USE OF THE MAGNETOTELLURIC METHOD FOR A BETTER UNDERSTANDING OF THE WEST AFRICAN SHIELD

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Abstract. Magnetotelluric soundings have been carried out in the Republic of Upper Volta and in the Niger Republic to gain a better understanding of the structure of the West African shield. The sounding stations are situated from east to west on a sedimentary basin on the Central African mobile belt (Pan-African orogeny at 550 ± 100 m.y.) and on the West African craton (Eburnean orogeny at 1850 ± 250 m.y.). The results show that the craton is characterized by a zone of high resistivity in the crust and uppermost mantle. The absence of a conductive zone at the interface between the crust and the uppermost mantle is consistent with the hypothesis of Hyndman and Hyndman (1968) on the dehydration of the crust of the stable shields. The first conductive layer of the craton is situated at a depth of 130 km with a temperature of about 860°C. In the mobile belt and the basin the presence of a low resistivity layer at a depth of 30-40 km has been established. If water is present in the lower crust, it can explain the origin of this conductive zone. A plausible explanation is that this layer may have been formed by the slow infusion of water from the mantle during the last thermal reactivation. Regional differences in electrical conductivity structure between the Central African mobile belt and West African craton appear to extend deeper than 200 km. Modeled conductivity variations with depth in the upper mantle obtained from magnetotelluric results are compared to other continental models (thermal model-seismic structure) in order to define a lower lithospheric boundary for West Africa. At the present stage the problem is not yet resolved (mobile crustal plate or anchorage in the African plate).

Introduction

A program of research in electromagnetic soundings has been carried out in West Africa by measuring the components of the electric and magnetic fields on the earth's surface. This program, which began in 1972 under the auspices of Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), had as its objective the determination of the electric properties of the crust and upper mantle and the acquisition of more complete knowledge of the structure of West Africa. To study the interior of the earth, it is necessary to make use of indirect methods of observation. One of the methods which we have used in this program is magnetotelluric sounding (MT), which was devised by Cagniard (1953). We have applied this method of sounding in the

study of the structure of the West African shield.

The research region is located in West Africa between the Niger River and the Mali/Upper Volta frontier (Figure 1). From the geological point of view most of region belongs to the West African craton, which was definitively stabilized during the Eburnean (or Birrimian) orogeny, the end of which is dated at about 1850 ± 250 m.y. (Figure 2). Birrimian rocks are by far the most plentiful in the Precambrian basement. Elsewhere the basement is concealed by a more recent sedimentary cover. We can distinguish metamorphic and crystalline rocks. The most significant part of the metamorphic rocks is made up of a thick series of argillaceous schists, graywackes, and volcanosedimentary formations (for instance, Riziam and Dacola groups). The tectonics of these formations is not well known, for in most of cases, only schistosity is visible and the stratification dip is unobservable (Ducellier, 1963). Crystalline Birrimian rocks extend considerably through Upper Volta, and petrographical types are quite varied. The granites contain biotite and amphibole; alkaline granites and granodiorites are also found. The deformation is generally quite strong and has produced overthrusts and sometimes shearing. Sedimentary rocks consist of series of the Infracambrian age, of the "continental terminal", a limnic and fluvial formation of Tertiary age and Quaternary dunes (Machens, 1973). The Infracambrian trangressed on a peneplaned basement. The Infracambrian series are situated on the northern border of our region (Firgoun sandstones) and on the southern border (Voltaian sandstones). The former belong to the Taoudenni basin of the western Sahara, the latter is part of the Voltaian basin of Ghana and Togo. On the western border we can distinguish a Nigerian system, of probable Infracambrian age (Toun schists and Sotuba sandstones). The Infracambrian series are never more than 1000 m thick. They are gently folded. The fold centers are outside our region in the southeastern part of the Taoudenni basin and in the southeastern part of the Voltaian basin. Geochronological studies have given ages of 550 ± 100 m.y. (Pan-African orogeny). The stable basement to the east of Niger River, with its relatively thin epicontinental cover, represents the foreland of this folding. In this way, transition zones (mobile belts) were formed all around the West African Precambrian craton (Bessoles, 1977). The "continental terminal" rests horizontally either on the basement or on the Infracambrian, which is also greatly eroded. Its exact age is unknown. In this article we are particularly interested in the eastern section of the craton (Niger and Upper Volta) as well as in the Central African mobile belt in Niger (Figure 1). So from a geological point of view we have in the west a resistive basement of Precambrian type (granite-gneiss) cropping out over most of the region and
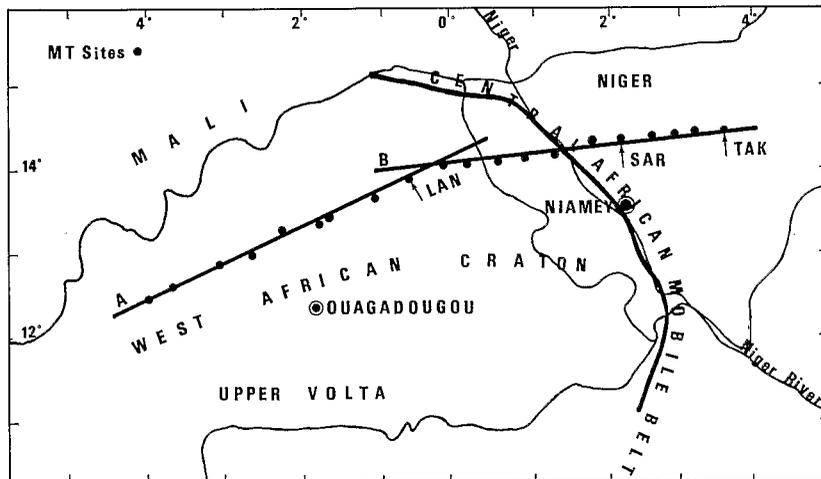
Fig. 1. Map of Niger-Upper Volta showing the measuring sites and measuring profiles.
The curved line represents the contour of the West African craton.

bordering on some Infracambrian series (clay-bearing sandstone of Central Niger). To the east the basement becomes more conductive (Compagnie générale de Géophysique, (CGG), 1958; Crenn et al., 1959; Greigert and Pougnet, 1965). Two profiles have been completed in this region by using the MT method. Profile A, situated entirely on the West African craton, extends some 400 km in length. It crosses the Baoulé-Mossi domain and ends in Liptako. In this region the greater part of the profile rests on very old granite and gneiss (Liberian or Eburnean age undetermined), interbedded between schistose and volcanic rocks. Profile B crosses the Liptako region, the Central African mobile belt, and the sedimentary basin; it is also 400 km in length, lying practically east to west in direction.

Data Collection and Analyses

Data were collected between January 1974 and June 1977 at the sites in Upper Volta and Niger shown in Figure 1. Instruments used to collect data consisted of two Mosnier-type sensors (horizontal variometers with a suspended magnet) for measuring components of the time variations of the earth's magnetic field (H) and two ortho-gonal sets of thin lead electrodes spaced 500 m apart for measuring the electric fields (E). Signals were preamplified and filtered before they were recorded on a "Servo-trace P2V Sefram" (paper chart recorder). For all the sites a low-frequency band 0.001-0.1 Hz was used; sections of continuous records 6 hours long were required. Periods as long as 1 day were recorded at two sites to extend the spectral range of the data (Ritz, 1982b). For each site the best recordings are chosen, and a digitizing interval of 3 s was used. Reduction of these data followed the methods described by Sims and Bostick (1969). The power spectra for the electromagnetic compon-ents were estimated by computing the Fourier transforms of each of the time series with the fast Fourier transformation. Auto-and-cross spectral estimates were averaged in frequency bands of constant bandwith. 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

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

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 resist-ivities for the principal directions were calcul-ated from the equation

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

where ρ_{ij} is the apparent resistivity in ohm m, T is the period in seconds, and Z_{ij} an off-diagonal element of the rotated impedance tensor. The 90% confidence limits for apparent resist-ivity is 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 structures. Large ratios are a measure of strong three dimensionality. The skew parameter is in the range 0.06-0.15 for the basin data. The average degree of skew for MT soundings on the Precambrian craton and on the mobile belt is less than 0.3.

As an example, Figure 3 shows for sites Landamaol (LAN), Sargan (SAR), and Takawar (TAK) the calculated values of the apparent resist-ivities in the principal directions with their 90% confidence limits. There are several feat-ures of interest in these results. First, con-sider the stations LAN and SAR, where the most obvious feature is the large difference in mag-nitude of the maximum apparent resistivities over the total period band between these sites (more than one order of magnitude). The differ-ence tends to decrease for the minimum apparent
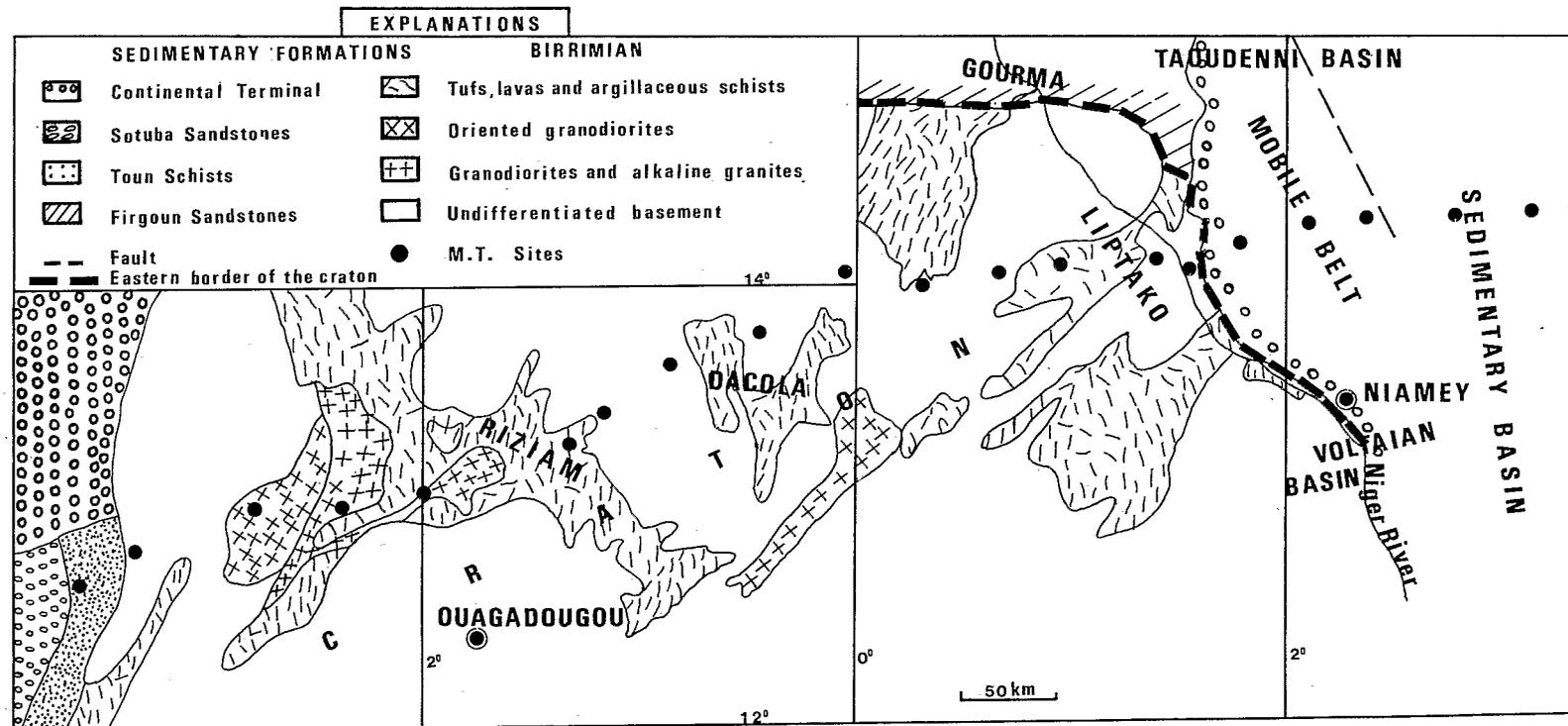
Fig. 2.   Sketch map of Niger–Upper Volta area showing the essentials of the geology and location of MT sites (from Bessoles, 1977).
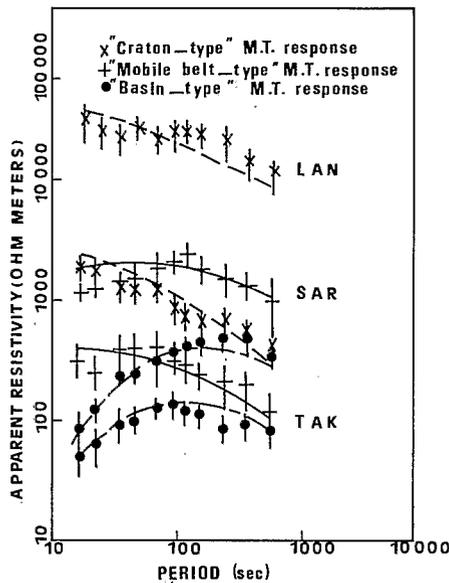
Fig. 3. Apparent resistivities as function of
the period calculated into principal axes, site
LAN (crosses), site SAR (pluses), site TAK
(dots). The superimposed solid curves represent
theoretical curves calculated from the model,
site LAN (dashed curve), site SAR (solid curve),
site TAK (dot-dashed curve).

resistivities, especially for the longer periods.
The MT response at LAN is common to all curves
of apparent resistivity in the West African
craton. All stations exhibit strongly anisotrop-
ic behavior, the apparent resistivities decrease
with increasing period, and the maximum apparent
resistivities are very high. The MT responses
at SAR and TAK also present a difference in
magnitude of the major apparent resistivities;
however, this difference is smaller than between
sites LAN and SAR. The amplitudes of the minim-
um apparent resistivities at these sites tends
to be similar at periods greater than about 100s.
At TAK the apparent resistivity increases with
increasing period, as may seen in Figure 3, and
the degree of anisotropy is small.

Magnetotelluric Data Interpretation

Recognizing that the resistivity structure
along the West African profile is probably very
complicated, we begin the interpretation of mag-
netotellurics by inversion of observed apparent
resistivity (and phase) results for each sound-
ing to obtain a one-dimensional resistivity dis-
tribution (Vozoff, 1972; Wannamaker et al.,
1980). It has been the custom to perform any
one-dimensional interpretation on the component of
the electric field parallel to the strike of the
discontinuity (TE mode). This is because the TE
mode of MT observations is less influenced by
the near-surface resistivity variations (provided
such variations are purely two dimensional with
uniform strike directions) and reflects in a less
distorted way the variation of the resistivity
with the depth (Berdichevsky and Dmitriev, 1976).
To do two-dimensional modeling, we use a starting
model constructed from the layered models fitted
to the TE mode at each site. Where correlation

is possible between adjacent sites, the results
from the local layered model have been continued
horizontally across the traverse for a regional
interpretation. A very important consideration
in MT soundings is the validity of assembling a
group of one-dimensional inversion results to
form a crude model of the two-dimensional struct-
ure. This approach is common (Word et al., 1971;
Vozoff, 1972). For each of the sites in the
West African profile, the best fit of layered
model inversion results were used together.
Boundaries are set halfway between sites. The
objective of two-dimensional modeling is then to
convert this crude model into a model represent-
ative of the conductivity structure which fit
the observed data well for the two modes of
polarization of the electric field.

The University of Utah has developed a two-
dimensional finite element algorithm for model-
ing MT field observations. Linear interpolation
of the unknown field over triangular subdomains
of the region where a solution is sought was used
in conjuction with the Galerkin technique to
derive a system of linear equations which approx-
imates the governing differential equation. The
solution of this linear system of equations gives
the approximate field values at the nodes of the
discretized domain (Rijo, 1977). Computations
of two-dimensional models were carried out by
using the methods of Rijo (1977) and Stodt 1978).

In fitting a model to any geophysical data we
should also address the question of uniqueness.
Model uniqueness problems can be treated by a
combination of three approaches: a high station
density in each profile, a wide spectrum of data
at each sounding, and MT data at sufficiently
high frequencies to tie down the upper crustal
structure. For this high-frequency range, the
earth will probably be effectively one dimension-
al, allowing us to set the near-surface intrinsic
resistivities close to their true values
(Wannamaker et al., 1980). Some model uniqueness
problems can be avoided if control on the near-
surface resistivity structure can be obtained.
Drilling in our research region (CGG, 1958) has
shown that the post-Palaeozoic cover of the
African platform possesses variable resist-
ivities, ranging from 50 to more than 1000 ohm m
with a thickness of 150-200 m. The cover seems
to lie on a conductive series 200-1000 m thick.
All available geophysical and geological evid-
ence was used to improve the starting model; we
used existing geophysical data as a constraint
(Crenn et al., 1959). Finally, with about 15
successive adjustments, we obtained a reasonable
fit between a realistic model (Figures 4 and 5)
and the MT responses (Figure 3). It should be
stressed that there is likely to be a degree of
nonuniqueness in the selected model, especially
because of the small number of MT sites. The
result of the two-dimensional model calculations
was as follows.

The craton model in Figures 4 and 5 shows high
resistivity ($\geqslant$ 10,000 ohm m) on the surface,
related to the undifferentiated crystalline rocks
(granitic gneisses, calcoalkaline granites,
migmatites). The crystalline rocks alternate
with metamorphic rocks of lower resistivity
(volcanosedimentary formations of the Riziam
and Dacola groups). In the SW part of the pro-
file a sedimentary cover appears, composed es-
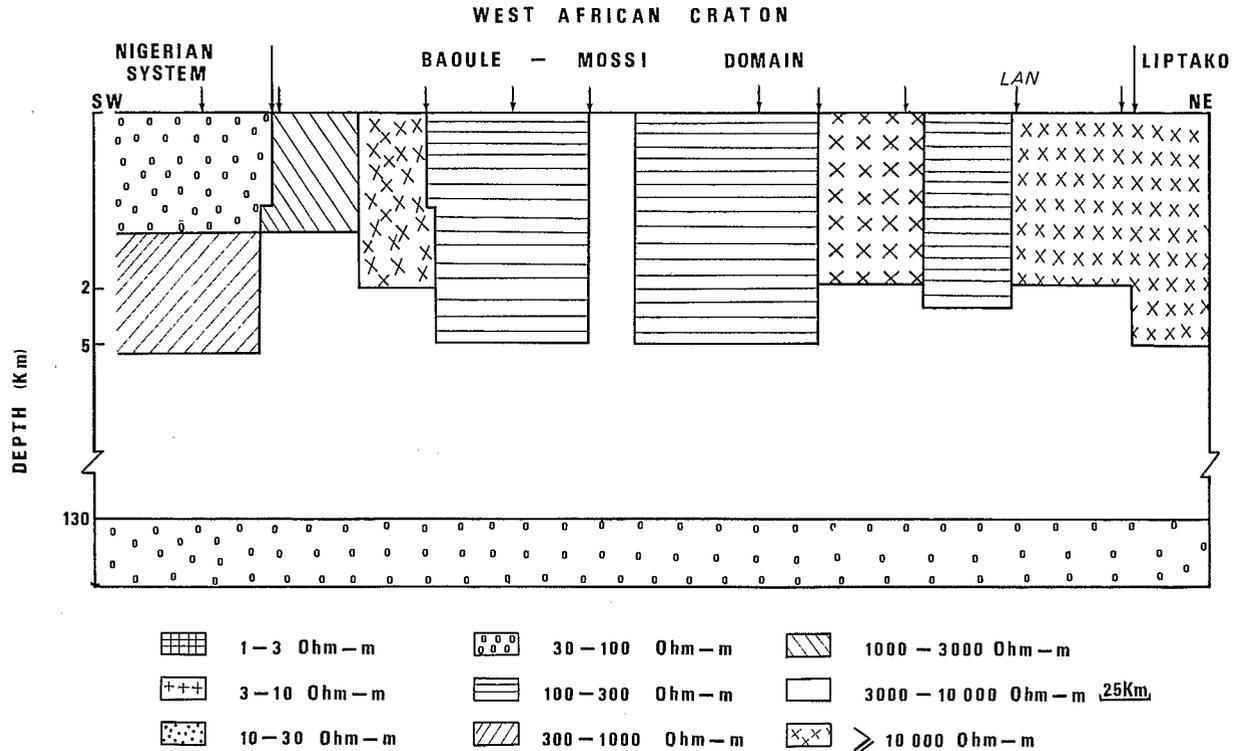
WEST AFRICAN CRATON

Fig. 4. A model displaying the distribution of the resistivity from two-dimensional model calculations for profile A. The little arrows show locations of MT measuring sites. Note the nonlinear depth scale.

sentially of subhorizontal layers of sandstone and of clastic rocks. Beneath these Birrimian formations we find the basement of the Eburnean or Liberean age with a resistivity of the order of 3000 ohm m, and finally, underneath we find the first conductive layer situated in the uppermost mantle at about 130 km depth. Soundings in the mobile belt and sedimentary basin can only be modeled with a crustal structure different from the craton, requiring the presence of a conductive zone at the base of the crust (Figure 5). We notice a regular deepening of the basement as it goes from west to east and a contrast in resistivity in the crust between the mobile belt and sedimentary basin. One passes from the resistant Birrimian to the relatively conductive Voltaian sandstone (Infracambrian series). In the absence of any compelling seismic data in the region, it is impossible to compare the low-resistivity zone with the seismic low-velocity layers, as delineated by Mitchell and Landisman (1971) and Jones (1981).

Discussion and Conclusions

An interesting result of this MT study is the existence under the West African craton of a "resistive crust" a lower crust with the same resistivity as the uppermost mantle with a decrease in resistivity occuring below 130 km. Ritz (1982a) has found practically the same configuration repeated on the Senegalese part of the West African craton 1000 km away. The Moho does not appear to be associated with a pronounced conductivity transition. Although an upper mantle conductivity increase is usual, it is typically deeper than the Moho. The thickness

of the "resistive crust" which we find under the West African craton is not unusual. It is common in eastern Australia, where a boundary at a depth of 100 km is found with resistivities between 10 and 50 ohm m underneath (Vozoff et al., 1975). On the South Africa cratons (Rhodesian and Kaapvaal cratons) the work done by Van Zijl (1977) shows a conductive layer in the uppermost mantle at a depth of 90 km. The two-layer model presented by Cantwell and Madden (1960) replaces the depth of the high-to-low resistivity interface at about 70 km. According to Schmucker and Jankowski (1972), numerous MT soundings in continental zones demonstrate a general reduction in resistivity at a depth of between 60 and 120 km. At this depth there would be a transition from 1000 ohm m or more down to about 50 ohm m. The absence of a conductive layer in the crust/ uppermost mantle interface in the interior of the craton supports the hypothesis of Hyndman and Hyndman (1968) according to which the crust in the stable shields has become dehydrated by metamorphic processes.

In the mobile belt and basin the most striking result is an order-of-magnitude increase in conductivity at about 30 km depth. There are many possible causes for low-resistivity layers at the crust/upper mantle interface. Both melting (Caner, 1970) and hydration processes (Hyndman and Hyndman, 1968) have been proposed as causes for a conducting zone in the crust. The hydration of the rocks produces a decrease of the resistivity and markedly lowers the melting point. Appreciable free water in rocks will support electrolytic conduction through pores and fractures and create hydrous minerals that are relatively good conductors. A moderate
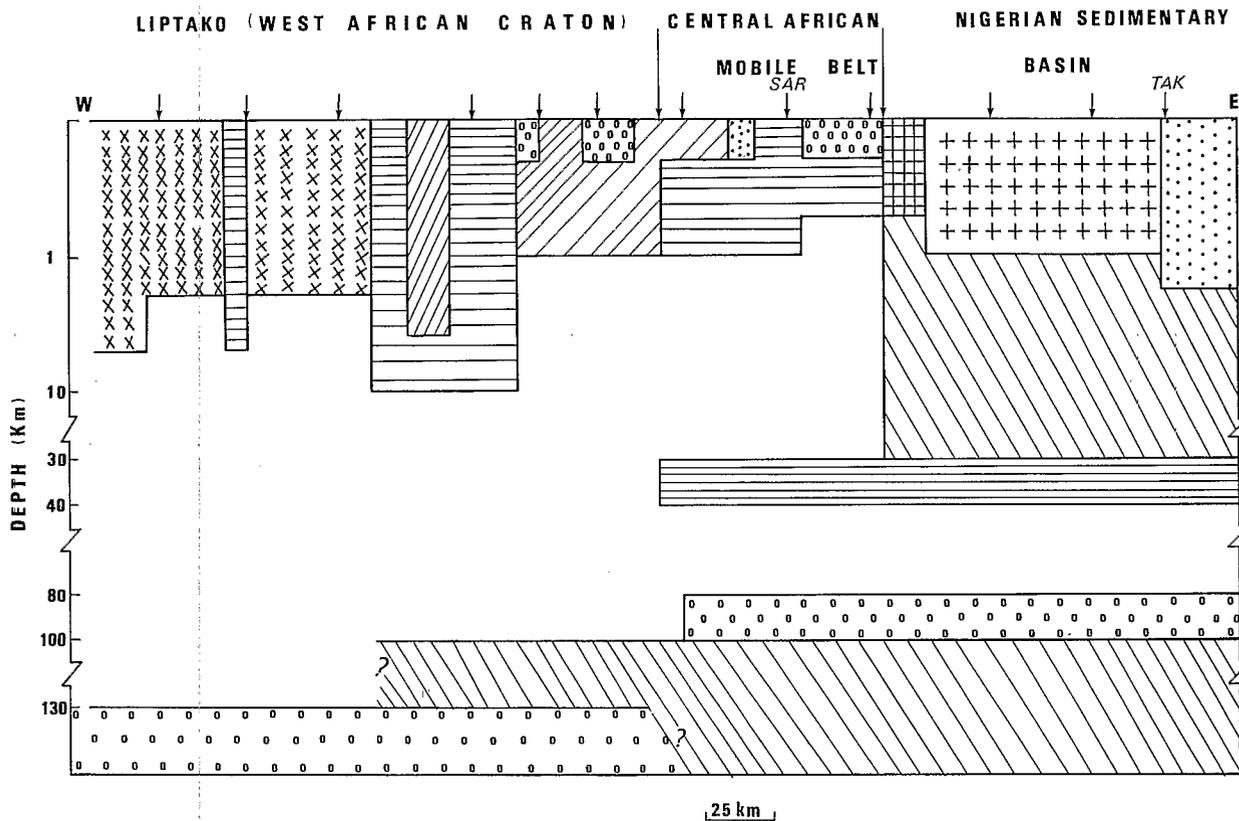
Fig. 5. Profile B. Same as Figure 4.

temperature of the order of 700°C is required to partially melt crystalline rocks under water-saturated conditions in the crust. It is unlikely that melting can occur at the crust/upper mantle interface, especially in regions of low heat flow. Heat flow measurements indicate very low values of 18–22 mW m⁻² on the West African shield in Niger Republic at 100 km to the north of profile B (Chapman and Pollack, 1974). It thus seems likely that either free water or water of hydration in crustal rocks is largely responsible for the conducting zone under the mobile belt. The water in the lower crust could be supplied by the upward migration of mantle water during the thermal reactivation at the time of the last tectonic event (Pan-African orogeny) in a manner similar to that suggested by Greenhouse and Bailey (1981) for eastern North America. This will cause a decrease in resistivity due to a higher water content near the base of the crust in the mobile belt. It seems that there is a correlation between the development of the conducting zone in the lower crust and age of tectonic activity. The layer of low resistivity found on the eastern periphery of the craton has a counterpart in the mobile belts of South Africa (Van Zijl, 1977).

The rise in conductivity in the upper mantle occurs at a depth of order 130 km beneath the craton and at a shallower depth of order 80 km beneath the mobile belt and basin. Regional differences of the conductivity structure within the upper mantle between a stable shield area and a younger continental area are common. Schmucker (1970) and Porath and Gough (1971) show a deepening of the conducting zone in the uppermost

mantle between the southern Rockies and the Great Plains in the United States. MT measurements indicate conductivity increasing at depths of about 150 km under Precambrian North Australia, and at depths less than 100 km under Phanerozoic Australia (Finlayson, 1982). Kurtz and Garland (1976) show a contrast in resistivity of the lower crust and upper mantle between the Precambrian shield and the northern Appalachians. As opposed to those in the lower crust, observed conductors at uppermost mantle depths under West Africa can be interpreted in terms of elevated temperature and partial melting (Beblo and Björnsson, 1980; Lilley et al., 1981; Vanyan, 1981). Tozer (1979) argues that conductivity may be closely related to viscocity, and low-resistivity zones may therefore be interpreted in terms of either viscocity or temperature.

Models for West Africa require the conductivity to increase in the 80–130 km depth range. Is this striking feature the base of the lithosphere? This conducting layer could appear to be due to partial melting processes occurring in the asthenosphere. Regional differences in seismic velocity structure can be seen using ScS times delays and surface wave dispersion. Sipkin and Jordan (1976) indicate differences in multiple ScS travel times through the upper mantle structure beneath continental regions between Phanerozoic and Precambrian provinces. Upper mantle lateral inhomogeneities under continental regions could extend to depths as great as 200 km (Anderson, 1979). An MT sounding carried out to greater depths in Upper Volta along profile A indicates that there is a major

conductivity increase at about 450 km depth under West African craton (Ritz, 1982b). Unfortunately, no exact information can be obtained on an ultimate conductive layer in Niger (mobile belt and basin) at the present stage, but the deviations of the phase from 45° indicate in the long-period observations a possible good conductor at perhaps 200-300 km depth (Ritz, 1983). It is possible that at greater depth the conductivity increase under the mobile belt may be part of an anomalous zone of mobile material associated with diapiric structure related to hot spots situated in the western Sahara. Gravity measurements along the perimeter of the craton northeast of our research area show numerous positive anomalies connected with basin intrusions (Crenn et al., 1959). The case for regional variations in the physical properties below West Africa at depths greater than 200 km seems consistent with the present result (Lilley et al., 1981), but further data are necessary.

Thermal models of the lithosphere can also explain lateral differences in electrical conductivity structure within the upper mantle of West Africa. Sclater et al. (1980) apply the concept of a thermal boundary layer to the continents. Following thermal reactivation the thickness of the thermal boundary layer increases with age until about 150 km. The West African craton is an area that was consolidated during the final Birrimian granitizations at about 1850 ± 250 m.y. and the thermal boundary layer extends to depths of 130 km. The thermotectonic reactivation in the border regions of the Precambrian craton (Niger) suggests that this boundary may exist at depths shallower than 130 km. MT data indicate conductivity increasing at depths of about 80 km under the mobile belt and sedimentary bassin, and this major conductivity feature can be interpreted in terms of thermal boundary layer.

On the West African scale if one can confirm that the boundary between high and low resistivity situated in the depth range from 80 to 130 km is in relation with the base of the tectonic plate, Keller's (1971) hypothesis can be put forward, namely, that marked reduction in resistivity at about 100 km in depth may be a feature of a mobile crustal plate.

However, other writers (Pollack and Chapman, 1977; Adam, 1978) suggest that on the platforms and the continental shields, the lithosphere could extend to the depth range 300-400 km. According to Vanyan et al. (1977) the total conductance S of the continental asthenosphere can serve as a geoelectrical criterion of the well-developed asthenosphere if its value is approximately $7.10^3 - 10^4$ ohm^{-1}. In the West African craton the total conductance of asthenosphere does not exceed 10^3 ohm^{-1} (assumed to extend from 130 to 460 km (Ritz, 1982b).

Since the results obtained seem compatible with other studies on Precambrian shields, one may consider the constraints provided by the MT interpretation on the thermal regime of the upper matle. Considerable scatter of the experimental data on electric conductivity of rocks at high pressures and temperatures is a barrier to reliable correlation of electric

conductivity with temperature. We can therefore only estimate that at the high-low resistivity interface of the upper mantle at 130 km depth the temperature should be in the range 770°-950°C (Duba, 1976; Shankland and Waff, 1977). Under certain conditions a strong decrease in the resistivities of uppermost mantle rocks at temperatures 850°-1100°C is possibly connected with a partial melting (Volarovich and Parkhmenko, 1976). It is probable that if partial melt is present in the asthenosphere here, it must be in an amount so small that the bulk conductivity is dominated by the solid-phase conductivity (Drury, 1978). A melt fraction of 1% would increase the dry mantle conductivity by only 10%; this could not be resolved by MT data. The absence of important amounts of liquid phase and a low value of the total conductance under the West African craton would then seem to indicate that the asthenosphere is not well developed in this region and suggests that the lithosphere extends to about 450 km depth. According to Chapman and Pollack (1974) the lithosphere is very thin or absent beneath West Africa. At the furthest limit the plate would be rendered immobile. Burke and Wilson (1972) suggest that such has been the case in the African plate since the early Miocene period.

The problem of defining a lower lithospheric boundary for West Africa is not yet resolved in the absence of any seismic studies, heat flow measurements, or palaeomagnetic data. Seismic research and heat flow measurements are scheduled to begin in the near future.

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