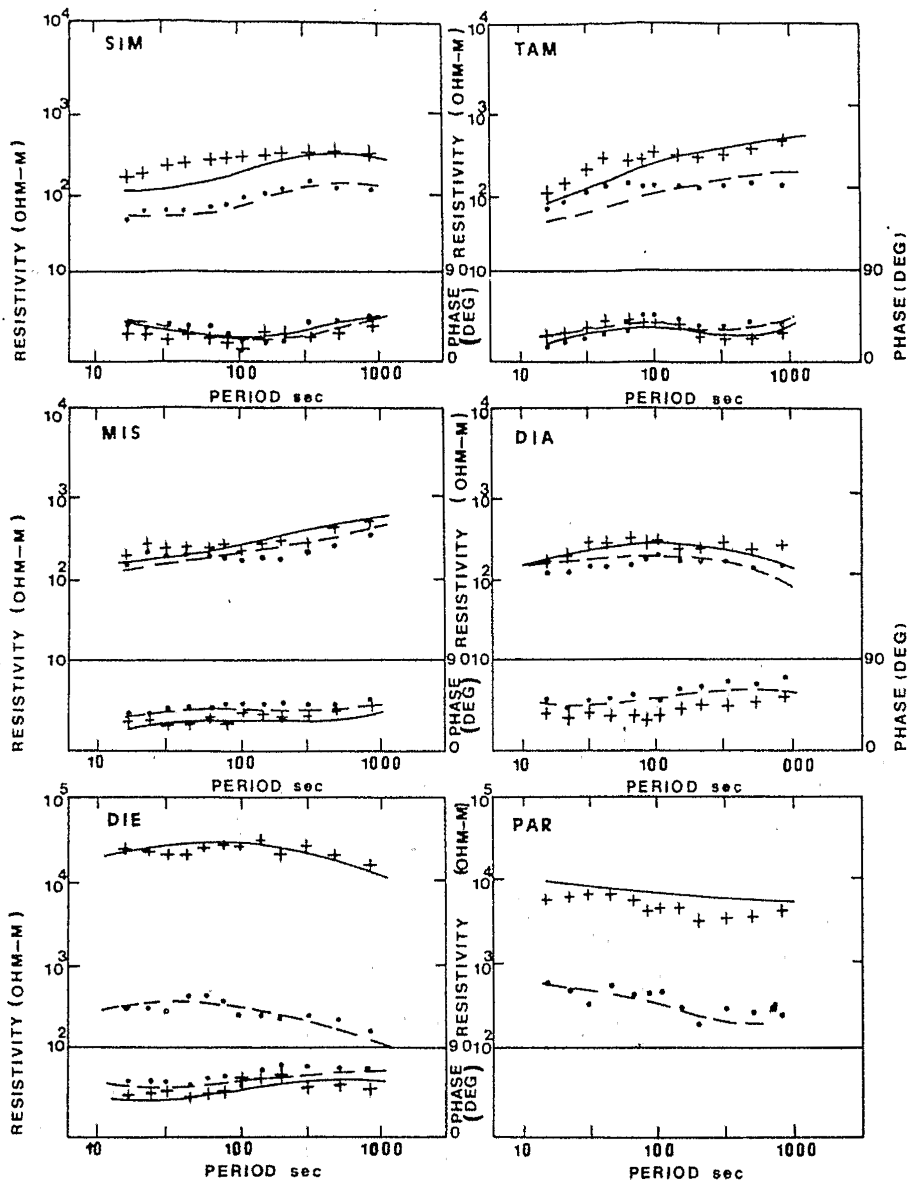


Fig. 5. Same as Figure 3 for sites SIM, TAM, MIS, DIA, DIE, and PAR.

nder the deep basin the crust/upper mantle transition does ot appear to be associated with a pronounced conductivity ansition in the range 20–40 km, and the highly resistive 000–2000 ohm m) layer extends to a depth of about 300 km. he resistivity decreases to 10 ohm m for depths below 300 n.

egion 2: Eastern Basin

This zone is characterized by the presence of a relatively ghly conducting layer in the lower crust. The resistivity is out 50 ohm m at depths between 20 and 30 km. The model sults show that in decreasing (or increasing) the depth of the nducting layer in the crust (or upper mantle), there is a vergence between the empirical data and the model values utside error bars). The structure of the upper mantle is the me as region 1 (Figure 9).

gion 3: Mauritanides or Mobile Belt

This region is remarkable in several ways. First is the deeping of the conductive level in the crust. The depth of the nductive layer seems to go from 20 in the west to 30 km in e east. This boundary is clearly marked by the gravity anomalies in Senegal (Figure 11). The anomaly pattern typically consists of positive anomalies in the marginal part of the eastern basin and slightly negative anomalies in the craton, and between these two regions are the Mauritanides, which are marked by strong variations of the Bouguer anomaly. The pattern has been interpreted by *Crenn and Rechenmann* [1965] in terms of a crustal dislocation and a thickening of the crust underlying the mobile belt. In this area one encounters a highly resistive (~ 5000 ohm m) prism; it extends to a depth of 10 km. Gravity studies carried out by *Guetat* [1981] have shown in the western part of the Mauritanides orogenic belt the existence of a large anomaly: the Gamon anomaly (Figure 11). This anomaly is interpreted as an intrusive body rooted at about 9500 m within the crust (about 650 m.y. ago). The highly resistive material could be related with a dense body which intrudes along a major crustal discontinuity during the upper Precambrian.

Region 4: West African Craton

The three sites occupied in this zone have a markedly different behavior from those in region 3, the abence of the conducting layer marking the crust/upper mantle transition and a

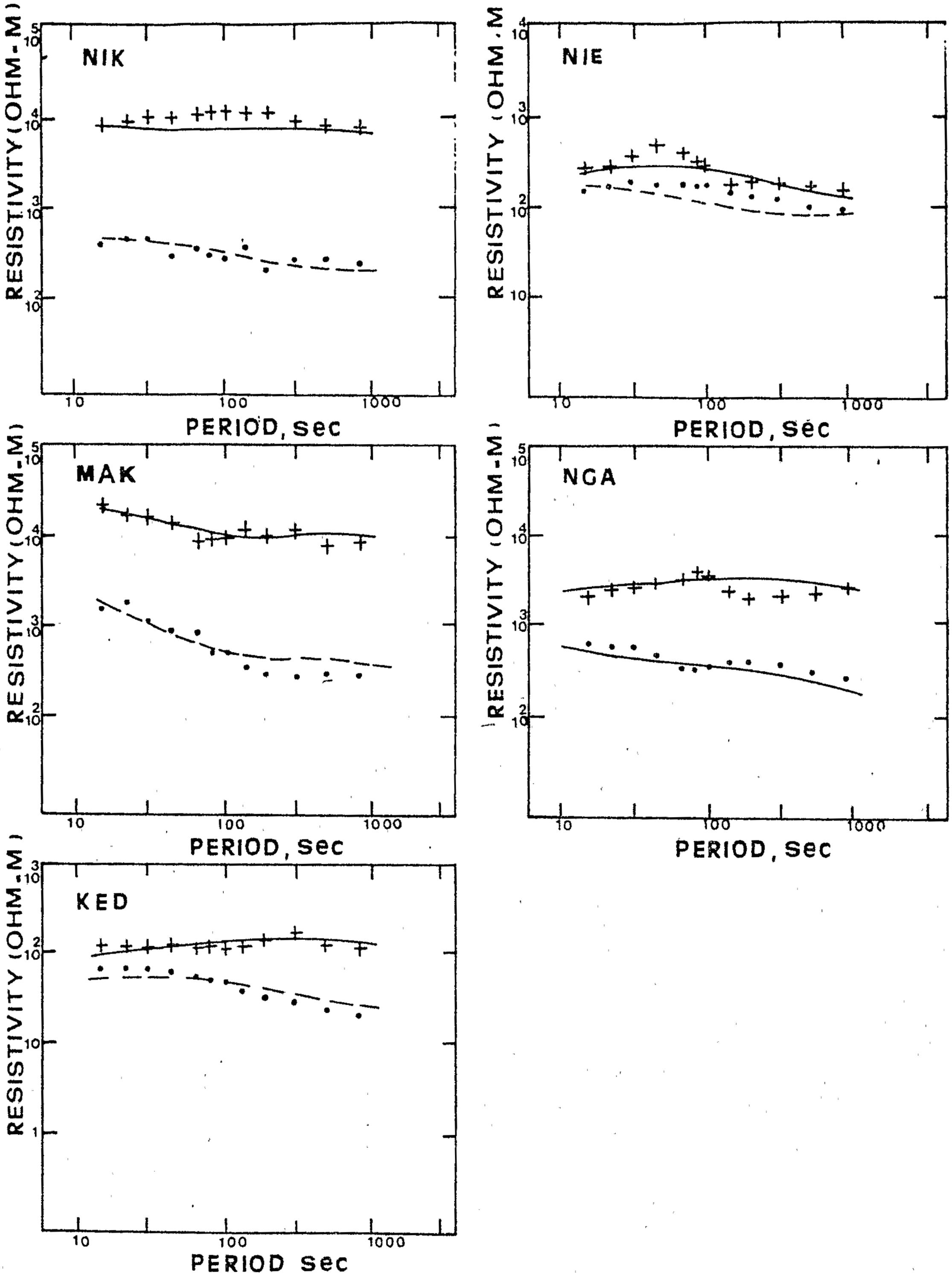


Fig. 6. Apparent resistivities (ρ_M and ρ_m) calculated from impedance tensors which have been rotated into principal axes for the period range 10–1000 s for NIK, NIE, MAK, NGA, and KED.

pid deepening of the conductive level in the upper mantle. r the site Kedougou (KED) the addition of a conducting er at depths between 10 and 30 km makes it possible to get etter fit to the data. No exact information can be obtained the lateral extension of this layer at the present stage be- use of the lack of measurements in this region. However, ng the differential geomagnetic sounding, *Albouy et al.* [1982] show a large conductive anomaly inside the craton along direction 30°E at KED which could extend northward over a distance of about 250 km (Mali) and eastward up to Guinea. Maximum depth estimates indicate that the causative currents flow at a depth of less than 50 km. The MT method could be used to map the northward and southward extent of this crustal conductor.

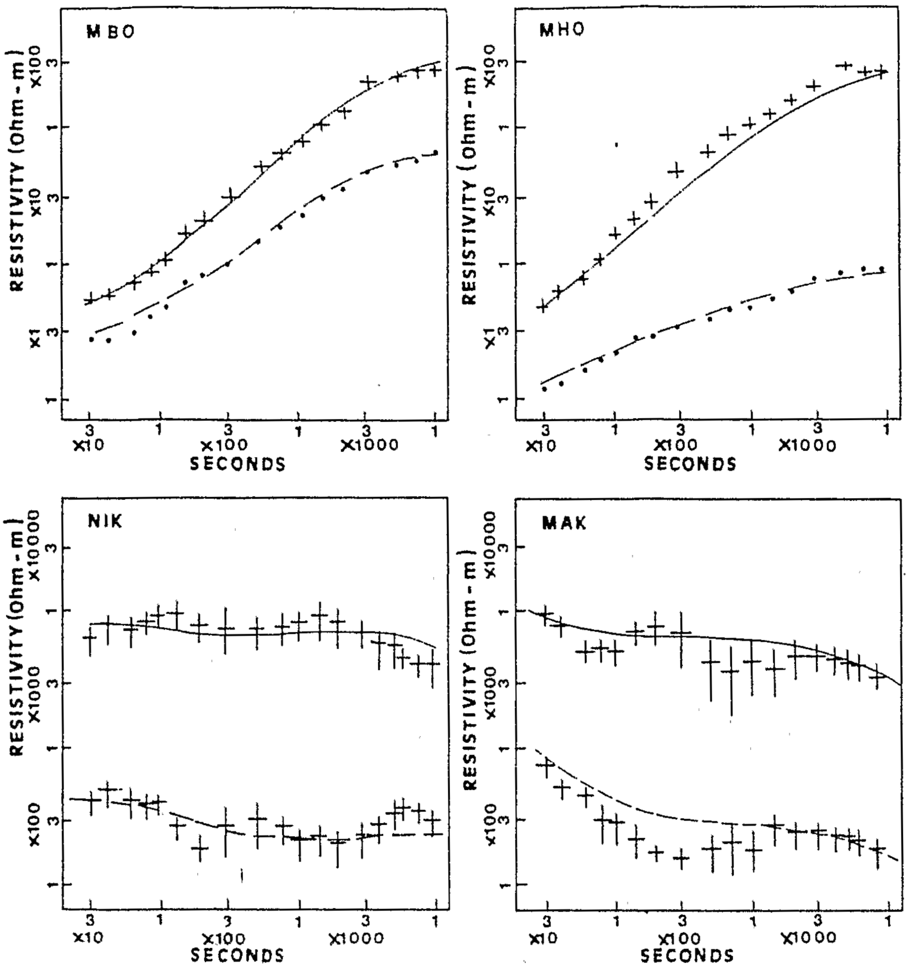


Fig. 7. Apparent resistivities (ρ_M and ρ_m) calculated from impedance tensors which have been rotated into principal axes for the period range 30–10,000 s for MBO, MHO, NIK, and MAK.

TECTONIC SIGNIFICANCE OF RESISTIVITY MODEL: DISCUSSION

Figures 9 and 10 show some lateral inhomogeneities on the vel with tectonic provinces (basin, mobile belt, and craton). 'e have in view to connect these discontinuities in the crust ıd upper mantle to main tectonic events that have taken ace in West Africa.

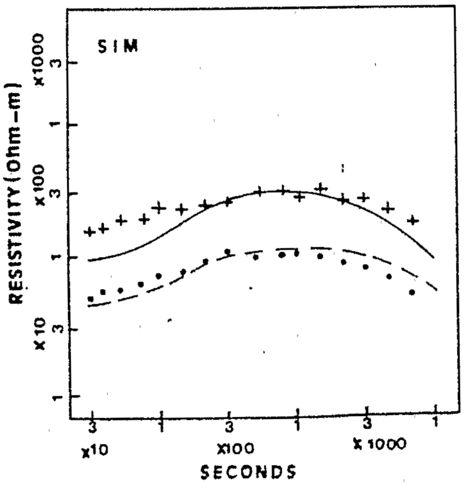


Fig. 8. Similar to Figure 7 for SIM.

Sedimentary Basin

The basin is poorly known from its surface geology. Below the basin, west of about 15°30′W, the basement slope increases, and the sediments markedly thicken seaward (Figure 1). What is known about the tectonic history of the Senegal basin may then help in finding answers to the conductive zone situated in the upper crust which runs approximately east-west from the north-south zone of flexures and faults (15°W) to the Atlantic coast. The major tectonic movement in this area is the continental separation of Africa and North America that began presumably in early Mesozoic about 180 m.y. ago or possibly in Paleozoic time [*Le Pichon and Fox*, 1971; *Dewey et al.*, 1973]. The Mesozoic rifting responsible for the formation of the basin has been accompanied by intrusion of basic igneous rocks into fissures and fractures during the continental fragmentation and contributes to an alteration of the original continental crust. *Aymé* [1965] states that a major subsidence started as early as the Jurassic. *Burke* [1976] reveals the existence of a graben (developed between 210 and 170 m.y. ago) between 50 and 100 km wide, striking for 400 km on shore (Casamance graben), associated with initial rupture of the Atlantic Ocean. *Burke and Whiteman* [1973] have shown that numerous rift systems in Africa have ceased their stage of development during the last 200 m.y. and never reached the complete ocean-opening state. Recent studies, car-

TABLE 2. Orientation of the Principal Axes of the Impedance Tensors (Clockwise From North)

Site	Orientation
MBO	54°
TAT	68°
GAN	45°
KAH	33°
BIR	13°
KAF	13°
MHO	7°
MBM	16°5
KOG	17°
KOP	48°
MAN	66°
KOS	undefined
SIM	62°
TAM	77°
MIS	72°
DIA	66°
DIE	−42°
PAR	−27°
NIK	−85°
NIE	14°
MAK	77°
NGA	−50°
KED	20°

ied out about 100 km in the north of this profile, also show he existence of the conductivity anomaly. It is interesting to ote the anomaly appears to be associated with an important inear positive magnetic anomaly (Figure 12). This aeronagnetic feature appears to be consistent with intrusive odies [*Roussel and Liger*, 1983]. This anomaly is also aligned arallel to the zone of N-S flexures and faults along longitude 5°W. These main features can mark the location of a rift zone oundary, which is underlain by a sharp discontinuity in the rust across which normal continental crust abruptly changes o the anomalous crust (rift zone). *Roussel and Liger* [1983] uggest that the crust in the Dakar Peninsula, where the basin considerably thicker (10,000 m or more), changes toward a rust of oceanic character. This boundary between oceanic nd continental crusts is marked by a steep gradient in the isostatic gravity profile, associated with an important linear magnetic high. This coastal magnetic anomaly was a direct continuation landward of the boundary of the magnetic quiet zone.

It is unlikely that the marginal basin was rifted with a clean break at this boundary (Dakar Peninsula) but rather, as suggested by *Talwani and Eldholm* [1973], was probably preceded by a phase of stretching and thinning of the continental crust achieved in part by faulting. The conductor in the marginal basin has a resistivity of less than 30 ohm m. These processes could lead to the decreasing of the resistivity as a result of increased porosity and electrolytic conduction [*Thayer*, 1975; *Van Zijl*, 1978]. As recent tectonic movements (Neogene volcanism) are located in the Dakar region [*Templeton*, 1971], the influence of temperature on lower crustal rocks is unlikely in the rest of the basin.

A distinct facies difference between the eastern and western parts of the basin may be related to the existence of a rift graben structure linked to the initial opening of the ocean. It is suggested that the low inferred resistivities might arise from the presence of such a buried failed rift; the anomalous crust is the relic of a large ancient rift zone crust. I believe that it would be appropriate to say that the marginal sedimentary basin, which extends over a distance of about 200 km, is underlain by transitional crust [*Talwani et al.*, 1978]. Unaltered crust of the basin continues to the rim of the rift. No refraction data control is available for the Moho in this area. It is important to establish the presence of the boundary between oceanic and continental crusts in a rifted margin basin. As outlined here, from MT data the transitional ocean-continent boundary was characterized by a rapid thickening of the basin and an important contrast between the crustal material inside and outside the anomalous structure.

The following sequence of events is suggested. The tensional regime set up along West Africa caused the fracturing of an area referred to as the margin basin. Basalt flows or magmatic intrusions intruded along existing regions of weakness that are the basement fractures. Very active sedimentation since the Cretaceous followed causing the rift valley to be buried under

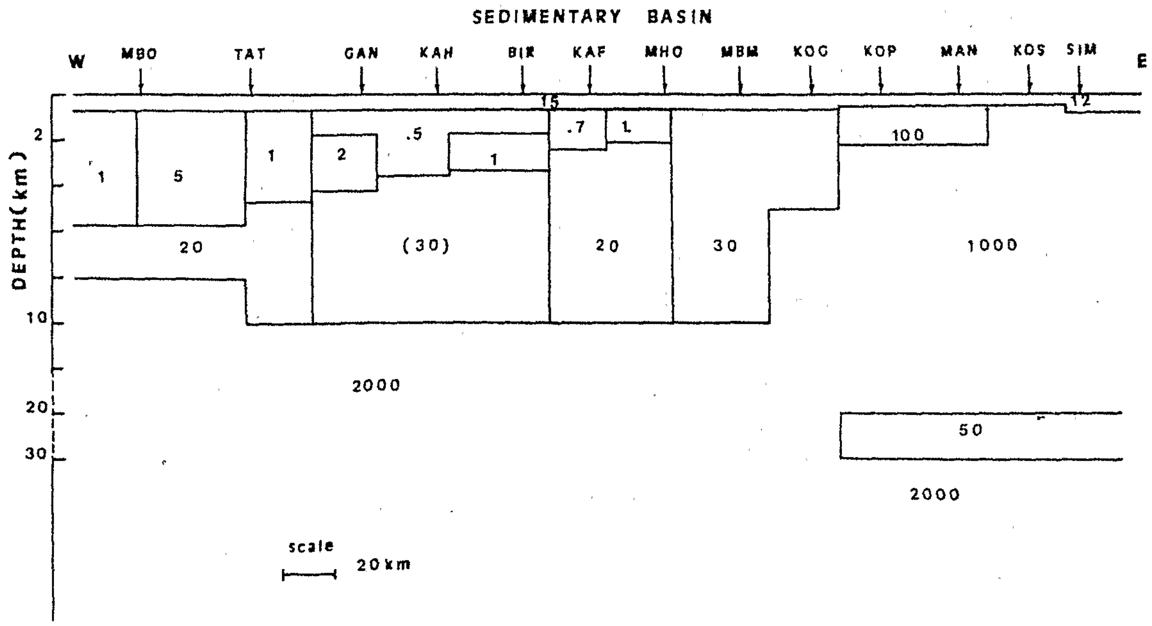


Fig. 9. Two-dimensional model resistivity profile across the Senegal sedimentary basin. The numbers indicate resistivities in ohm meters. Note the nonlinear depth scale. The parameter in parentheses is poorly resolved.

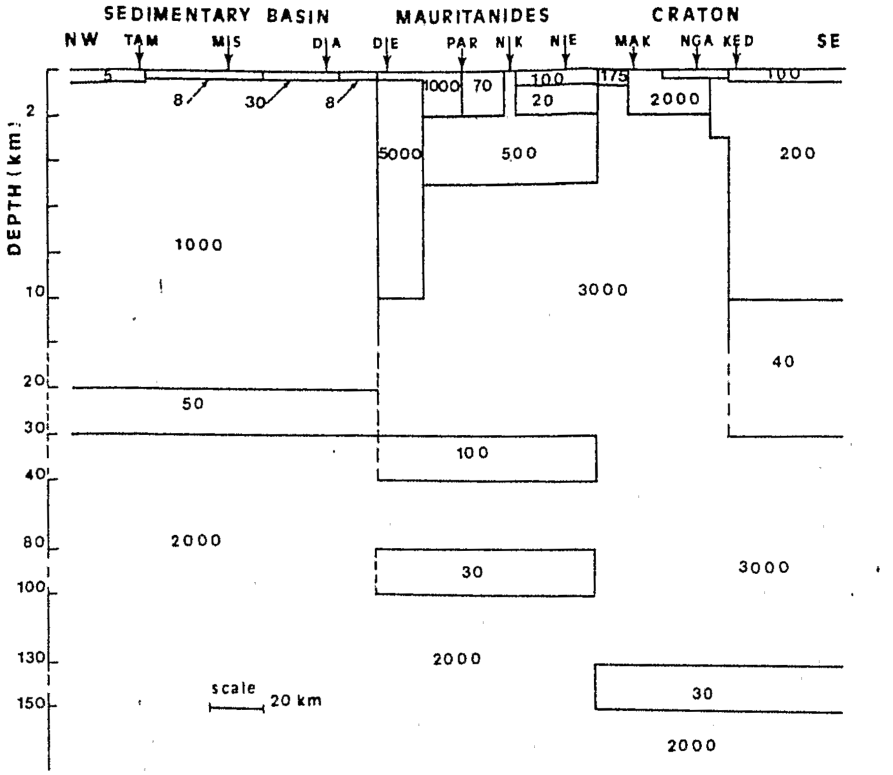
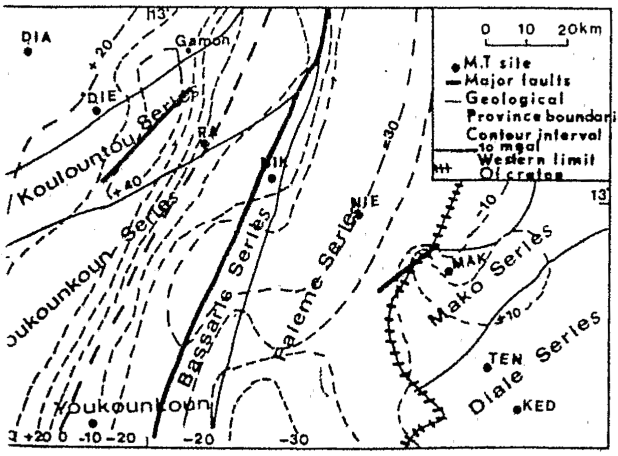


Fig. 10. Two-dimensional model of the resistivity distribution beneath Mauritanides and West African craton. The numbers indicate resistivities in ohm meters. Note the nonlinear depth scale.

lesozoic and Cenozoic sedimentary cover. The crust in this gion was of continental origin with strong contamination by asaltic intrusion (transitional crust).

Geomagnetic induction anomalies have been ascribed to the esence of narrow bands of oceanic material buried in the ntinental crust [*Drury and Niblett*, 1980]. The lowering of sistivities in the lower crust is caused by the presence of rpentinized ocean rocks [*Stesky and Brace*, 1973]. *Rabino-itz* [1974] states that the western part of the Senegal basin is tuated on an oceanic crust and that the basin has been filled ith sediments and prograded seaward over a distance of at ast 200 km. *Dillon and Sougy* [1974] showed a general sea-ard migration of the West African shore line from the Eocene to the end of the Oligocene. It appears, therefore, that the suggestion that the basin anomaly is caused by the presence of buried ocean crust should not be dismissed. Because of the lack of other geophysical data (seismic refraction profiling,



ig. 11. Bouguer gravity map of the Mauritanides and West Afri- craton [*Crenn and Rechenmann*, 1965]. The contour interval is 10 al, and the dots indicate the locations of MT sites.

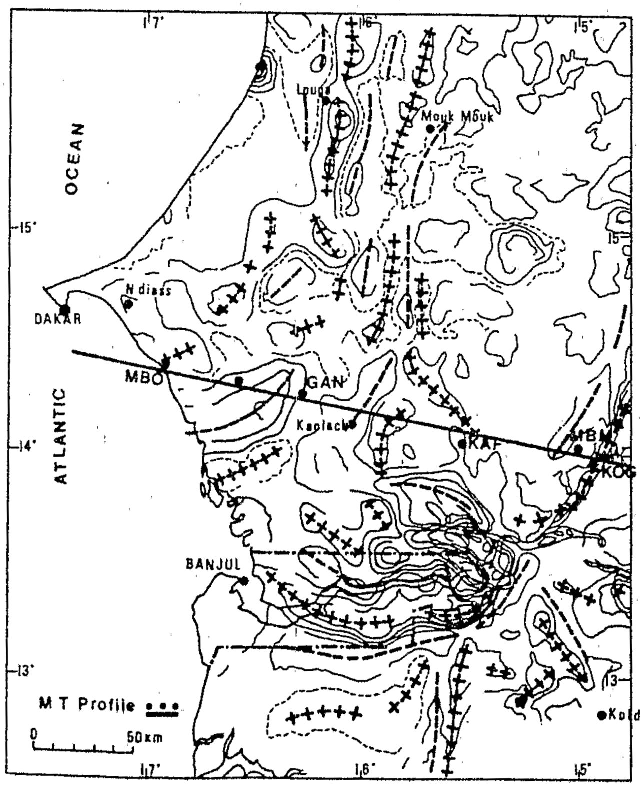


Fig. 12. Regional aeromagnetic map of the Senegal basin after *Roussel and Liger* [1983]. Lines of crosses: magnetic highs; dashed lines: magnetic lows. Dots represent MT sounding points.

heat flow measurements) it seems impossible at this stage to arrive at a unique interpretation of this anomaly.

The high resistivities below the crustal conductor do not decrease for several hundred kilometers. The depth of the conducting layer in the upper mantle is about 300 km under the whole of the basin, and its resistivity is 10 ohm m (ultimate conducting layer). This layer can be identified with the olivine-spinel phase transition. Such a rise is consistent with the sharp increase in averaged conductivities noted in global studies [*Garland*, 1981]. MT soundings in continental areas imply that a general reduction in mantle resistivity takes place between 60 and 120 km base of lithosphere [*Fournier et al.*, 1971; *Drury*, 1978]. It is possible that the resistivity increases before undergoing the abrupt rise at a depth of about 400 km [*Gough*, 1974; *Camfield and Gough*, 1975]. No conducting layer exists at asthenospheric depths (assumed to extend from 100 to 300 km). Many authors regard this case as a characteristic signs regions where the asthenosphere is poor [*Vanyan et al.*, 1977]. According to *Pollack and Chapman* [1977] the lithospheric thickness over West Africa is in the range 300–400 km.

Mobile Belt

Plate tectonic concepts have given new definitions to orogenic events and geosynclines by relating them to lithosphere plate interactions. Geosynclines are interpreted now as sedimentary troughs and volcanic islands along rifted continental margins, and those geosynclines that occur as fold belts within continental blocks represent sutures where oceans are closed and where continents have collided. This model explains the siting of orogens at continental margins through subduction and continental collision [*Wilson*, 1966; *Williams and Stevens*, 1974]. The Appalachian-Caledonian orogen has been taken to be a belt of this type from the plate convergence that caused closure of a Proto-Atlantic ocean [*Bird and Dewey*, 1970]. The relevance of the plate tectonic model to the tectonic and metamorphic events of the Mauritanides is not easy. A model for orogenic evolution through continental collision, ocean cloure, and ensuing crustal thickening with basement reactivation was presented by *Burke and Dewey* [1973].

The ancient continental margin of West Africa can be defined as the Mauritanides fold belt that was an integral part of he West African craton in the early Proterozoic [*Guetat*, 981]. The limit of this zone coincides with several significant eological and geophysical changes as follows: (1) it is the eastern limit of Precambrian basement inliers, (2) a volcanic rend is reported in the Mauritanides fold belt: basic volcanism in the Faleme trough and calc-alkalic in the Youounkoun basin (Infracambrian or perhaps late Precambrian), 3) it is a zone of faulting, contrasting structural style, and contrasting metamorphic facies, (4) the zone is coincident with regional gravity gradient (Figure 11) from positive Bouguer anomalies on the western side of the Mauritanides (ridge Kouountou) and to negative values on the eastern side (Faleme ough), (5) it is marked by contrasting seismic profiles that eflect deep structural contrast, and (6) the MT model shows a ustal thickening below the Mauritanides, and a major discontinuity extends deep in the lithosphere on the western dge.

Some aspects of the Mauritanides are possibly consistent with an old subduction zone. *Dillon and Sougy* [1974] suggestd the presence of a subduction zone during the Silurian and parts of the Ordovician and Devonian. Recently, *Dorbath et al.* [1983] have suggested that the discontinuity zone of the eastern Senegal basin (the Missira discontinuity) could be interpreted as marking a late Precambrian subduction zone. Their proposed subduction zone dips steeply to the east. A major discontinuity extends deep in the lithosphere from the surface to 150–200 km. Unfortunately, no seismic data indicating the lithospheric thickness exist for this region. It is interesting to note that the MT model also found that a similar discontinuity occurs 130 km inside the sedimentary basin between MIS and DIE. Another discontinuity exists at a depth of 300 km (lithosphere?).

It is convenient at this stage to propose a sequence of tectonic events which account for the known geological and geophysical data. In early Proterozoic time the West African craton and mobile belt formed part of the Archean craton adjacent to an ocean. During an end of Precambrian to Cambrian time, there is the individualization of the Faleme trough (marginal basin) inside the Archean craton, with the distribution of basic volcanics (Faleme trough) between two zones with rhyolitic and andesitic volcanics (Youkounkoun basin and eastern side of the trough) that are similar to those of interarc basins. Volcanic rocks, probably of subductional origin, give us an idea about the maximum subducting activity time (Infra-Cambrian or late Precambrian). The collisional suture, marked by arc-type volcanics at the margins of the basin, must be located in front of the arc, perhaps near it, in the present sedimentary basin. As is consistent with the volcanic arc, it is suggested that the heterogeneities located in the lithosphere at the west of the margin of the West African craton could be interpreted as marking an old subduction zone dipping to the east. During the Cambrian to upper Ordovician time interval, the mechanism of closure of the marginal basin is not clear, but it resulted in the formation of Bassari and Koulountou ridges with a collision with a western continental basement (present sedimentary basin). During this Caledonian event the crust is remobilized following the zones of weakness, presumably as the convergent plate is consumed in the Mauritanides.

The West African Craton

The West African craton in eastern Senegal has been intensely affected by the Eburnean orogen (1850 ± 250 m.y.) and contains principally Birrimian formations (lower Proterozoic). The Dialé, Dalêma, and Mako series have certain characteristics of geosynclinal formations [*Bassot*, 1966; *Bessoles*, 1977]. The Mako series formed by a submarine eruptive complex with an ophiolitic tendency, sedimentary layers, graywackes, and schists interstratified with the ancient volcanic rocks corresponds to the eugeosynclinal basin. An andesitic volcanism started in this region with the development of Cordilleran belts. The Dialé and Dalêma series are essentially nonvolcanic, with the predominance of flysch facies, and correspond to the miogeosynclinal basin. During the geosynclinal stage, various granitisations affect these formations (Kakadian and Saraya batholiths). These intrusives outcrop within the eugeosyclines and miogeosynclines.

On the basis of tectonic events the following question is to be considered: Is it possible that the Proterozoic province of the Senegalese craton may have been related to ocean opening and continental collision in a way similar to orogenic belts in the Phanerozoic [*Burke et al.*, 1977]. Some salient geologic features of the west edge of the craton can be related to plate tectonic concepts: (1) the existence of Birrimian geosynclinal

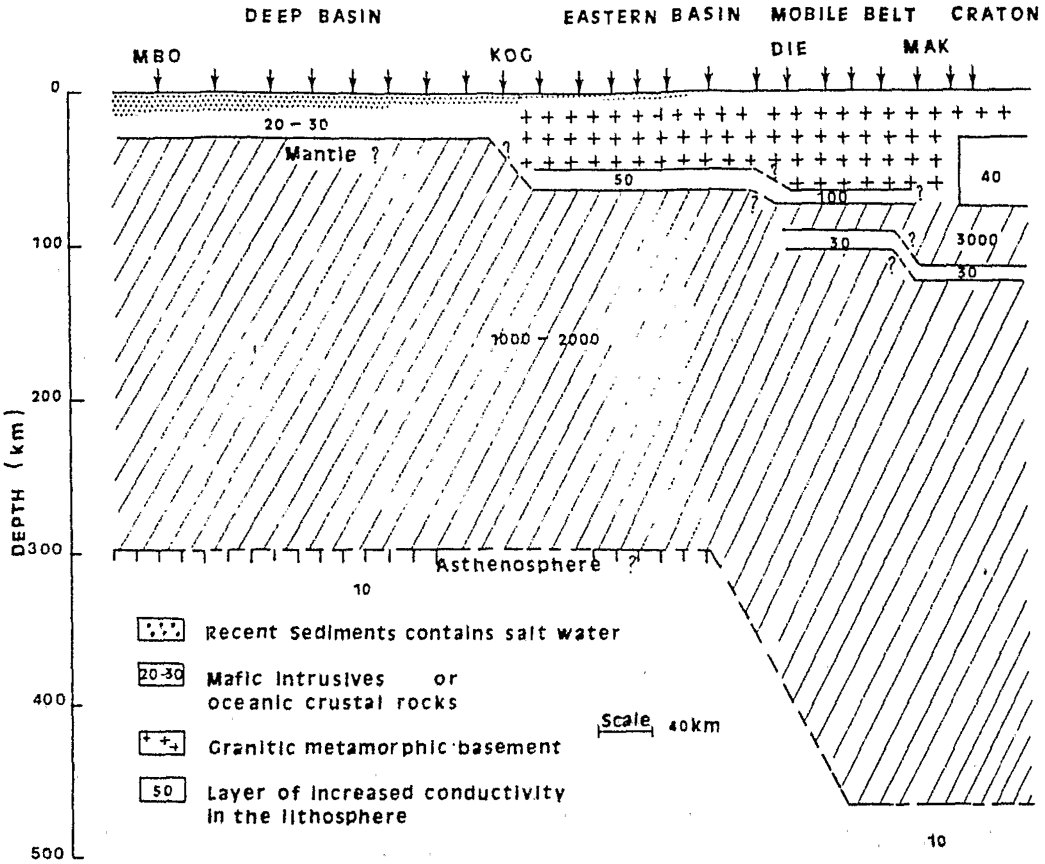


Fig. 13. Schematic generalized electrical model of the lithosphere showing the conductive layers which have been detected. The numbers indicate resistivities in ohm meters.

sedimentary and volcanic assemblages, particularly volcanics with ophiolite affinity, (2) the existence of molasse deposits, (3) the presence of Birrimian granitoid batholiths and andesitic volcanism, and (4) the production of granodiorite in the Mako series.

It is customary at present to regard all ophiolite sequences as representatives of oceanic lithosphere and to postulate that they were emplaced on continental margins by compressive thrusting, possibly above a zone of subduction [*Karig*, 1970]. It is indeed possible that those Birrimian ophiolites associated with the flysch deposits were emplaced in some such manner. Another possibility is that the ophiolites might represent the effects of collision with island arcs [*Sugimura and Uyeda*, 1973]. It is commonly considered that andesitic volcanicity at continental margins is related to subduction of oceanic crust, and if this is true, subduction has been active in eastern Senegal during Proterozoic. Accordingly, it would seem that eastern Senegal was initiated during a regime of eastward directed subduction and that the formation of the eugeosynclines and miogeosynclines together with attendant volcanicity took place under the same plate tectonic regime of subduction. The subduction is associated with the ascent of melt and the remobilization of the cratonic crust.

The only complication to this simple picture is the emplacement of a conductive lower crust under the miogeosynclinal basin (KED) and its absence under the eugeosynclinal zone (MAK). The Moho does not appear to be associated with a pronounced conductivity transition for sites MAK and NGA. Using the differential geomagnetic sounding (DGS), the course of the crustal low-resistivity layer can be traced continually from eastern Senegal across the craton to western Mali, over 300 km long [*Albouy et al.*, 1982]. It is interesting to note that the belt of rocks of high conductivity, discovered in North America [*Camfield and Gough*, 1977] over a distance of 1400 km, could be interpreted as the trace of a Proterozoic subduction slab. High conductivity might be associated with oceanic crustal material incorporated into the miogeosynclinal basin. Serpentized basalts, perhaps typical of oceanic crustal material, have shown high conductivity [*Stesky and Brace*, 1973]. The high crustal conductivity might also be associated with hydration processes at depth [*Hyndman and Hyndman*, 1968]. Water-saturated granites exhibited a dramatic lowering of both resistivity and melting temperature [*Lebedev and Khitarov*, 1964]. More recently, *Drury and Niblett* [1980] have suggested that some crustal conductivity can be explained by a hydrated oceanic layer containing saline-free water. The high conductivity associated with the Birrimian geosyncline is analogous to the geosynclines of southern Africa [*De Beer and Gough*, 1980; *De Beer et al.*, 1982] and North America [*Whithman*, 1963; *Edwards and Greenhouse*, 1975]. The question of a conductive layer in the lower crust is fraught with difficulty, but in the present state of knowledge, interpretations are likely to remain speculative.

Discussion of the Deep Heterogeneities

Seismological studies have shown that structural differences may exist through the upper mantle beneath continental regions between Phanerozoic and stable Precambrian regions [*Sipkin and Jordan*, 1976; *Lilley et al.*, 1981*a*, *b*; *Dorbath et al.*, 1983]. *Lilley et al.* [1981*a*, *b*] indicate that there is a major conductivity increase at about 200 km depth under Phanerozoic Australia but not until about 500 km depth under Precambrian Australia. In this continental region, lateral heterogeneities possibly extend to depths as great as 500 km. *Dorbath et al.* [1983] have reported regional differences in seismic velocity structure between cratonic areas and continental platforms, which appear to exist at depths greater than 150 km. Lateral variations of *S* travel time residuals occur between oceans and continents and extend deeper than 400 km [*Okal and Anderson*, 1975]. Magnetotelluric measurements in Senegal (Figure 13) show structural differences extend at about 130 km depth in lithosphere between Proterozoic and Phanerozoic provinces (craton and mobile belt). However, the more substantial difference in conductivity structure appears between craton/mobile belt and sedimentary basin where lateral inhomogeneities possibly extend to depths as great as 460 km. It appears that the MT sites in the eastern part of the West African craton (Upper Volta and Niger) have very similar conducting layers in the lithosphere [*Ritz*, 1983]. The Dori site (latitude 14°02′N, longitude 00°02′W) where long-period MT were carried out [*Ritz*, 1982*b*] shows that the top of the ultimate mantle conductor is at a depth 460 km. It is interesting to note the broadly analogous development of the eastern and western parts of the West African craton, and thus it is possible to think that the eastern province may have been related to subduction in a similar way to the western part of the craton (Senegal). The model of plate convergence and oceanic closure has been applied to the Pan-African event along the eastern margin of the West African craton [*Caby*, 1970].

REMARK

Not much accurate information can be obtained on the age and grade facies of the regional metamorphism as well as the age of tectonic events at the present stage, and it is difficult to indicate unambiguously the exact chronology of events that have taken place in the mobile belt and West African craton.

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