TECTONICS, VOL. 6, NO. 4, PAGES 395-409, AUGUST 1987

MAGNETOTELLURIC SOUNDINGS AND THE GEOLOGICAL STRUCTURE AND TECTONICS OF THE SENEGALO-MAURITANIAN BASIN IN NORTHERN SENEGAL, WEST AFRICA

Michel Ritz

ORSTOM, Dakar, Sénégal

Yves Bellion

Département de Géologie, Faculté des
Sciences, Dakar-Fann, Sénégal

René Flicoteaux

Laboratoire de Géologie Dynamique,
Faculté des Sciences de Saint Jérôme,
Marseille, France

Abstract. The results of the magnetotelluric soundings provide new insights on the geological structure and tectonics of the onshore Senegalo-Mauritanian basin in northern Senegal (West Africa). Electrical resistivities can be correlated with the major geological units. In the upper 1000 m, resistivity variations indicate a transition from freshwater saturated sediments near the surface to saline water saturated sediments above the basement. The resistivity of the sediments is dominated by their porosity and the resistivity of the contained fluids. The resistivity of the Cretaceous sediments is unexpectedly low, especially in the western part of the basin. The top of the metamorphic/granitic basement cannot be located on the west portion of the profile because of the feeble resistivity contrast between the impervious, compacted Aptian-Jurassic limestones and the metamorphic/crystalline rocks. The magnetotelluric estimates of the depth of the basement range from 600 m in the east to 4000 m in the west. Based on the magnetotelluric interpretation and other independent geophysical and geological information, a cross section through the Senegalo-Mauritanian basin along the magnetotelluric traverse is presented. A zone of high electrical conductivity is observed in the crust, at depths of 4-6 km, on the eastern margin of the deep basin. This conductive structure may be the extension of one further south that was revealed by an earlier investigation. The entire conductive zone, which runs north-south between longitudes 15° and 16°W, may be a major fracture zone related to the opening of the Atlantic Ocean; however, its origin remains to be established.

Paper number 7T0170.
0278-7407/87/007T-0170$10.00

INTRODUCTION

This paper discusses the geological and tectonic implications of the conductivity structure outlined by Ritz and Vassal [1986] on the basis of magnetotelluric (MT) soundings in the Senegalo-Mauritanian (S-M) basin, West Africa (Figure 1). Table 1 indicates the full names, abbreviated station names, and the station coordinates for the MT study. Figure 2 shows two different shallow electrical conductivity models along the MT line that have been proposed by Ritz and Vassal [1986]. They differ in the interpretation of the thickness and resistivity contrast of the sedimentary section but are similar in the interpretation of deep structures (Figure 3). The model in Figure 2a is an attempt to explain the MT data on the basis of large uniform sedimentary layers

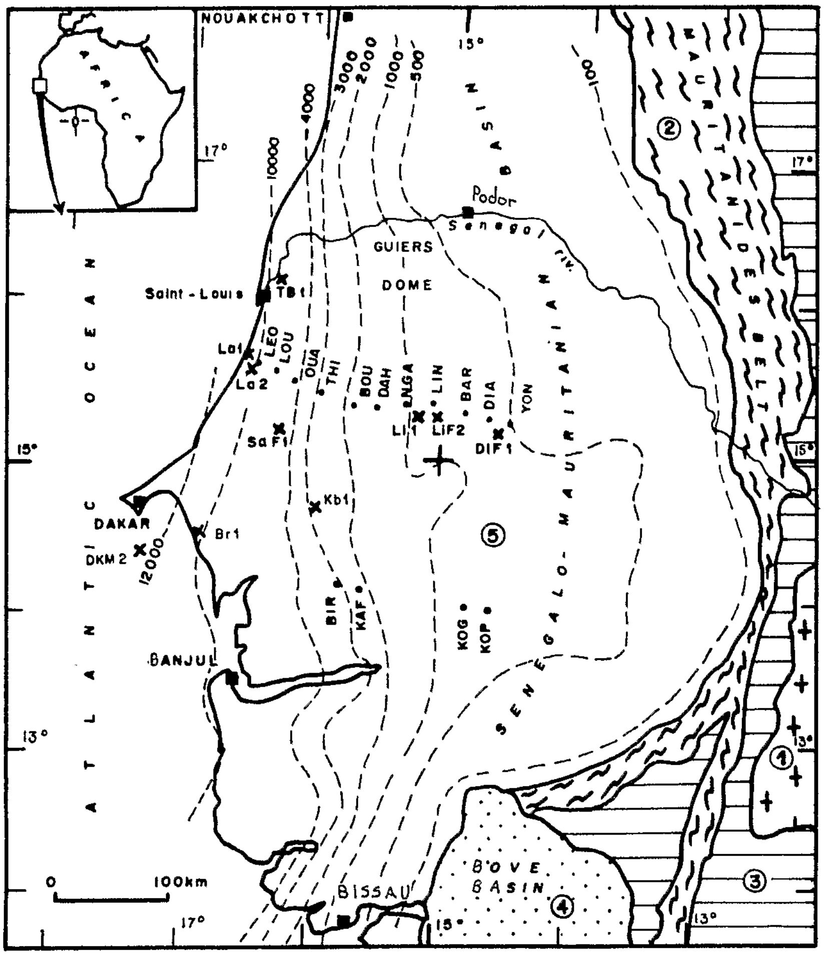

Fig. 1. Simplified basin structure and MT site locations in the Senegalo-Mauritanian basin (after ASGA-UNESCO [1968] and Ritz and Vassal [1986]). Solid circle, MT sounding. Cross, borehole. Dashed line, basement isobath (depth in meters). (1) Precambrian West African craton, (2) Mauritanides belt, (3) Late Precambrian to Paleozoic cover, (4) Paleozoic cover, (5) Mesozoic to Quaternary cover.

and abrupt truncations of the deep conductive material of the basin. A more complicated model compatible with our MT data (Figure 2b) may be considered as an alternative. Bodies with relatively high resistivity (200 ohm-m) are embedded in layers of lower resistivities (0.4 - 0.6 ohm-m) at a depth of 1000 to 3000 m. It is inherent in a MT study with data of limited bandwidth that there is a nonuniqueness associated with any proposed electrical model [Jiracek et al., 1983], and constraints imposed by other independent geophysical and geological data are necessary to distinguish between the possibilities. On the basis of drilling data (see next section), the top of the resistive unit depicted in Figure

TABLE 1. Location of the Stations of the Northern MT Profile

Station Name	Code Name	Latitude N, deg	Longitude W, deg
Yonofere	YON	15.26	14.47
Diagueli	DIA	15.27	14.65
Barkedji	BAR	15.28	14.85
Linguere	LIN	15.38	15.10
Ngarafe	NGA	15.39	15.28
Dahra	DAH	15.33	15.48
Boulel	BOU	15.38	15.65
Thiamene	THI	15.49	15.87
Ouarak	OUA	15.52	16.07
Louga	LOU	15.62	16.22
Leona	LEO	15.72	16.45

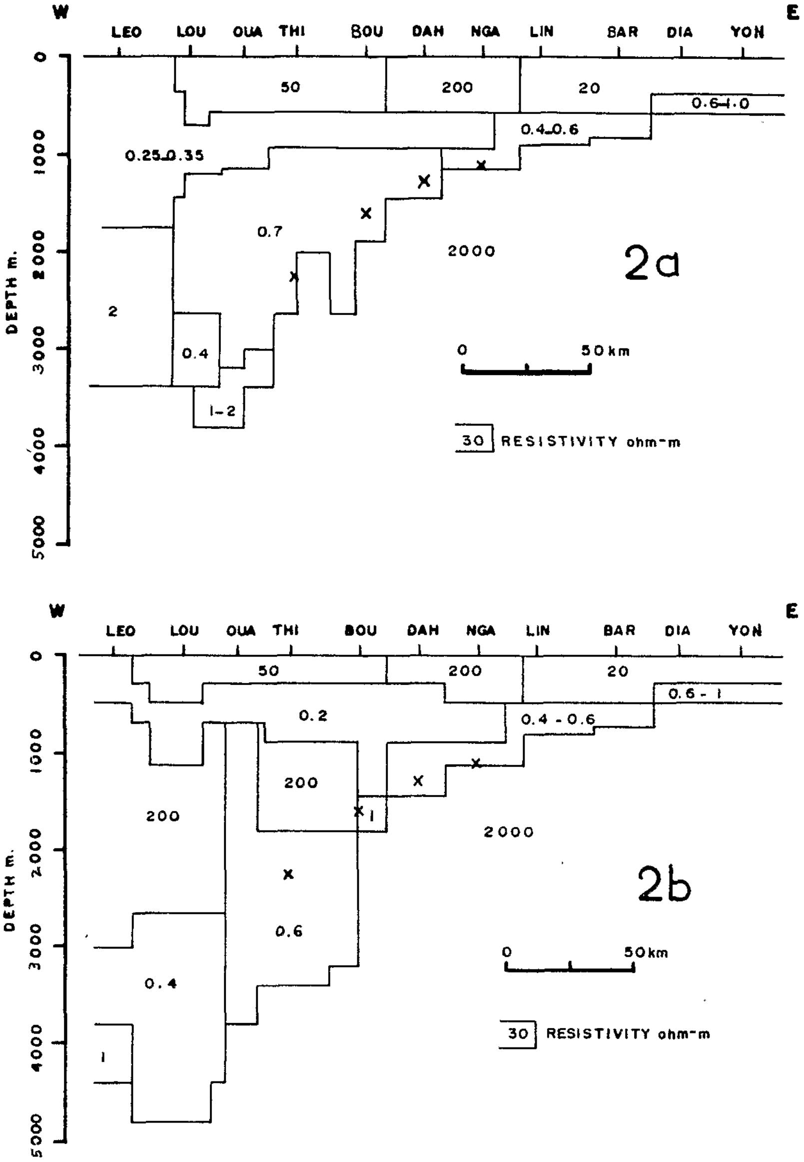

Fig. 2. Alternative geoelectrical models (a and b) for the sedimentary section of the Senegalo-Mauritanian basin in northern Senegal derived from MT results [after Ritz and Vassal, 1986]. Crosses indicate the seismic basement (after Société des Pétroles du Sénégal, unpublished report, 1960).

2b between soundings LEO and LOU could be associated with an intrusive body (syenite) which was detected on Leona 1 well (La 1, 8.5 km west of station LEO, Figure 1) at a depth of 460 m. However, this intrusion was not detected on Leona 2 well (La 2, 4 km southwest of station LEO). The resistive body (200 ohm-m) is accompanied by a circular positive Bouguer anomaly of about 90 mGal. The Bouguer anomaly has been attributed to a narrow intrusive body that provides a positive density contrast and is postulated to occur just west of sounding LEO in a depth range between 460 and 7000 m [Liger, 1980]. The existence of a large amount of resistive rocks at the west end of the profile, in the form of dense intrusions in the Leona region, does not seem very likely. On the other hand, an interpretation in which no shallow resistive layer is assumed in the area between MT soundings LEO and LOU would be more consistent with borehole data and the

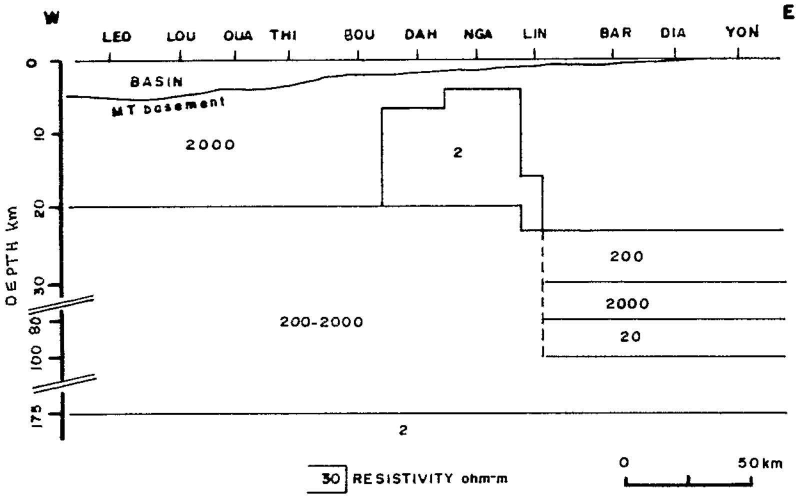

Fig. 3. Deep resistivity structure along the MT traverse [after Ritz and Vassal, 1986].

gravity interpretation. The MT model in Figure 2a, which accommodates these considerations, will be discussed in relation to the geological and geophysical constraints on the tectonics of the basin. The shallow resistivities of the MT model can be used for correlation, or with Archie's Law they can be used to estimate porosity, as is done in well log interpretation. A borehole near the profile (Toundou Besset, TB1, Figure 1) is about 4 km deep and provides excellent porosity control.

An important deep feature (Figure 3) in the model of the conductivity structure is the presence of strong conductor (2 ohm-m) in the crust beneath the eastern margin of the deep basin between stations BOU-LIN. The presence of such a conductive zone and the bounds on it are of fundamental significance to our understanding of the crustal structure and of tectonic evolution of the S-M basin.

GEOPHYSICAL AND GEOLOGICAL BACKGROUND

The S-M coastal basin, situated on the western edge of West Africa, lies between the 10° and 21° N latitude (Guinea Bissau and Mauritania), and is bounded to the east by the West African mobile belt (late Precambrian to Devonian orogenic belt-Mauritanides). The major stratigraphic and tectonic features of the S-M basin in Senegal are illustrated by schematic sections [Bellion and Guiraud, 1984] in Figure 4.

The S-M coastal basin developed in response to the opening of the Central Atlantic Ocean in Early Mesozoic time about 180 Ma [Dewey et al., 1973]. Chanut [1984] suggested that the crustal stretching started around 243 Ma in the S-M basin because of a thermic event dated in the basement of Kolobane 1 borehole (Kb1, Figure 1). The Triassic rifting and the post-Triassic subsidence of the West African margin that was responsible for the formation of the S-M basin very likely was accompanied by the intrusion of magmatic material into fissures and fractures that predominantly parallel the coast [Van der Linden, 1981] and into E-W trending faults [Reyre, 1984]. During the Jurassic a carbonate platform formed along the continental margin of West Africa [Von Rad et al., 1982]. Figure 4 shows this carbonate platform in the S-M basin. Sedimentation was very active in Cretaceous time, and consisted of terrigenous deposits (clays, sands, sandstones, and carbonates). Tertiary sediments in the S-M basin consist of Paleogene chemical or biochemical deposits (carbonates and phosphates) with a more sandy facies eastward and a more clayey facies westward. This unit is overlain by a 50- to 100-m-thick Neogene layer of sand. From Late Cretaceous to Mio-Pliocene a major phase of vertical tectonic movements continued the disruption of the basement blocks. Late Cretaceous volcanism is known in the Leona area (west end of the MT profile), and in the Dakar region,

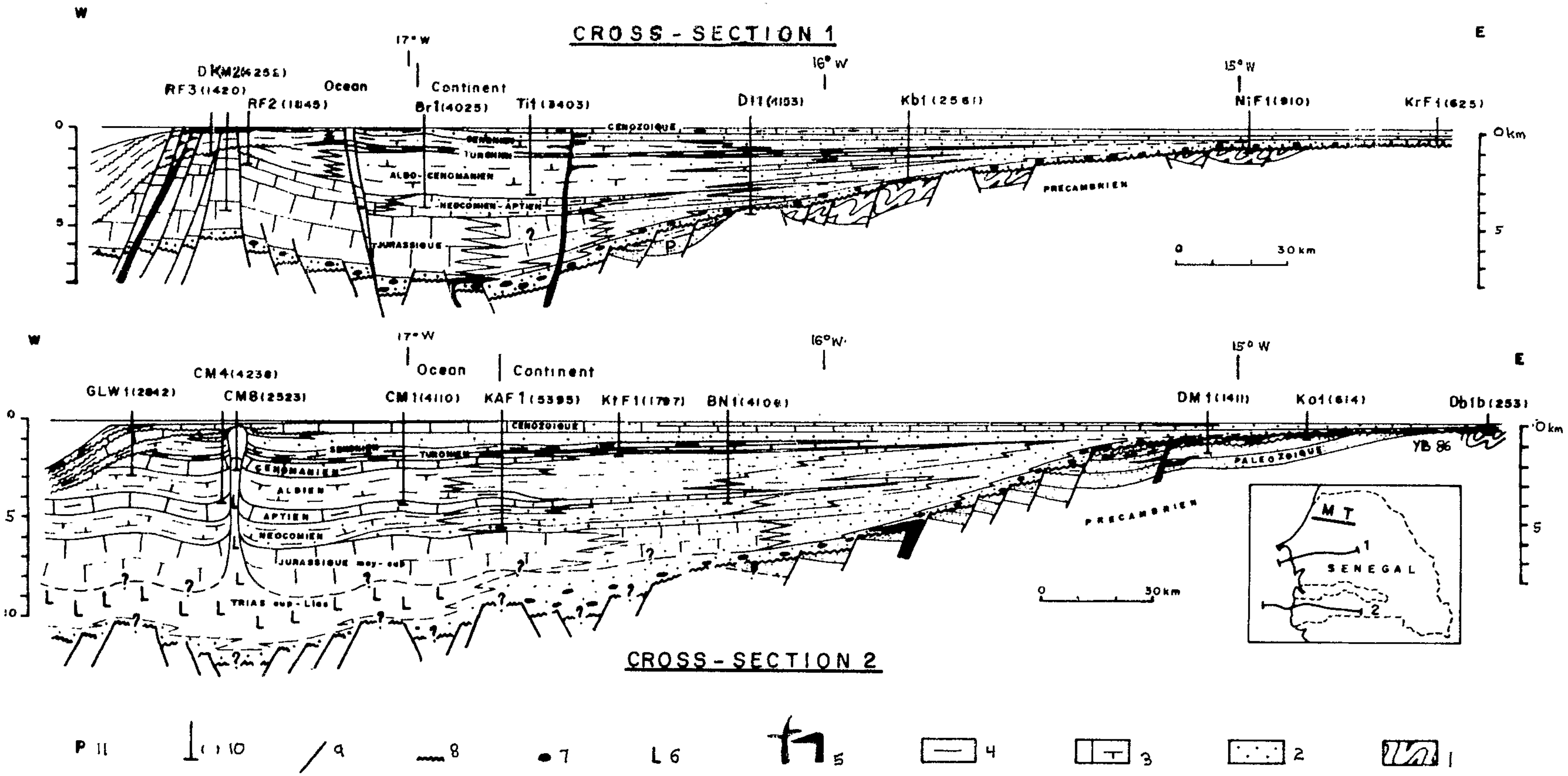

Fig. 4. Semi-interpretative geological cross sections of the Senegal basin constructed from borehole data (modified after Bellion and Guiraud [1984]). (1) Metamorphic rocks, (2) Sand, sandstone, (3) Limestone, (4) Clay and shale, (5) Igneous rocks (intrusive or lava flow), (6) Evaporite, (7) Conglomerate or coarse grain detritic rocks, (8) Unconformity, (9) Fault, (10) Borehole (total thickness in meters). P, Paleozoic.

volcanism is estimated to range in age from 1 to 35 Ma [Cantagrel et al., 1976; Crevola, 1980] and to have peaked during the Miocene and the Quaternary [Dillon and Sougy, 1974].

The S-M basin is poorly known from its surface geology. The main knowledge of the basin comes from drilling [Castelain, 1965; De Spengler et al., 1966; Templeton, 1971; Dillon and Sougy, 1974; Bellion and Guiraud, 1984], electrical soundings [Mathiez and Huot, 1966], aeromagnetic profiles [Bureau de Recherche Pétrolières, unpublished report, 1956], gravity studies [Crenn and Rechenmann, 1965; Liger and Roussel, 1979; Liger, 1980; Guetat, 1981; Roussel and Liger, 1983; Ponsard, 1985] and seismic refraction profiles [S. M. Wyrobek, unpublished report, 1960]. The Paleozoic-Precambrian granitic and metamorphic basement dips westward under the Meso-Cenozoic S-M basin, but its western extension under the sediments of the basin is only known within certain depth limits because of limitations in the geophysical methods used to locate it. The resistant basement is easily visible in the east, but disappears in the west in a zone between 15° and 15°30' W. West of longitude 16° W, boreholes (Figure 4) have reached Lower Cretaceous at about 3000 m and the basement at 4000 m. At the west end of the MT profile the basin is likely covered with more than 7000 m of post-Paleozoic sediments (see Figures 1 and 4).

Four holes (see Figure 1): Linguere 1 (Li 1), Leona 2 (La 2), Sagata F1 (Sa F1), and Toundou Besset 1 (TB 1), were drilled to depths of 970, 1150, 1720, and 4000 m, respectively, and bottomed in sedimentary rocks of inferred Cretaceous age. The well La 1, sited near the Atlantic coast, bottomed in Lower Maastrichtian igneous breccia at a depth of 710 m, a total of more than 250 m of metamorphosed sandy limestone with inclusions of microsyenite was intersected [Bellion and Guiraud, 1984]. The borehole Linguere F2 (Li F2) penetrated altered schists at a depth of 820 m, interpreted as metamorphic basement. To the east of the well Li F2, the hole Dioumanan F1 (Di F1) encountered the granitic basement at a depth of 600 m. Except for the igneous rocks, drilling indicates that the Cretaceous sediments are generally poorly consolidated and porous. Composition is dominantly coarse sandstones, but some clays and carbonate rocks are also encountered [Michaud, 1985]. In the depth range 600 to 3500 m, porosities decrease from 50% to about 10%. Below 3500 m an abrupt decrease in porosity occurs, probably caused by an increase in compaction. The temperature at the bottom of the deepest hole (TB 1-about 4 km deep) was found to be 93°-95°C, giving a gradient of 24°C/km.

Magnetic and gravity interpretations have indicated that the basement and Mesozoic-Cenozoic cover are contaminated by numerous mafic intrusions. The coastal positive gravity gradient area is interpreted in terms of a thinning of the continental crust, whereas oceanic crust is suggested in the Dakar area [Liger, 1980]. The circular positive anomaly (Leona Dome) [Pascal and Michel, 1967] at site Leona (90 mGal) is caused by a Late Cretaceous intrusive batholith of igneous rock [Bellion and Guiraud, 1984]. The structure of the sedimentary sequence in the region has a dominantly north-south trend and is characterized by linear faults. The combination of faulting and draping of the overlying sediments is probably due to complex basement block faulting.

GEOLOGICAL IMPLICATIONS OF MODEL RESISTIVITY STRUCTURE

Description and discussion of the resistivity structure beneath the MT line is divided into two parts: (1) the general sedimentary structure (shallow model in Figure 2a) and (2) the deep structure within the crust and upper mantle (Figure 3). The general resistivity trends in near surface rocks are easily understood in terms of electrolytic conduction via pore fluids [Flovenz et al., 1985]. The electrical conductivity of the rocks forming the sedimentary cover is almost totally due to three factors: (1) the conductivity of the pore fluid, (2) the fluid content of the rock, and (3) the way the fluid is distributed in the rock [Keller, 1971]. In fully saturated sediments the main source of bulk resistivity variation appears to be variation in the resistivity of the fluid. The effect of temperature is to increase conductivity of electrolytic fluids by a factor of 10 between 0° and 250°C, independent of pressure [Quist and Marshall, 1968].

The contribution to bulk resistivity

from electrolytic conduction through pores can be described approximately by the empirical Archie's Law:

$$\rho = \rho_o / \Phi^2$$

where ρ is the bulk resistivity, ρ_o is the fluid resistivity, and Φ is the porosity.

The pore fluid resistivity and the porosity are known from borehole data, and the bulk resistivities are estimated for the Cretaceous sediments from wells TB 1 and Sa F1. These wells are at a longitude close to the one of MT soundings LEO and OUA, respectively (Figure 1). The Cretaceous sandstones have bulk resistivities varying between 0.28 and 0.41 ohm-m at a depth of about 600 m and in the range 0.34 - 0.46 ohm-m at a depth of approximately 1700 m. At a depth of about 3500 m in the well TB 1, the bulk resistivity is about 1.4 ohm-m.

The gross structure of the sedimentary sequence in the S-M basin in northern Senegal can be outlined by using calculated resistivities derived from the MT model (Figure 2a). Generally, there is a basic division of the sedimentary section into four resistivity layers:

1. The shallowest layer has resistivities in the range of 20 to 200 ohm-m, except at LEO near the coast, where the shallow 50 ohm-m layer is replaced by a zone of low (0.25-0.35 ohm-m) resistivity. Saline groundwater may be the cause of the lower resistivity in the area west of LOU. Facies differences between the eastern and western parts of the basin are marked by lateral variations of resistivity. The Tertiary deposits generally consist of carbonates with sands and clays in the east (resistivity-20 ohm-m), carbonates toward the center of the profile (resistivity-200 ohm-m), and clays in the west (resistivity-50 ohm-m). The 200 ohm-m zone lies on an extension of an uplift (Guiers dome, Figure 1) [Trénous and Michel, 1971], located just north of the MT profile, between soundings BOU and LIN, where the Tertiary rocks consist mainly of carbonates .

2. Underlying the shallowest layer is a thin layer of very low resistivity which can be followed across the entire profile. It varies from about 1 ohm-m in the east to 0.25 ohm-m in the west (deep part of the basin), and is thickest (at least 1700 m) at sounding LEO. It can be correlated with Upper Cretaceous sandstones and sandy clays, and the more conductive part lying beneath sites NGA to LEO is interpreted as being intensely brine-saturated. The resistivities in the range of 0.25 to 0.35 ohm-m correspond quite well with those deduced from borehole measurements. Westward from sounding THI to sounding LOU the thickness of the 0.25- to 0.35-ohm-m unit increases strongly, and this may indicate a zone of faulting. The mixing patterns between fresh and salt water are complex, but the lower boundary of fresh water generally is at depths of less than 500 m (Di F1 well, 530 m; Li F2 well, 500 m; Li 1 well, 420 m).

3. A deeper, thick unit with resistivities in the range 0.7-2 ohm-m extends westward from sounding DAH to sounding LEO. Except at the west end of the profile, this layer includes much of the sedimentary sequence from Turonian to the basement. To the west, in the well TB 1, the Lower Cretaceous sandstone sequence has bulk resistivity values as low as 0.34-0.46 ohm-m at depths greater than 1700 m. The most reasonable estimate of rock composition in this sequence is a combination of both high-resistivity (carbonates) and low-resistivity (sandstones and clays) rocks. Below 2600 m, this unit is not present at LOU and is replaced by a more conductive unit (0.4 ohm-m) which can be correlated, for example, with a more sandy facies. These low resistivities might be caused by an increased fracturing at depths in excess of 1000 m, whereby the pores, fissures, and caverns might be filled with highly conducting fluids. The 0.4- to 0.7-ohm-m unit is thought to be a reservoir of saline fluids. Between sites LOU and LEO a lateral resistivity variation from 0.7 to 2 ohm-m marks a facies change of the Lower Cretaceous to a more argillaceous sequence west of the site LOU.

4. Abrupt eastward truncations of the deeper layers may mark vertical steps in the basement resulting from steep faults that formed during subsidence of the continental margin and seafloor spreading. This appears to be consistent with other geophysical results. For example, the zone between soundings BOU and LEO is marked by linear positive magnetic anomalies with an approximately north-south trend (Figure 5), in particular, a long positive magnetic anomaly associated with a large gradient in the gravity field in the vicinity of the site LOU (Figure 6). Liger

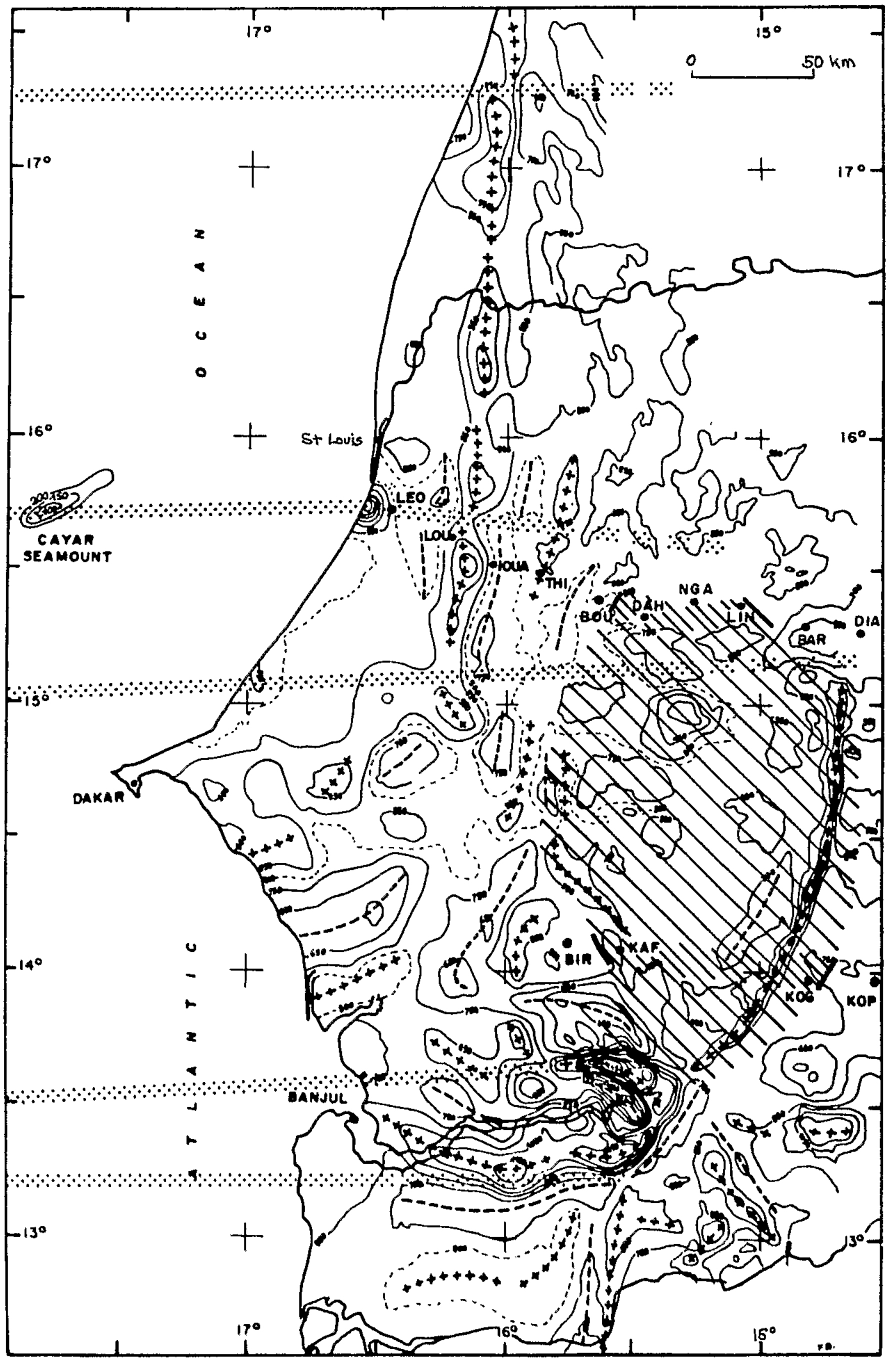

Fig. 5. Simplified aeromagnetic map of the Senegal basin (after Bureau de Recherches Pétrolières, unpublished report, 1956). The contour interval is 100 gammas, the lines of crosses indicate positive magnetic anomalies, and the dashed lines indicate negative magnetic anomalies. Continuous and discontinuous stippled areas indicate transform faults and their inferred extensions, respectively [after Bellion and Guiraud, 1984]. Heavy lines indicate the boundaries of the anomalous crustal layer along the northern profile (stations DAH to LIN) and along the southern profile (stations KAF to KOG). Wide-spaced hatched area indicates the supposed zone where electrical resistivity in the crust is abnormally low.

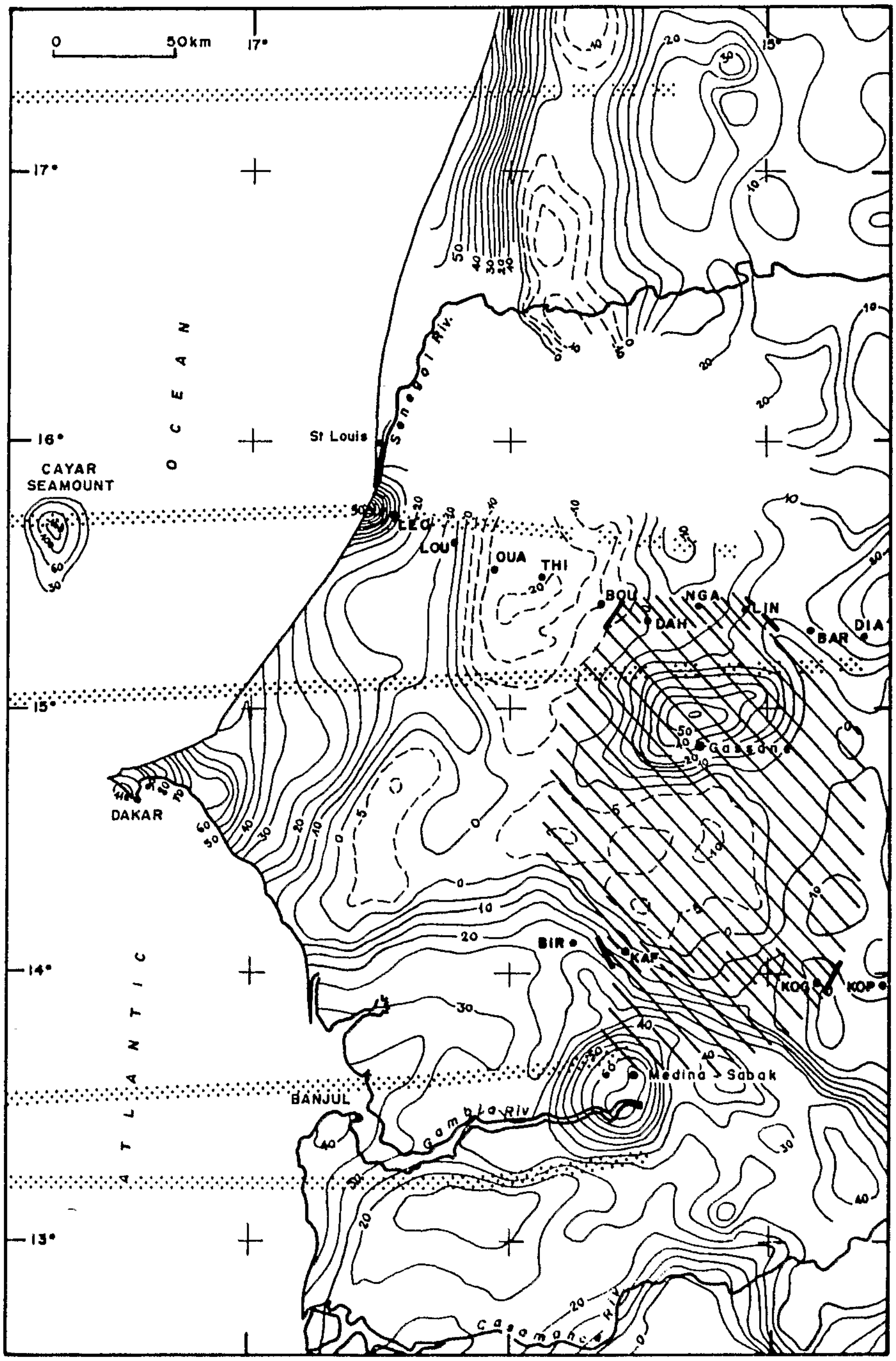

Fig. 6. Bouguer gravity map of the Senegal basin [after Crenn and Rechenmann, 1965]. The contour interval is 5 mGal. Other symbols as in Figure 5.

[1980] and Roussel and Liger [1983] have suggested that the strong positive gravimetric anomalies, such as in the Louga area, can be explained by mafic intrusions within the basement. The Société Africaine des Pétroles (unpublished report, 1960) seismic refraction profile revealed north-south trending faults with the west side downthrow near the basement surface close to 16°W latitude. A horst and graben system occurs at the basement surface between BOU and THI. Beneath OUA, the resistivity structure displays a slightly less conductive (1-2 ohm-m) material from 3000 to 3800 m depth. This material is associated with a negative magnetic anomaly between two linear, north-south positive anomalies (Figure 5). This change in resistivity can be attributed to variations in porosity (increase in compaction) and/or salinity of associated fluid, in an area of complex faulting. At a depth of 3500 m, the bulk resistivities estimated from the Archie's Law (well TB 1) indicate values of 1.3-1.5 ohm-m.

Across the entire profile, there is a downward transition from low to high resistivity (of the order of 2000 ohm-m). This occurs at depths of about 600-1000 m in the east and at a depth exceeding 3000 m in the west. The great depth to the high-resistivity rocks in the west probably indicates that these are either basement or near basement rocks. The extreme variation in depth of the top of this layer is in agreement with borehole data and other independent geological and geophysical information on the depth of the basement which have been obtained east of the site OUA. A major seismic refractor dipping to the west appears to correlate with the resistivity boundary (Figure 2a). It has a P wave velocity of 6 km s^{-1}, which must represent well-indurated rocks, perhaps basement gneisses. There is, however, a significant difference between MT results and the depth of the basement west of site OUA. The high resistivity (2000 ohm-m) detected below 3500 m at sites LOU and LEO is not in accord with the resistivity (1.3-1.5 ohm-m) found in the Aptian section at that depth in well TB 1. It is worthy of note, however, that pre-Albian rocks are known to appear as high-resistivity limestones along section 1 (Figure 4) at wells Dakar Marine 2 (DKM 2) and Mbour 1 (Br 1). It is not unreasonable to assume that the resistive unit observed below the thick conductor at LOU and LEO consists of limestones.

By combining the resistivity structure and other independent geophysical and geological information a model for the tectonic evolution of the S-M basin in northern Senegal is proposed here (Figure 7). The conflict between the shallow (3 to 4 km) electrical conductivity estimates of depth to basement and deeper sedimentary layers inferred from drilling (Figure 4) is reconciled by inferring that high (2000 ohm-m) resistivity below LEO and LOU is partly due to a thick unit of Aptian limestone. The positive magnetic anomalies are related to intrusions within the basement (soundings LOU and THI) [Liger, 1980]. Other major features of the model include basement disruption by strong, intermittent Cretaceous normal faulting, a horst-graben system between THI and BOU, and a large, low-resistivity Lower Cretaceous sediment-filled basin between sites THI and LOU that is bounded by west dipping listric normal faults.

The deep crustal rocks are generally highly resistive (2000 ohm-m), isotropic, and free of large lateral resistive discontinuities, except below sites LIN, NGA and DAH (Figure 3), where the MT data require the presence of highly conductive (2 ohm-m) material at depths of about 4-23 km. At depths of about 19-23 km there is a general trend toward lower resistivities from 2000 ohm-m to about 200 ohm-m. However, both the resistivity and depth of this layer below the deep part of the basin are very ill resolved because of the obscuring effect of the thick low-resistivity sediments. The existence of the 200- to 2000-ohm-m layer beneath the deep part of the basin is poorly constrained inasmuch as the observed data are fitted nearly as well by an entirely resistive crust and the presence of the 200 ohm-m material becomes suspect between soundings NGA and LEO. In the case of a tectonically stable crust a conductive layer at a depth of over 20 km would be interpreted as representing the upper mantle [Garland, 1975]. Liger [1980] infers a crustal thickness of about 30 km below the sedimentary basin from gravity data. The anomalously low electrical resistivity (2 ohm-m) which was detected by the MT soundings in the crust below the sites LIN, NGA, and DAH (Figure 3) is a very consistent and striking feature. Perhaps, surprisingly, this is located just to the east of the deep part of the basin and not under it. The very strong lateral variation of resistivity, however, is enigmatic considering other independent geophysical information and the plausible mechanisms by which significant lateral resistivity contrasts could have been expected to develop in this zone.

Recent magnetotelluric and differential geomagnetic sounding studies [Ritz, 1984a,

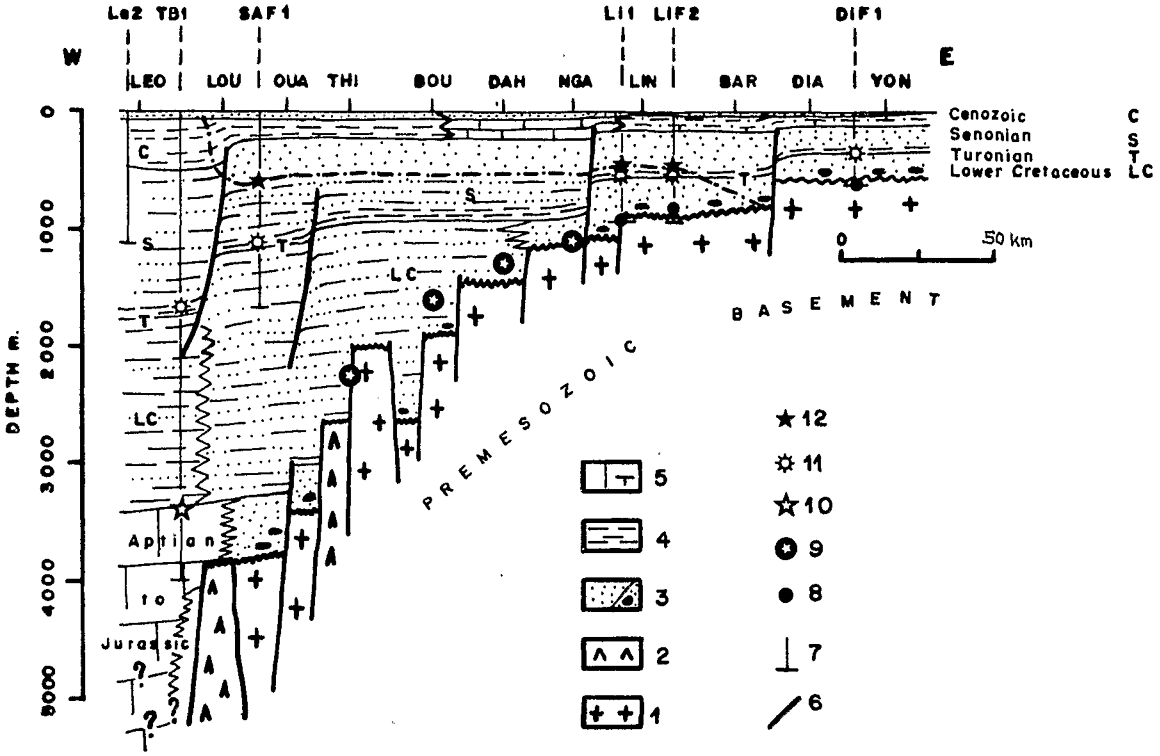

Fig. 7. Schematic model for the tectonic evolution of the Senegalo-Mauritanian basin in northern Senegal (see text for discussion). (1) Granitic or metamorphic rocks, (2) Triassic to Liassic igneous rocks, (3) Sand, sandstone, conglomerate, (4) Clay, shale, (5) Limestone, (6) Fault, (7) Borehole, (8) Basement after borehole data, (9) Seismic basement (after Société des Pétroles du Sénégal, unpublished report, 1960), (10) Top of the Aptian limestone (TB1 borehole), (11) Turonian beds after borehole data, (12) Freshwater/saltwater interface (the star refers to borehole data).

1984b] across the southern part of the S-M basin (Figure 1) have shown that the upper crust beneath the eastern margin of the deep basin, between Kounghel (KOG) and Kaffrine (KAF), has an anomalous electrical conductivity (resistivity 20-30 ohm-m) and a maximum thickness of 10 km. However, the conductor in southern Senegal lies closer to the base of the sediments, and has a higher resistivity and a smaller thickness compared to the northern conductor. Both the very highly conductive zone beneath the sites DAH, NGA, and LIN in northern Senegal and the KOG-KAF conductor in southern Senegal are major structures. Of particular significance is the fact that both margins of the southern conductor appear to be associated with linear north-south positive magnetic anomalies (Figure 5). The magnetic anomaly of the east side swings to the southwest south of 14°30'N, and the western one swings to the southeast around KAF station. It may coincide with an extensional structure in basement between DIA and BAR (Figures 5 and 7); however, there is no pronounced magnetic and/or gravity variation north of 15°N latitude indicating a continuation of such major structures. In general, the positive magnetic anomalies can be correlated with dikes or other magmatic intrusions in the basement and locally in the cover [Liger, 1980]. In the survey area, two transform faults have been projected onshore (Figures 5 and 6) on the basis of east-west truncations of gravity and magnetic anomalies in latitudes 15°N and 15°40'N [Bellion and Guiraud, 1984]. The transform faults and magnetic anomalies provide the basis for speculating that the southern conductor links with the northern one, and the low-resistivity zone at crustal depth beneath the eastern margin of the deep part of the basin may be considered as the tectonic response to changes in regional stress, induced by Mesozoic rifting and/or later tectonic and volcanic events. Figures 5 and 6 indicate supposed boundaries of the anomalous crustal body in connection with magnetic highs and gravity anomalies. The circular gravity anomalies (Gassane and Medina Sabak) are supposed to be associated with thick mafic intrusions within the basement complex [Liger, 1980].

There is a variety of ways in which water can lower the resistivity of rocks. Additional factors which must be considered in studying the relationship of low resistivities to water are the anisotropy of the resistivity and the apparent resistivity principal directions. At most of the stations the electrical impedance strike direction is approximately north-south [Ritz and Vassal, 1986]. MT data display moderate anisotropy at stations inside the deep basin, while at stations outside the deep basin the anisotropy is especially important, with the minimum resistivity along the north-south regional strike. Adam [1984], among others, draws attention to the fact that the resistivity is considerably smaller in the direction of the known fracture lines. If the water is in open fractures, one expects anisotropic resistivity with the minimum value along strike, and if the water is in connected pore spores, the resistivity should be more isotropic. This suggests that the deep crustal conductor under DAH, NGA and LIN can be connected with fractures full of water, associated with normal faulting as the Atlantic opened. In the western part of the MT profile (deep basin) the very low resistivity values in the near-surface zones can be due to a combination of two effects: water in interconnected spaces, especially in the extreme western part of the basin, and water in open fractures.

The possible causes of the lowering of the bulk resistivity of the crust beneath the eastern margin of the deep part of the basin will be reviewed.

It could be the effect of present anomalously high temperature, presumably in the deeper parts of the crust, where temperature may be high enough that electrical conduction in the solid rocks decreases the resistivity to 2 ohm-m. Adam [1978] and Shankland and Ander [1983] found a good correlation between depth and low electrical resistivity in the crust and high heat flow. Recent heat flow measurements at 24 points in the Dakar region [O. Fambitakoye, personal communication, 1985] gave a mean value of 60 mw/m^2. This value is too low to be compatible with a thermal origin of the high conductivity. However, great care is required in drawing conclusions from low heat flow through an upper crust fractured and filled with water. Local vertical movement along faults of water may seriously perturb the heat flow, and the possibility of a small fraction partial melt in the crust on a regional scale beneath the eastern part of the basin cannot be ruled out as a possible contributor to the higher than normal conductivities. If so, elevated temperatures most probably would be related to modern tectonic activity.

The crustal high-conductivity zone could derive from the formation of the continental margin through continental fragmentation, rifting, attenuation, and subsidence. Of particular interest is the degree of possible fracturing landward. Note that mafic intrusions within the basement persist eastward (Figure 5). The electrical anomaly could then be connected with deep fracture zones of pre-Atlantic or rift age, i.e., Jurassic or older, and that could be reworked later. If so, the presence of a large volume of fractured and fissured rocks below the margin of the deep basin could provide a path for percolation of water to a deeper zone, and pore and crack-fluid conduction effects would become significant and could appreciably lower the bulk rock resistivity. This possible source for the conductivity anomaly could explain both the absence of a magnetic anomaly and a significant gravity anomaly by the fact of the weak density between the fractured and host rocks.

Drury and Niblett [1980] have suggested that segments of buried oceanic crust in the present continental crust can explain the high conductivities. The presence of bands of oceanic crust beneath the margin of the deep basin is compatible with the observed resistivities there if the rocks have been serpentinized. Their occurrence throughout the S-M basin would be comprehensible and could be explained from the existence of a buried failed rift associated with Mesozoic rifting. It should be noted that such a failed rift does not give rise to high heat flow. However, if the conductivity anomaly is caused by an accumulation of oceanic crustal rocks, the observed gravity and magnetic fields must be satisfied. The southern Senegalese conductor correlates closely with a magnetic high (Figure 5). In South Africa, a similar result has been reported by De Beer et al. [1982], who attribute the high conductivity and magnetization to an accumulation of serpentinized marine crustal rocks.

These are simply possible explanations for the unexpected presence of very conductive bodies within relatively resistive crust. Because of the lack of pronounced magnetic and gravity anomalies over the northern conductor, the relatively low values of the heat flow (60 ± 8 mw/m^2), and the fact that both gravimetric and magnetic anomalies in the western part of the basin are highly elongated in a north-south direction and probably reflect extensional structures in S-M basin basement, we believe that the most attractive hypothesis is that a large crushed zone in the basement of the eastern part of the basin provides the porosity for saline waters which act as an electrolytic fluid to produce the condutivity anomaly. The anomaly probably identifies the eastern limit of the extensional deformation of the S-M basin.

No conductive layer has been inferred at great depths for the westerly stations; nevertheless, at depths in excess of 150 km there is a general trend toward lower resistivities. The transition from 2000 ohm-m to about 2 ohm-m occurs at about 175 km (Figure 3). A similar general decrease in resistivity also occurs beneath the easterly stations. Some degree of partial melting in the mantle has been the most frequent interpretation for conducting layers in the upper mantle at depths of about 150 km [Shankland and Waff, 1977; Lilley et al., 1981].

Another interesting feature of this geoelectric profile is the existence of a layer 20 km thick with resistivity of about 20 ohm-m at 80 km depth under the eastern part of the basin. A possible explanation for the low mantle electrical resistivity is the presence of water produced by dissociation of amphibole [Wyllie, 1981] under pressure and temperature conditions found around 90 km. For the westerly sites, the main traits of the deep conductivity distribution are ill resolved because of the obscuring effect of the thick low-resistivity sediments.

CONCLUSIONS

The MT method has been used to obtain information about the electrical condutivity structure and tectonics of the S-M basin in northern Senegal. Other independent geophysical and geological observations place significant constraints on the crustal structure and thus on acceptable tectonic models, but the conductivity anomalies add significant new information to aid in tectonics studies. The shallow geoelectric section is dominated by the water-saturated, unconsolidated, low-resistivity sediments. The details of the electrical characteristics of the sedimentary sequence are of interest, even though they are not always accurate. They do, however, add information about the gross division of the subsurface in a region in which not much is known because of the scarceness of deep boreholes.

The tectonic significance of the near-surface resistivity structure is illustrated with a schematic section through the S-M basin in northern Senegal that is in agreement with borehole data and with other geophysical data.

An interesting feature of this geoelectric profile is the existence of a very good crustal conductor under the eastern margin of the deep basin, similar to the one previously reported along a traverse in the southern part of the S-M basin [Ritz, 1984a]. The basement outside the deep basin may be fractured and filled with conducting fluids, but the origin of this conductive body cannot be established with confidence because of the scarcity of detailed geophysical data.

REFERENCES

Adam, A., Geothermal effects in the formation of electrically conducting zones and temperature distribution in the earth, Phys. Earth Planet. Inter., 17, 21-28, 1978.

Adam, A., Fractures as conducting dykes and corresponding two-dimensional models, Geophys. Prospect., 32, 543-553, 1984.

ASGA-UNESCO, Carte tectonique internationale de l'Afrique à 1/5,000,000, Paris, 1968.

Bellion, Y., and R. Guiraud, Le bassin

sédimentaire du Sénégal, Synthèse des connaissances actuelles, in Plan Minéral de la République du Sénégal, pp. 4-63, BRGM and DMG, Dakar, Sénégal, 1984.

Cantagrel, J.-M., J. R. Lappartient, and F. Tessier, Nouvelles données géochronologiques sur le volcanisme ouest-africain, paper presented at 4e Réunion Annuelle Sciences Terre Paris, Soc. Géol. France, Paris, 1976.

Castelain, J., Aperçu stratigraphique et micropaléontologique du Bassin du Sénégal, historique de la découverte paléontologique, Mém. BRGM, 32, 135-156, 1965.

Chanut, C., Le bassin sédimentaire Sénégalais, paper presented at The West African connection, evolution of the central Atlantic Ocean and its continental margins, SGA Penrose Conference and CNRS-NSF Colloquium, Giens, France, 1984.

Crenn, Y., and J. Rechenmann, Mesures gravimétriques et magnétiques au Sénégal et en Mauritanie occidentale, Cah. ORSTOM Sér. Géophys., 6, 1-59, 1965.

Crevola, G., Principaux caractères du volcanisme de la Presqu'île du Cap-Vert (Sénégal), paper presented at 8e Réunion Annuelle Sciences Terre Marseille, Soc. Géol. France, Paris, 1980.

De Beer, J. H., J. S. V. Van Zijl, and D. I. Gough, The Southern Cape Conductive Belt (South Africa): Its composition, origin and tectonic significance, Tectonophysics, 83, 205-225, 1982.

De Spengler, A., J. Castelain, J. Cauvin, and M. Leroy, Le bassin secondaire-tertiaire du Sénégal, in Bassins Sédimentaires du Littoral Africain, Littoral Atlantique, edited by D. Reyre, pp. 80-94, Association Services Géologiques Africains, Paris, 1966.

Dewey, J. F., W. C. Pitman, W. Ryan, and J. Bonnin, Plate tectonics and the evolution of the Alpine system, Geol. Soc. Am. Bull., 84, 3137-3180, 1973.

Dillon, W. P., and J. M. A. Sougy, Geology of West African and Canary and Cape Verde islands, in The Ocean Basins and Margins, vol. 2, edited by A. E. M. Nairn and F. G. Stehli, pp. 315-390, Plenum, New York, 1974.

Drury, M. J., and E. R. Niblett, Buried ocean crust and continental crust geomagnetic induction anomalies: A possible association, Can. J. Earth Sci., 17, 961-967, 1980.

Flovenz , O. G., L. S. Georgsson, and K. Arnason, Resistivity structure of the upper crust in Iceland, J. Geophys. Res., 90, 10136-10150, 1985.

Garland, G. D., Correlation between electrical conductivity and other geophysical parameters, Phys. Earth Planet. Inter., 10, 220-230, 1975.

Guétat, Z., Etude gravimétrique de la bordure Occidentale du craton ouest-africain, Thèse 3e cycle, 446 pp., Univ. de Montpellier, Montpellier, France, 1981.

Jiracek, G. R., E. P. Gustafson, and P. S. Mitchell, Magnetotelluric results opposing magma origin of crustal conductors in the Rio Grande rift, Tectonophysics, 94, 299-326, 1983.

Keller, G. V., Electrical characteristics of the Earth's crust, in Electromagnetic Probing in Geophysics, edited by J. R. Wait, pp. 13-76, Golden Press, Boulder, Colo., 1971.

Liger, J. L., Structure profonde du bassin côtier sénégalo-mauritanien. Interprétation de données gravimétriques et magnétiques, Trav. Lab. Sci. Terre S. Jérôme Marseille Sér. B, 16, 1-158, 1980.

Liger, J. L., and J. Roussel, Etude gravimétrique du bassin côtier profond sénégalais, Rev. Géol. Dyn. Géogr. Phys., 21, 419-427, 1979.

Lilley, F. E. M., D. V. Woods, and M. N. Sloane, Electrical conductivity profiles and implications for the absence or presence of partial melting beneath central and south-east Australia, Phys. Earth Planet. Inter., 25, 419-428, 1981.

Mathiez, J. P., and G. Huot, Prospection géophysique et recherches d'eaux souterraines. Exemples d'applications en Afrique occidentale. Bassin de Sénégal-Mauritanie, pp.72-78, Com. Int. Afr. Et. Hydraul., Paris, 1966.

Michaud, L., Les milieux de sédimentation crétacés du Sénégal et leur évolution diagénétique (Etude de subsurface), Thèse 3e cycle, 285 pp., Univ. d' Aix-Marseille III, Marseille, 1985.

Pascal, M., and P. Michel, Notice explicative de la carte géologique à 1/200,000 Louga, BRGM, Dakar, Sénégal, 1967.

Ponsard, J.F., La marge du craton ouest-africain du Sénégal à la Sierra Leone: interprétation géophysique de la chaîne panafricaine et des bassins du Protérozoïque à l'Actuel, Trav. Lab. Sci. Terre S. Jérôme Marseille Sér. B, 25, 1-198, 1985.

Quist, A. S., and W. S. Marshall, Electrical conductances of aqueous sodium chloride solutions from 0-800°C and at pressures to 4000 bars, J. Phys. Chem., 72, 648-703, 1968.

Reyre, D., Remarques sur l'origine et l'évolution des bassins sédimentaires africains de la côte atlantique, Bull. Soc. Géol. Fr., 7, 1041-1059, 1984.

Ritz, M., Electrical resistivity structure of the Senegal basin as determined from magnetotelluric and differential geomagnetic soundings, Geophys. J. R. Astron. Soc., 79, 635-649, 1984a.

Ritz, M., Inhomogeneous structure of the Senegal lithosphere from deep magnetotelluric soundings, J. Geophys. Res., 89, 11317-11331, 1984b.

Ritz, M., and J. Vassal, Geoelectrical structure of the northern part of the Senegal basin from joint interpretation of magnetotelluric and geomagnetic data, J. Geophys. Res., 91, 10443-10456, 1986.

Roussel, J., and J. L. Liger, A review of deep structure and ocean-continent transition in the Senegal basin (West Africa), Tectonophysics, 91, 183-211, 1983.

Shankland, T. J., and M. E. Ander, Electrical conductivity, temperatures, and fluids in the lower crust, J. Geophys. Res., 88, 9475-9484, 1983.

Shankland, T. J., and H. S. Waff, Partial melting and electrical conductivity anomalies in the upper mantle, J. Geophys. Res., 82, 5409-5417, 1977.

Templeton, R. S. M., The geology of the continental margin between Dakar and Cape Palmas, in The geology of the East Atlantic Continental Margin, Rep. 70/16, edited by F. M. Delaney, pp. 43-60, Gt. Brit. Inst. Geol. Sci., London, 1971.

Trénous, J.-Y., and P. Michel, Etude de la structure du dôme de Guier (Sénégal nord-occidental), Bull. Soc. Géol. Fr., 7, 133-139, 1971.

Van der Linden, W. J. M., The crustal structure and evolution of the continental margin off Senegal and the Gambia, from total-intensity magnetic anomalies, Geol. Mijnbouw, 60, 257-266, 1981.

Von Rad, U., K. Hinz, M. Sarnthein, and E. Seibold, Geology of the northwest African continental margin, 700 pp., Springer-Verlag, New York, 1982.

Wyllie, P.J., Plate tectonics and magma genesis, Geol. Rundsch., 70, 128-153, 1981.

Y. Bellion, Dép. Géologie, Fac. Sci., Dakar-Fann, Sénégal.

R. Flicoteaux, Laboratoire de Géologie Dynamique, Fac. Sci. Saint Jérôme, 13397 Marseille, France.

M. Ritz, ORSTOM, BP 1386 Dakar, Sénégal

(Received July 8, 1986;
revised February 11,1987;
accepted February 13, 1987.)