TECTONIC INTERPRETATION OF ELECTRICAL STRUCTURES BENEATH THE WEST AFRICAN CRATON EDGE IN EASTERN SENEGAL

MICHEL RITZ* and BERNARD ROBINEAU**

ABSTRACT. Recent measurements of the electric and magnetic fields (magnetotelluric method) in two traverses across eastern Senegal, from the Senegal coastal basin to the West African craton across the Mauritanides orogenic belt, have led to two-dimensional geoelectric models in which lateral electrical conductivity inhomogeneities extend deep in the lithosphere. Lateral inhomogeneities are mainly represented by an elongate north-south striking change in crustal thickness west of the outcropping margin of the craton and variation of the lithosphere's thickness. Geoelectric cross sections also reflect the lateral resistivity changes associated with lithological and structural changes and provide new information on the depth extent of the older sequences of the Mauritanides belt. The conducting zones at lower crustal depths beneath both the mobile belt and the craton are believed to be the result of many effects: hydrated rocks and trapped pore water. A major electrical discontinuity extends from the surface to 175 to 250 km depth and separates two structural blocks. The eastern block, with higher resistivities and a larger thickness, is interpreted as being the West African craton. At crustal depths this major electrical feature could be due to a major suture within the craton between crusts of different ages. At greater depths the major discontinuity rotates and runs parallel to a regional lineament (Bissau-Kidira Lineament) suggesting that the discontinuity may be associated with an ancient zone of weakness in the lithosphere. With the details provided by the geoelectric sections, the tectonic setting of the study area can be outlined more accurately. The better knowledge of the deep structures of the southern segment of the Mauritanides orogenic belt confirms the geodynamical process already proposed, that is, a west-dipping suture between the craton and the Senegalese microplate, which collided during the Panafrican orogenesis.

INTRODUCTION

In 1980 and 1984 magnetotelluric (MT) surveys were carried out in eastern Senegal to study crustal and upper mantle structures related to the Mauritanides orogenic belt and to determine regional differences in lithosphere electrical properties among the various tectonic provinces of this area: the Eburnean West African craton, the Panafrican Mauritanides mobile belt, and the Mesozoic-Cainozoic Senegal basin (fig. 1). Field work was done on two profiles from the Senegal basin to the craton, approximately perpendicular to the main structural trends at 20 sites. The measurements were performed in the period range of 10 to 10,000 sec. The technique is based on surface measurements of electromagnetic fields from which an apparent resistivity-frequency relationship is obtained (Vozoff, 1972; Thayer, ms). This is interpreted to give resistivity structure by using a combination of one-dimensional inversions (Jupp and Vozoff, 1975) and two-dimensional (2-D) forward modeling (Wannamaker, Stodt, and Rijo, 1985). For traverse I, results of the numerical modeling were discussed by Ritz (1984), and for traverse II a similar account has been presented (Ritz and Vassal, 1987a). For traverse II, MT observations in the Senegal basin have been taken into account to provide a model across the entire eastern Senegal (Ritz and Vassal, 1987b). On profile I a good correlation was found between electrical resistivities on the one hand and geological formations on the other (Ritz and Robineau, 1986). Major differences in crustal and upper mantle electrical structures were observed in the Mauritanides compared to the Senegal basin and the craton. In particu-

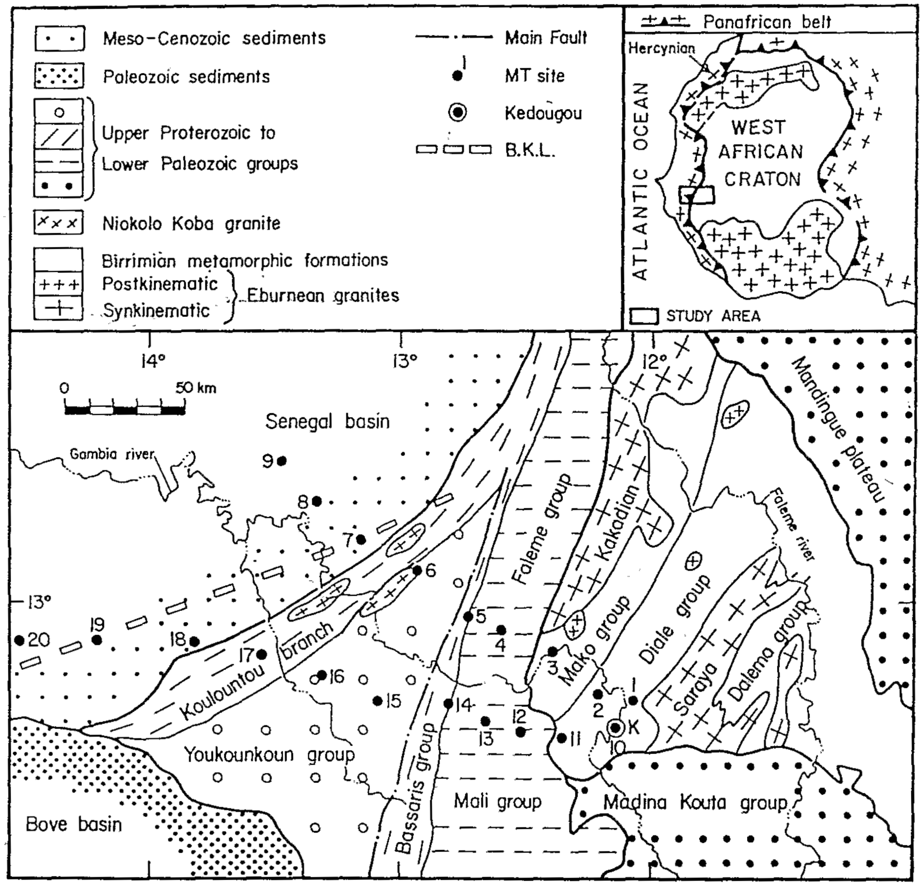

Fig. 1. Main geological units in eastern Senegal with location of magnetotelluric measurement sites along traverses I (1–9) and II (10–20).

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American Journal of Science Vol. 288 No 7 Sept 1988 lar, structural differences extend deep in the lithosphere between the West African craton and the Senegal basin. Such information is of fundamental significance to the tectonic evolution of eastern Senegal. Therefore, the purposes of this paper are to discuss the geological interpretation of MT cross sections and to provide better constraints on the nature of subduction-related structure for the Mauritanides orogenic belt. We compare this structure with other available geophysical data and tectonic observations and interpret it qualitatively in terms of geodynamics.

GEOLOGICAL AND GEOPHYSICAL BACKGROUND

A good control exists for the Precambrian lithology of the orogenic belt, and the general structure of the study area has also been investigated by geophysical means. Nevertheless, the tectonic evolution of the Mauritanides orogenic belt has long been and continues to be the subject of intense debate.

The main geological units in eastern Senegal.—The West African craton is represented in eastern Senegal by the Kedougou basement inlier. Three different lithostructural units, trending northeast-southwest, have been defined by Bassot (1966) in his famous regional synthesis (fig. 1). The *Mako group* consists of magmatic rocks (gabbro, dolerite, basalt, andesite, rhyolite, ultramafite) and volcano-sedimentary materials (tuff, breccia, cinerite, jasper associated with graywacke, and schist). In the *Diale group* are exposed mainly sedimentary rocks (schist, graywacke, cipolin, jasper, and conglomerate) with a few occurences of volcano-sedimentary rocks. The *Dalema group* has a similar flysch facies but exhibits more calcareo-magnesian rocks and volcanics (andesite, spilite, dacite). The three groups have been tightly folded during the Birrimian tectonic event and show a steep west-dipping foliation, trending roughly northeast-southwest. A low grade metamorphism, green schist facies to amphibolite facies locally, goes with the main deformation phase. The Birrimian event (around 2000 Ma) is characterized also by a strong granitization. Bassot (1969) distinguishes syn- to tardikinematic granites, like Kakadian and Saraya large batholiths, and post-kinematic smaller intrusions.

The Kedougou inlier is bordered westward by the Panafrican (550-650 Ma; Dallmeyer and Villeneuve, 1987) Mauritanides belt (fig. 1) which runs north-south from Mauritania to Liberia (Rokelides) through Guinea and Sierra Leone (Williams and Culver, 1982; Villeneuve, ms). In eastern Senegal, after Bassot (1966) most of the authors divide the belt into four lithostructural units: *Faleme*, *Bassaris*, *Youkounkoun*, and *Kouloumtou groups*. A short description of each group is proposed in the next chapter. If an Hercynian orogeny has been proposed for the origin of the Northern Mauritanides (Lécorché, ms; Le Page, ms), recent studies have shown that it overprints a Panafrican suture in the Central Mauritanides (Dia, ms), and the intensity of the Hercynian event decreases drastically in eastern Senegal and mainly in Guinea where the

Paleozoic basin overlies unconformably the Mauritanides-Rokelides belts (Villeneuve, ms). Most recent studies agree on a collision type of belt with an oceanic (or rift) suture zone dipping to the west, bordered eastward by a calc-alkaline province. The eastern part of the belt is buried under the Senegal coastal basin.

Meso-Cainozoic sediments have filled a typical passive margin type of basin, created on the edge of the West African craton during the opening of the Central Atlantic Ocean. In the study area, a thin layer of Tertiary shales and sands and upper Cretaceous sands overlies the Kouloumtou branch (Bellion and Guiraud, 1984).

Previous geophysical studies.—Geophysical methods, particularly gravity and seismic methods, have been used to determine the crustal structure of the West African margin. The belt is associated with a negative-positive gravity anomaly pair (Crenn and Rechenmann, 1965) interpreted as a collision signature due to modern-type plate tectonics (Ponsard, Lesquer, and Villeneuve, 1982; Lécorché and others, 1983; Dia, ms; Villeneuve, ms). The paired gravity anomaly signature is explained by juxtaposed crustal blocks of different density and thickness. The crust of the western block is both denser and thicker than that of the eastern block corresponding to the craton. The discontinuity in density separating the Senegalese block and the West African cratonic block is considered to be the suture. The rocks of the suture, rooted at between 5 and 20 km and dipping west under the Kouloumtou branch, are supposed to be mainly dense mafic volcanics (Ponsard, ms; Villeneuve, ms). However, for Guétat (ms) the negative gravity anomaly associated with the external zone of the belt can be related to a crustal thickening in connection with a shortening occurring during the growth of the belt and the positive anomaly to uplifted dense mantle. Guétat (ms) has interpreted the gravity signature in terms of a simple model of intracontinental collision. Although the available information from eastern Senegal does not allow a clear distinction between these models, interpretations of teleseismic arrivals along traverse I (fig. 1) indicate that the craton crust is about 6 km thicker than the crust beneath the Senegal basin (Dorbath and others, 1983); in that case the concept of thickened crust under the outer zone of the belt as proposed by Guétat (ms) from gravity modeling may be more appropriate. A different geological evolution of these crustal blocks could be reflected in differences in their present-day resistivities. In light of these various indications for major structures and changes in crustal thickness within or close to a zone postulated to contain a collision signature, the geoelectric cross sections place new geotectonic markers which can be coupled to gravity and seismic data to provide better constraints on the crustal thickness and thus on acceptable tectonic models.

Electromagnetic results.—The complexity of the structure along two traverses was indicated by diverging components of apparent resistivity, significant changes in the character of the MT responses from east to west, strong rotation of the electrical strike direction between diversurface distortion in the MT response (in particular for soundings 19 and 20), and the presence of a telluric current concentration beneath the craton (Ritz and Vassal, 1987a). At all the MT sites, the resistivity structure appears to be at least 2-D. However, the data computed along the electrical strike or TE data, especially from traverse II, show a good consistency from site to site, and the similarity of the responses suggests that the TE mode for soundings 19 and 20 is less affected by surface distortion effects. For these sites, the TE data appear more accurate for a 1-D interpretation. To provide some information on resistivity structure, the data for all other sites were interpreted to be 2-D in character, so that a straight line from sounding 10 to sounding 20 would be at right angles to the strike. This assumption is supported by the electrical strike directions at stations along the traverse line approximately parallel to each other and consistent with the regional strike of eastern Senegal (N 28° E).

The existence of a conductive anomaly in eastern Senegal was first suggested by Albouy, Babour, and Guétat (1982) who noted anomalously large horizontal component variations of the magnetic field at stations inside the craton, with much smaller values at stations inside the Mauritanides. Anomalous fields were used to obtain maximum depth estimates of around 50 km for the induced currents. The conductive structure thus appears to be in the crust or uppermost mantle and located under the craton. Initial 2-D models used structures of this type with a wide variety of resistivities, depths, and thicknesses.

One cannot minimize the distortion effects of shallow 3-D heterogeneities on regional electromagnetic studies, and the possibility must be considered that the anomalous fields may be due to channel currents that are not related to the local induction process (Jones, 1983). In general, questions on local induction and telluric current concentration can only be answered by solving regional induction in 3-D configurations in which the two effects are distinguishable from each other (Vasseur and Weidelt, 1977; Hermance, 1982). With the preceding limitations in mind, modeling of the MT data was done with constraints imposed by geologic, seismic, and gravity studies. The models that best fit the MT response are shown in figures 2, 3, and 4. Inverse MT modeling never yields an unique result, and figures 2, 3, and 4 are no exception.

GEOLOGICAL INTERPRETATION OF GEOELECTRIC TRAVERSE II

This is an attempt to correlate surface geology with lateral electrical conductivity inhomogeneities found in the uppermost part of the crust along traverse II. Measurement sites being widely spaced, the 2-D geoelectric model remains too schematic to be directly superimposed with a detailed geological section across the various lithological formations. Moreover the geology of the area is poorly known (no detailed survey, a few good exposures, extensive laterite), and structures are quite complicated. Meanwhile some good connections can be proposed

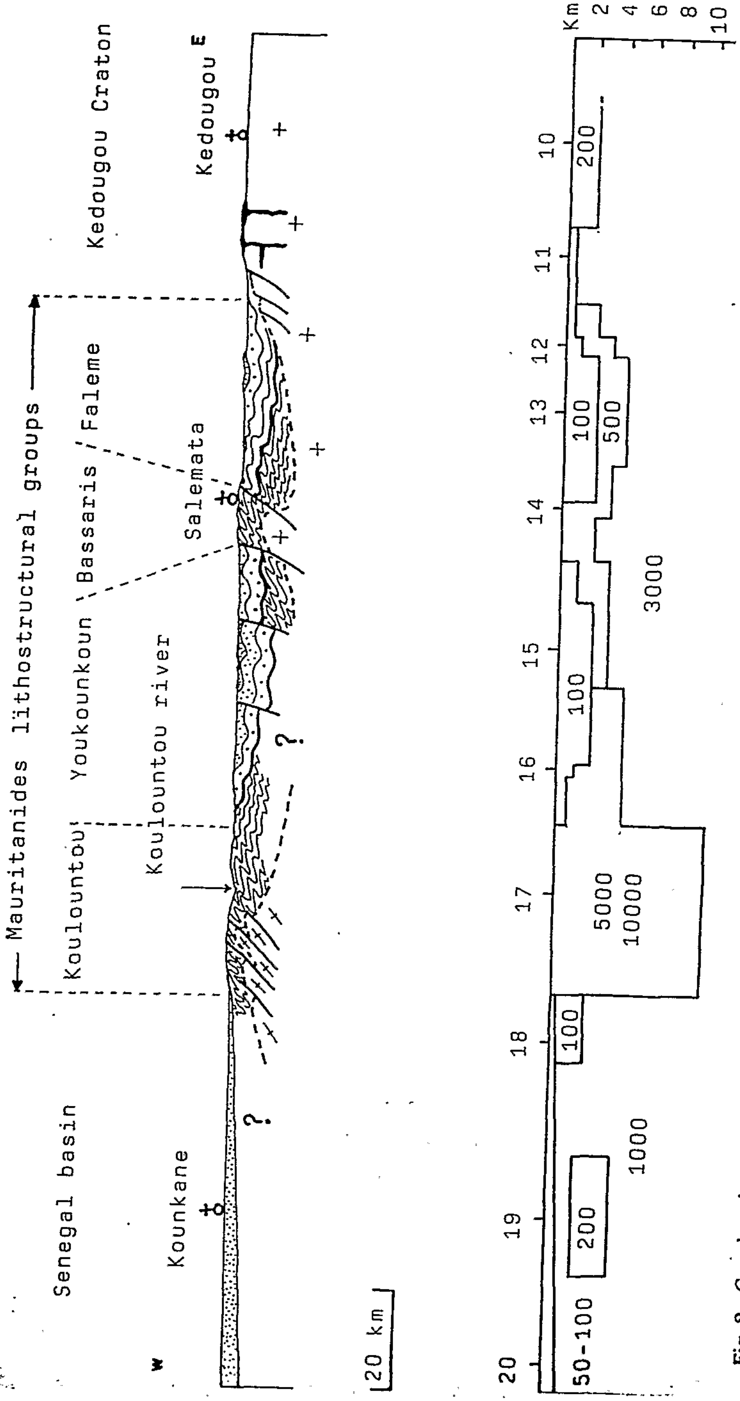

Fig. 2. Geoelectric model for traverse II (located on fig. 1) and corresponding geological section (based on Bassot, 1969 and Villeneuve, ms).

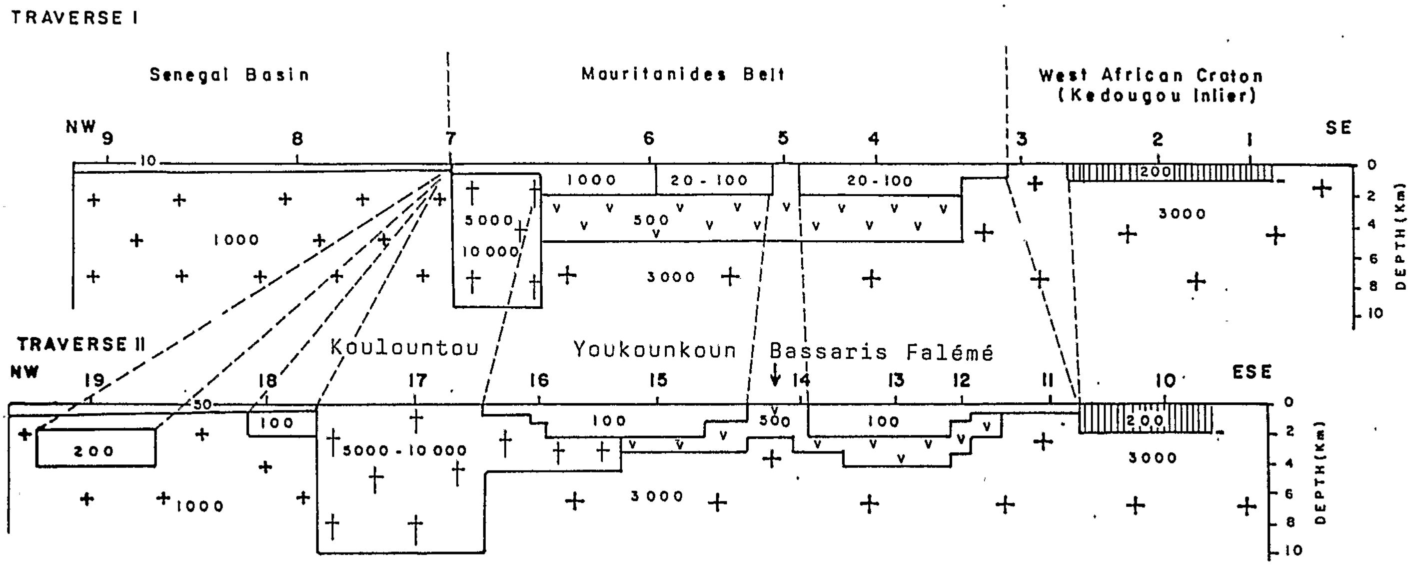

Fig. 3. Geoelectric models of the uppermost crust in eastern Senegal showing lateral correlations between traverses I and II. Traverses are located on figure 1.

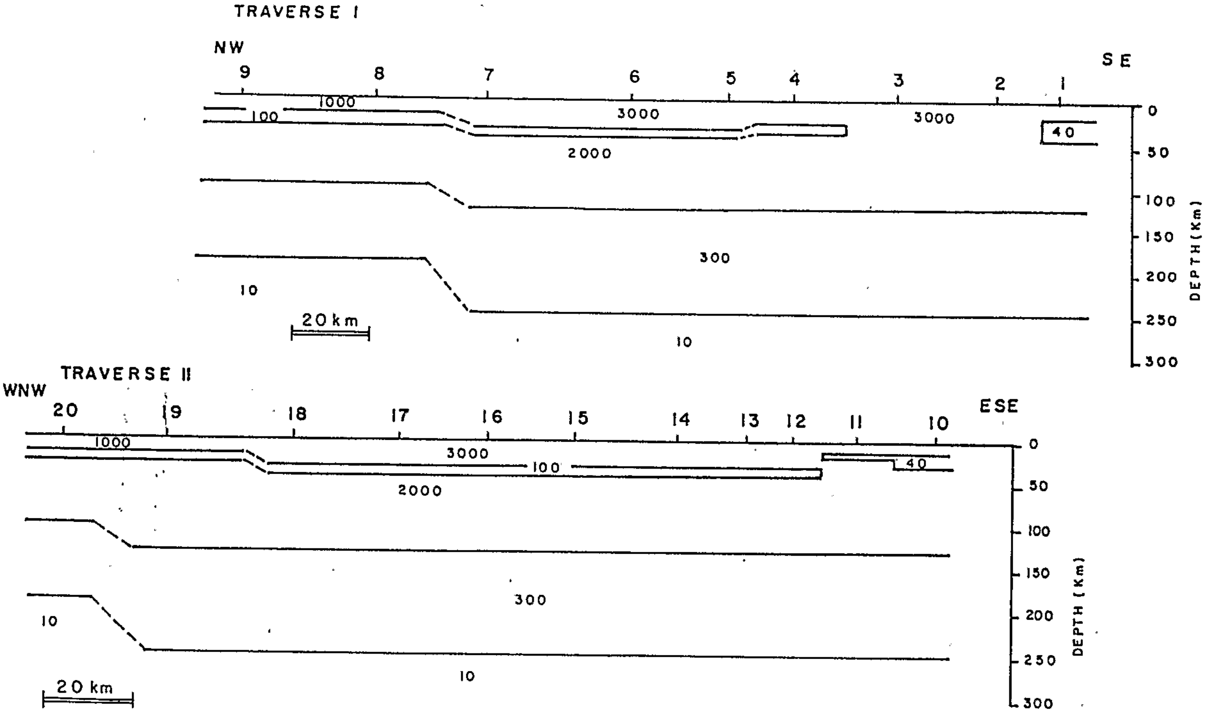

Fig. 4. Crustal and upper mantle electrical resistivity structures in eastern Senegal along traverses I and II.

at a larger scale between the constructed model and the geological section (fig. 2), drawn after Bassot (1969) and Villeneuve (ms). Correlations with traverse I give new information on the deep lateral and longitudinal extensions of lithostructural units.

Kedougou inlier.—The southern Kedougou inlier has been investigated by the easternmost soundings on traverse II, which are located in the *Diale group.* This lithostructural unit described in the previous chapter, consists mainly of flysch deposits with some interbedded volcano-sedimentary layers. The relevant electrical zone indicates a relatively low-resistivity layer (200 ohm m) less than 2 km thick, underlain by a highly resistive basement (3000 ohm m) of assumed granitic composition. Compared with the Birrimian Baoulé Mossi Domain, (Machens, 1973) and its deep roof pendants of volcano-sedimentary belts in granites and migmatites (Ritz and Robineau, 1986), the geoelectric model indicates a pellicular or shallow feature of the *Diale group.* This was also proposed in the interpretation of traverse I, where *Diale and Mako groups* have an even weaker electrical signature (1 km of 200 ohm m material), and the prevalent explanation is tangential tectonics. After Ponsard (ms) and according to new geological surveys (Ngom, ms; Ndiaye, ms), we believe that the outer position of the Kedougou inlier relative to the Eburnean belt and the generalized isoclinal overfolding of Birrimian formations evoke tangential structures.

Mauritanides belt.—Along this part of traverse II, clear connections appear between the various lithostructural units of the belt as defined by Bassot (1966) and the relevant electrical zones of the resistivity model (fig. 2).

The *Faleme group* displays a different lithology from east to west. Near the craton, it consists of subhorizontal beds of pelites, arkosic sandstones, and argillites, underlain locally by a glaciogenic conglomerate which overlies unconformably basement rocks of Kedougou inlier and *Termesse group* in Guinea (Villeneuve, ms). Westward, a zone of gently folded layers shows the same sediments but interbedded with rhyodacitic and basaltic flows. Farther west, a tight folding and very low-grade metamorphism affect a basic volcano-sedimentary formation including red jaspers, cinerites, basalts, and spilites interbedded with shales and graywackes. The relevant electric zone in the geoelectric model does not show any lateral changes in the lithology. It only suggests a trough structure, roughly 2 km deep, filled with a low-resistivity material (about 100 ohm m). The trough, apparently bounded by a major fault to the west, is underlain by a layer of higher resistivity (approx 500 ohm m) which outcrops in the Bassaris range.

The *Bassaris group* is composed mainly of volcanic and volcano-detrital rocks, metamorphosed in the greenschist facies and highly tectonized. If Bassot (1966) believes it is a lateral equivalent to the lower *Faleme group,* other authors (Chiron, 1964; Villeneuve, ms) think it could be older. The relevant electrical zone, fitting perfectly with the outcrop of the *Bassaris group,* indicates a material with a 500 ohm m resistivity. This layer, roughly 2 km thick, called the basal volcanic complex (Ritz and Robineau, 1986) is offset by steep deeping faults on each side of the Bassaris range. It underlies the *Faleme group* and also part of the *Youkounkoun group.*

The *Youkounkoun group* consists mainly of a thick sequence of gently folded red feldspathic sandstones and argillites, underlain by a dacitic complex with granitic intrusions. Bassot (1966) considers the upper sedimentary layer as a lateral equivalent to the upper *Faleme group.* On the geoelectric cross section, the relevant zone indicates a 3 km deep trough filled with a low-resistivity (100 ohm m) material. The trough is underlain in its western part by a highly resistive body, with resistivity in the range 5000 to 10,000 ohm m, which we propose to relate to the basal dacitic complex. This body thickens sharply westward from a thickness of some 2 km just a few kilometers to the west of site 15 to about 10 km east of site 18.

Muscovite-schists and porphyroides, with large thrusted basement slices (Bassot, 1969) outcrop in the Koulountou branch. In Niokolo-Koba area, Villeneuve (ms) describes reworked gneisses, strongly intruded by calc-alkaline granitic and rhyolitic rocks. *Koulountou formations* are tightly folded and thrusted to the southeast. They are supposed (Bassot, 1969) to be a lateral equivalent of the Youkounkoun lower volcanic complex. As expected for such a lithology in the Precambrian (Keller and Frischnecht, 1966), a highly resistive body (5000 to 10,000 ohm m), at least 10 km thick, characterizes the Koulountou branch in the geoelectric section. A lateral continuity with the lower Youkounkoun is obvious on this model. Westward, sediments of the Senegal basin hide this body which disappears suddenly between sites 17 and 18.

In the light of new constraints brought by the geoelectric cross section, an interpretative section showing deep geological structures across the Mauritanides belt can be proposed. *Koulountou and Bassaris groups* represent volcanic complexes that reach the surface in the core of large fault-bounded anticlinoriums. *Youkounkoun and Faleme groups* appear as synclinoriums filled by molassic sediments during the Panafrican event. This hypothesis is partly in agreement with Bassot's (1960) or Villeneuve's (1984) interpretations.

A similar geoelectric traverse cutting across the Mauritanides 30 km to the north (fig. 1) has already been interpreted (Ritz and Robineau, 1986). Correlations with new traverse II give much information on lateral continuity or extension of the various lithostructural units (fig. 3). Faleme and Youkounkoun synclinoriums are easily recognized on each traverse, but the second one clearly spreads out southward. If the outcrop of the basal volcanic complex reduces northward (*Bassaris group*), its lateral extension beneath the *Youkounkoun group* seems to increase. An important southward widening of the *Koulountou formation* is observed, partly due to the fact that traverse II is not perpendicular to the structures. In the light of these new data, a better geoelectrical model for traverse I may now be proposed between sites 6 and 7, showing a small eastward extension of the *Koulountou formation* under Youkounkoun synclinorium. On both traverses, the same 3000 ohm m resistivity layer beneath the belt units is interpreted as a granitic basement.

Senegal basin.—Though never exposed because of a thick sandy alteration cover, Meso-Cainozoic sediments of the Senegal basin are known in this area from oil exploration data. A layer of Tertiary shales and sands and upper Cretaceous sands, reaching 600 m in Tambacounda, overlies the basement (Bellion and Guiraud, 1984). On traverse II (fig. 2), the relevant electrical zone of the model indicates a thin layer of 50 to 100 ohm m material which thickens gradually westward to reach a maximum of 1 km beneath site 20. This layer overlies two restricted electrical zones of different resistivity. The eastern one of 100 ohm m resistivity is thought to represent a small sedimentary infilling comparable to Youkounkoun molassic deposits. The western one, of higher resistivity (200 ohm m), corresponds probably to fractured and hydrated basement rocks marking out the Bissau-Kidira fault zone. If the existence of the Bissau-Kidira lineament (BKL) was inferred from geological data (Villeneuve, ms), its precise localization and importance were confirmed by geophysical surveys (Ponsard, ms; Ritz and Robineau, 1986).

Correlations with traverse I show important lateral changes. BKL electrical zone disappears northward. Geologic and geophysical evidences discussed in a previous paper (Ritz and Robineau, 1986) suggest that the lineament joins the Koulountou branch to the north and verticalizes its deep structures. The very high resistivity of Koulountou material then overprints the electrical signature of BKL fractured rocks. On the other hand, the two models indicate that the Senegal basin remains very thin over the whole area and that it is underlain by the same basement of 1000 ohm m resistivity, different from the one observed eastward under the craton and the belt.

DEEP CRUSTAL AND UPPER MANTLE RESISTIVITY STRUCTURE

Knowledge of the deep electrical structure of the Earth on regional and local scales is important for tectonic interpretations and our understanding of plate tectonics and its orogenic implications. Thus, the retention of a characteristic conductivity structure over geological eras has been demonstrated, for example by the identification of a Proterozoic subduction zone in South Africa (De Beer, Van Zijl, and Gough, 1982). The two geoelectric cross sections for eastern Senegal contain some important results on the electrical properties of the deep lithosphere, and the following points can be raised.

Crust.—Geoelectric models across the craton margin differ in detail, but the gross crustal structure is similar (fig. 4). The mid-crustal layer has a resistivity that varies from 1000 to 3000 ohm m, and its thickness varies from 15 to 30 km. Both resistivity and thickness of this layer are smaller beneath the Senegal basin than beneath the craton margin. Just to the west of the craton, the resistive zone is underlain by a more conductive zone (100 ohm m) approx 10 km thick and probably extending to the Moho. However, its depth varies greatly from east to west and could be the result of intensive tectonic effects. The depth to the enhanced conductivity zone is about 30 km beneath the craton margin and about 15 (on traverse II) to 20 km (on traverse I) beneath the Senegal basin. Strong variations in depth of the low resistivity layer (crustal anomaly) occur within or close to a zone that coincides with the internal zone of the belt (Kouloountou branch), and a certain correlation can be seen with the Mauritanides gravity high (about 40 mGal). Although an electrical boundary corresponds sometimes with the Moho boundary (Hutton, Ingham, and Mbipom, 1980), it often does not. In our case the resistivity sections show the thinning of the crustal layers beneath the Senegal basin suggested by teleseismic p-wave delay studies (Dorbath and others, 1983). Of interest is the variation in the depth to the low-resistivity layer between traverses I and II under the Senegal basin. If the lower crustal layer of 100 ohm m is shallower on traverse II (Casamance region) than on traverse I, an explanation could be the proximity of the "Casamance rift" associated with the initial break up of the Atlantic (Burke, 1976) and the expected eastward crustal thinning in the transition from a continental crust to an oceanic type crust. A surprising feature of the geoelectric models is that the craton is not electrically homogeneous. In particular, the east end of two traverses can be interpreted as indicating a lower crustal layer (and a portion of the upper crust) almost two orders of magnitude more conductive (40 ohm m) than the upper 10 km of the crust at depths ranging from 10 to 15 km and apparently deepening to the north. Such a conducting lower crustal layer under the stable craton is rather uncommon. Usually conductive zones in the crust appear to be typical of regions of recent activity (Vanyan, 1981).

Upper mantle.—An important feature of the resistivity structure is the drastic decrease in depth of the highly conductive mantle zone from the craton to the Senegal basin (upper mantle anomaly). Beneath the Mauritanides and the craton, at depths of about 130 km, the resistivity first decreases on the order of 300 ohm m before experiencing a sharp fall (10 ohm m) at depths in excess of 250 km (fig. 4). The equivalent depths in the Senegal basin are about 100 km and 175 km, respectively. The asthenospheric effect is presumably the rise in conductivity seen at depths of 100 to 250 km (Jones, 1982), and the highly conducting layer within the depth range 175 to 250 km could be correlated with the top of the asthenosphere. According to Vanyan and others (1977) and Adam (1978) the asthenosphere is absent or at least not "well developed" in old shield regions characterized by low heat flow, the first rapid increase in mantle conductivity being at perhaps 400 km. In eastern Senegal the heat flow is, at the most, normal over the Senegal basin and low (37 mW/m^2) over the craton (Brigaud and others, 1985) which would imply that the asthenosphere may well be absent beneath the craton. That a conductive layer appears under a shield region, the existence of which is strongly suggested by our data, may be due to the fact that the MT traverses are located near the margin or to the edge of the shield. Note that in areas such as the Baltic and Canadian shields a conductive layer is reached at depths of 155 to 185 km (Jones, 1982) and 100 km (Kurtz, 1982), respectively.

Finally, the geoelectric models (fig. 4) show pronounced lateral electrical conductivity inhomogeneities extending deep in the lithosphere. Particularly a fundamental difference in resistivity structure within the upper mantle exists between the Senegal basin and the craton. The major inhomogeneity extends downward from the surface to a depth of 175 to 250 km and separates two structural blocks. The eastern block characterized by higher resistivities and a larger thickness (approx 250-300 km) represents the structure of the craton. For traverse I, this major structural feature appears as a vertical boundary in the crust and upper mantle and cuts the surface at about 115 km west of the outcropping margin of the craton. On the southern traverse the discontinuity cuts the surface about 180 km to the west of the Kedougou inlier; it begins as a vertical boundary, but at greater depths it rotates westward. This rotation is abrupt and almost certainly reflects a different trend within the lithosphere. It is worthy of note, however, that the crustal anomaly (crustal thickening) runs approx N15°E, and the main trend of the upper mantle anomaly (lithospheric thickness change) is rather N45°E. The crustal anomaly coincides approximately with a large gradient in the gravity field and has been interpreted as a Panafrican suture (Ponsard, ms; Villeneuve, ms). The northeast-southwest trend approximately aligns with the Bissau-Kidira lineament, a major Panafrican shear zone (Ponsard, ms; Villeneuve, ms), suggesting that the lineament is a structural zone that extends deep into the lithosphere and that its location was controlled by an ancient zone of weakness in the upper mantle. Note that for traverse I, the electrical discontinuity within the lithosphere correlates well with the existence of a seismic discontinuity extending from the surface to a depth of 150 to 200 km. The eastern block (craton) has higher velocities than the western one. This discontinuity, striking north-south, has been interpreted as the trace of a Precambrian east dipping suture (Dorbath and others, 1983). But Villeneuve (ms) suggests that this seismic discontinuity could be correlated with the Bissau-Kidira fault zone rather than the Panafrican suture.

The presence of two different blocks beneath eastern Senegal would lead to new information about the geodynamic evolution of this part of West Africa.

CRUSTAL CONDUCTIVITY ANOMALIES IN EASTERN SENEGAL

The relatively conducting layers (resistivity <200 ohm m), detected at mid-crustal and lower crustal/uppermost mantle depths, are found in a number of different continental tectonic environments in many parts of the world, namely in rift zones such as the East African rift (Banks and Ottey, 1974) and Rio Grande rift (Jiracek, Ander, and Holcombe, 1979), in regions of continental collision such as the Canadian Appalachians (Cochrane and Hyndman, 1974) and the Precambrian mobile belts in South Africa (Van Zijl, 1977), and in old shield regions such as the North American shield (Koziar and Strangway, 1978; Connerney, Nekut, and Kuckes, 1980; Duncan and others, 1980; Kurtz, 1982) and the Aldan shield in central Asia (Berdichevsky and others, 1976). However, the physical explanation for abnormally high electrical conductivity of the lower crust is not clear, in particular inside stable cratonic areas.

Possible causes of high electrical conductivity.—The distinctive features that need explanations are the relatively conductive mid to lower crust that appears to be required beneath two traverses. Possible mechanisms to explain the conducting zones at depths ranging from 15 to 40 km beneath the craton margin and beneath the stable cratonic edge of West Africa are the presence of special mineralogical constituents such as graphite, oxides, or hydrous silicates (serpentine, amphibole), the influence of temperature on usual lower crustal rocks, the existence of water-saturated rocks in the lower crust, and the presence of highly saline solutions without fracture systems.

A partially molten lower crust would produce high temperatures over the region, inconsistent with the normal heat flow values observed in the Senegal basin (O. Fambitakoye, personal commun., 1984) and the existence of a low heat flow over the craton (Brigaud and others, 1985). Graphite and magnetite have been observed in the metamorphic rocks of the Kedougou inlier (Bassot, 1966); however, they are not in sufficient abundance to increase the bulk conductivity of the cratonic zone.

The high conductivity zone was suggested to be the result of dehydration water escaping into pore spaces (Hyndman and Hyndman, 1968). Nevertheless, for Precambrian regions, the crust is generally considered to be depleted of water. Conduction via pore fluids is probably not significant below a maximum depth of about 15 km (Dvorak, 1975). However, Berdichevsky and others (1972) argued that water can be released during dehydration at the boundary of amphibolite and granulite facies. This crustal hydration process is irreversible with time, the water being removed during the upward migration of the granulite facies boundary, leaving the stable lower crust of shield areas. Thus, although conduction by pore fluids in the lower crust is likely to be small, it is possible that dehydration water causes a significant decrease of the electrical resistivity beneath the Senegal basin. How completely the crust is dehydrated and whether water can be reintroduced is uncertain. Nevertheless, Feldman (1976) has suggested that the anhydrous minerals of amphibolite facies could be rehydrated by the addition of water from below through mantle dehydration during any later thermal reactivation (subduction process, for example). The low inferred resistivities beneath both Mauritanides and craton might arise from the presence of hydrous silicates (serpentine, amphibole) commonly found in tectonic collision zones. Hydration water would be released as the lithospheric slab slides down during subduction. Van Zijl (1977) notes that only serpentinite rocks can provide the low resistivities of the order of 50 ohm m or less inferred at 25 to 40 km depth in the South African shield. Under lower crustal conditions, porosity would be kept open by the high pore pressure (Walder and Nur, 1982), and only 0.1 percent free water could explain the enhanced conductivities in cratons (Shankland and Ander, 1983). Kozlovsky (1982), from drilling information in the Kola Peninsula (Baltic shield), indicated brine solutions at depths greater than 11 km.

Drury and Niblett (1980) have suggested that elevated electrical conductivity found at the edges of cratons and along fold belts may be explained by incorporation of ancient oceanic crustal material. It is, however, likely that if buried oceanic material does exist in this region, it most probably will be highly metamorphosed and as such will bear little resemblance to the original material.

Of possible ways to enhance crustal conductivities, the presence of either free water or water of hydration remains most frequently proposed, and the favorite explanation at this stage is that the conductive zone beneath both the mobile belt and the craton is due to a combination of two effects—hydrated rocks and trapped pore water with high ionic concentrations (Kozlovsky, 1982).

Comments on the craton anomaly.—The pronounced increase in conductivity in the crust of mobile belt and cratonic regions of eastern Senegal, perhaps due to the presence of water at depth, suggests possible tectonic implications.

During the last decade the evidence for Precambrian plate tectonics increased steadily, and the concept found growing acceptance (Kröner, 1981). Proterozoic plate-tectonic models are proposed by several researchers, for instance, in the structural provinces of the Canadian shield (Lewry, 1981; Gibb and others, 1983). It has been suggested that conductivity anomalies in stable shield regions should be associated with geological boundaries marking ancient plate margins (Law and Riddihough, 1971). In West Africa there are evidences that such a boundary exists in the vicinity of the craton conductor (Bassot, 1966; Villeneuve, ms). A new geological argument favoring an evolution of the Senegalese craton through a context of subduction and collision tectonics is the presence of superimposed Birrimian volcano-sedimentary assemblages with tholeitic (Debat and others, 1984; Ngom, ms) and calc-alkaline (Ngom, ms; Ndiaye, ms) affinities. There are no substantial gravity data to support any of these lithotectonic elements. The conducting layer at lower crustal depths in the interior of the craton could extend northward in Mali over a distance of about 250 km and southward to Guinea (Albouy, Babour, and Guétat, 1982) with a trend parallel to Birrimian structures. It is suggested that the conductor may be associated with hydrated minerals from the subducting Proterozoic lithosphere beneath the craton, but the steps from the hydration water released by descending lithospheric slab approx 2000 Ma ago to the present-day conductor are enigmatic. Hyndman and Hyndman (1968) suggested that hydrated minerals in ophiolites could be highly conductive. The association between the conducting zone in the crust beneath the craton and a possible subduction zone is necessarily speculative. There seem nevertheless sufficient grounds to propose that a close relation may exist between the complex geoelectric structure of the crust in eastern Senegal and tectonic features. Such conductive structures revealed by means of large magnetometer arrays and probably related to ancient subduction zones have already been postulated in North America (Camfield and Gough, 1977; Handa and Camfield, 1984).

GEODYNAMIC IMPLICATIONS: A DISCUSSION ON THE DEEP STRUCTURES OF THE MAURITANIDES BELT

Geoelectric models and their geological interpretation represented on a block diagram (fig. 5) give new constraints on the nature of the various geotectonic units and their deep extensions. The Koulountou branch with calc-alkaline affinities (Villeneuve, ms) consists of highly resistive material, probably dehydrated granitic and rhyolitic rocks, strongly deformed during the Panafrican collision and maybe rejuvenated by the Hercynian event. A steep west-dipping of this unit can be observed on traverse II down to 10 km. For Villeneuve (ms), the *Bassaris group* represents the volcanic material related to the Panafrican suture. If the ophiolitic sequence is not observed, volcanic rocks clearly fall in the tholeitic domain (Dupont, Villeneuve, and Lapierre, 1984), and pillow lavas have been recognized. This basal volcanic and volcano-sedimentary complex was emplaced in a geosyncline, with a possible but reduced oceanic spreading or a wide intracontinental rift. Despite other geophysical (Gamon gravity anomaly) evidences of a west-dipping dense layer, no clear suture plane can be noticed on geoelectric models. Furthermore, field observations of Bassaris tectonics confirm the west-dipping of all structures, thrusts, foliation, and axial planes of isoclinal folds related to the main deformation event.

In the geoelectric models, *Youkounkoun and Faleme* (at least its upper part) *groups* appear as sedimentary infilling of molassic basins, contemporaneous with the formation of the belt. This could explain the increasing deformation of the layers with the depth. A small comparable basin could exist under the Senegal Mesozoic basin beneath site 18 of traverse II.

Geological and geophysical characteristics discussed above, confirmed by recent geochemical investigations, argue for a Panafrican continental collision to explain the tectonics of the Southern Mauritanides belt. A model with a west-dipping suture plane seems the most suitable to explain the spatial arrangement of the belt structural units.

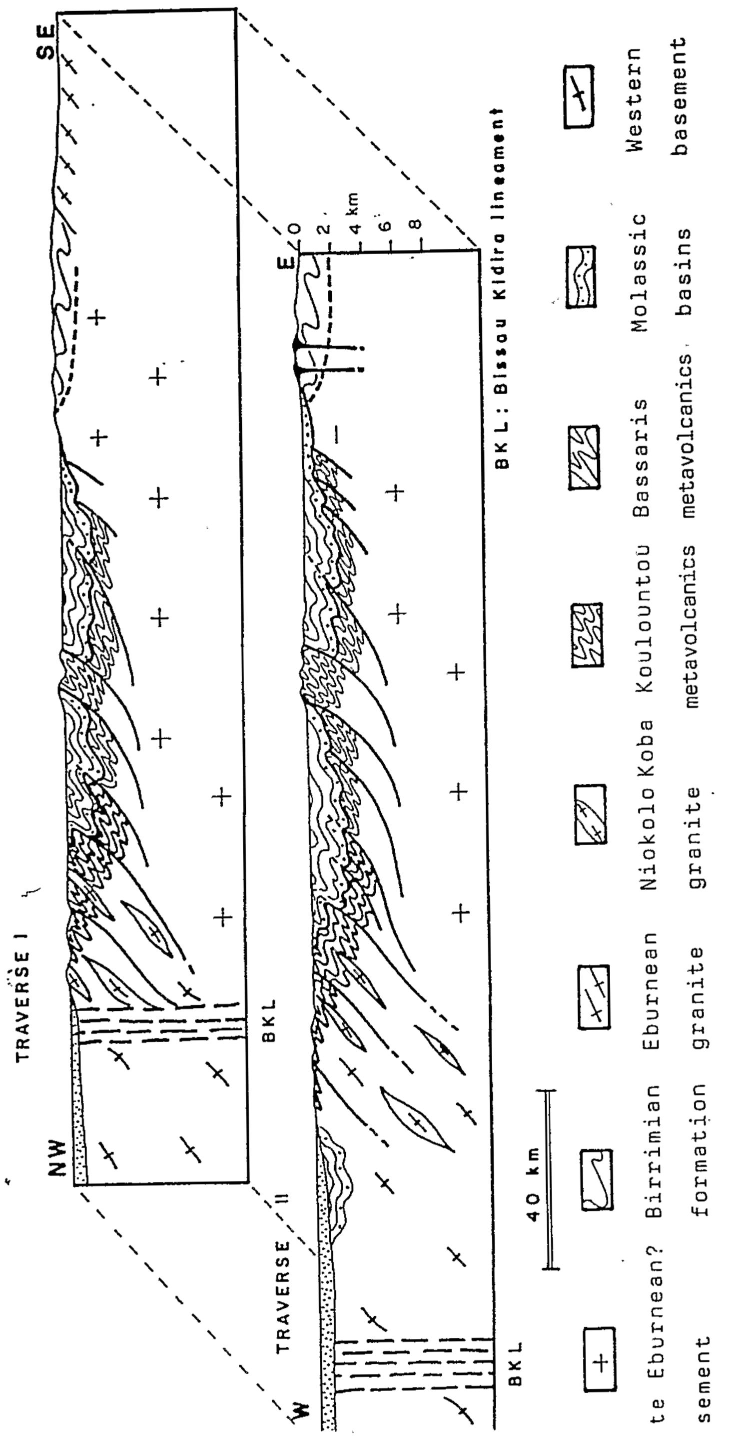

Fig. 5. Interpretative geological sections along traverse II (fig. 3) and traverse I.

On both traverses, the belt is underlined by a crustal root 40 km deep which widens considerably southward. It separates two domains of different crustal resistivity and thickness. The western domain, corresponding to the Senegalo-Mauritanian micro-plate, has a thinner crust (15 to 20 km) of lower resistivity (1000 ohm m) that could be either of different lithology or younger age (Piper, 1983). The southward thinning of this crust seen on traverse II is attributed to the formation of the "Casamance rift" in relation to the Atlantic opening or to an early Paleozoic crustal stretching which occurred during the Proto Atlantic ocean. The eastern crust, beneath the West African craton, is more resistant and thicker. If the Mauritanides belt separates two different lithospheric plates on traverse I, the western one being thinner, it is not the case on traverse II where the change in thickness appears beneath the electric signature of the Bissau-Kidira Lineament (fig. 6). As

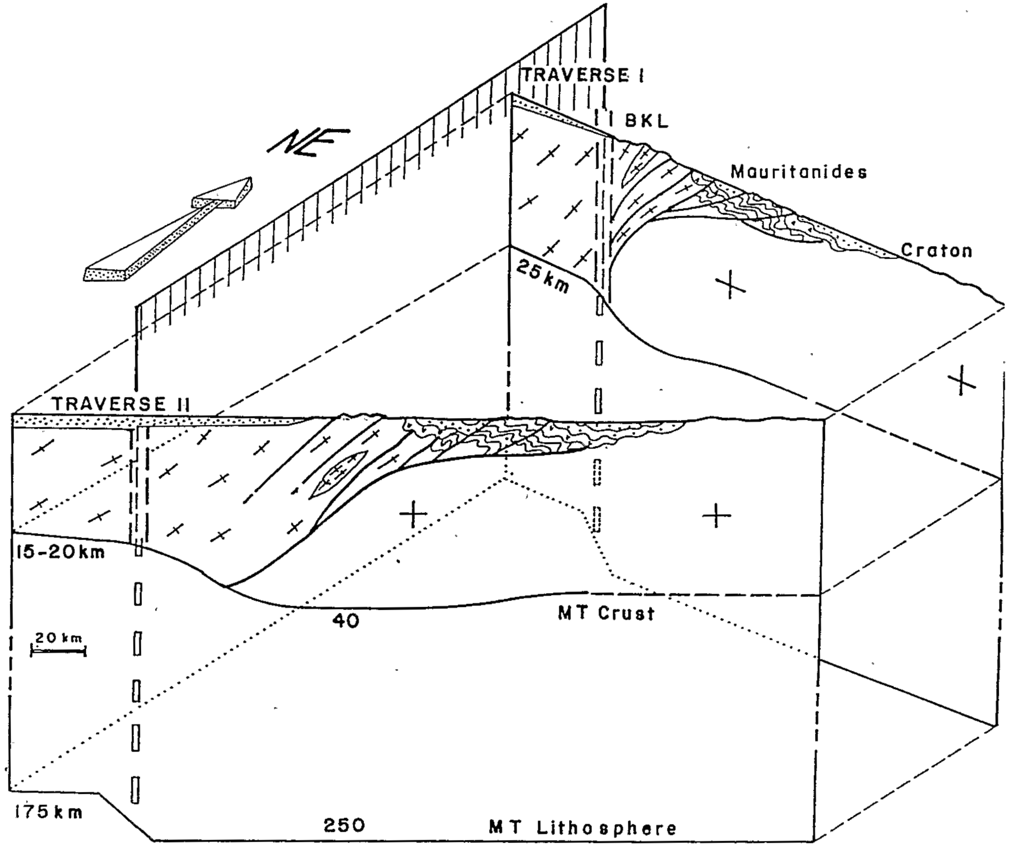

Fig. 6. Synthetic block diagram for crustal and upper mantle structures of eastern Senegal with geotectonic provinces derived from geoelectric models shown in figure 5.

expected in a previous paper (Ritz and Robineau, 1986), the major inhomogeneity in the upper mantle can be attributed to the Bissau-Kidira lithospheric fracture zone. Its prominent role as a transform fault during the Panafrican and Hercynian event (Villeneuve, ms) is therefore obvious, underlined by the virgation of the Southern Mauritanides and the drastic change in the intensity of the Hercynian deformation on each side of the lineament.

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