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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 Afric-

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.

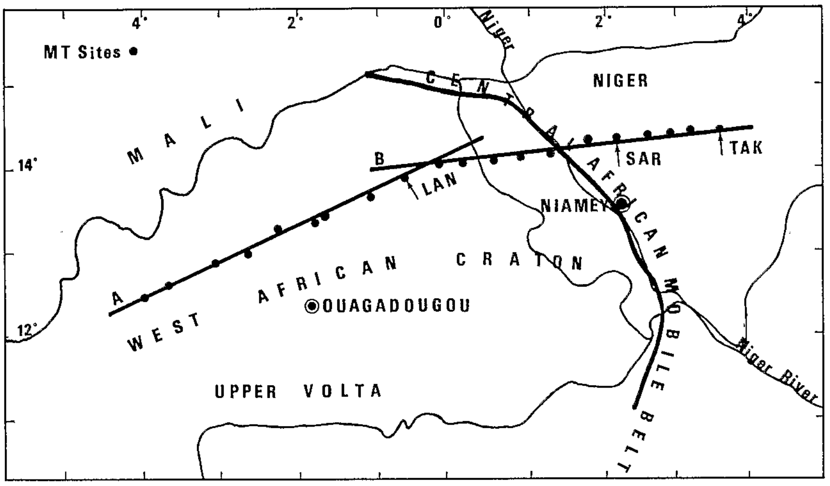

Fig. 1. Map of Niger-Upper Volta showing the measuring sites and measuring profiles. The curved line represents the contour of the West African craton.

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 orthogonal 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 components 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 the elements of which relate the components of E to those of H via the equation

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

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 resistivities for the principal directions were calculated from the equation

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

where ρij is the apparent resistivity in ohm m, T is the period in seconds, and Zij an off-diagonal element of the rotated impedance tensor. The 90% confidence limits for apparent resistivity 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 resistivities in the principal directions with their 90% confidence limits. There are several features of interest in these results. First, consider the stations LAN and SAR, where the most obvious feature is the large difference in magnitude of the maximum apparent resistivities over the total period band between these sites (more than one order of magnitude). The differ-

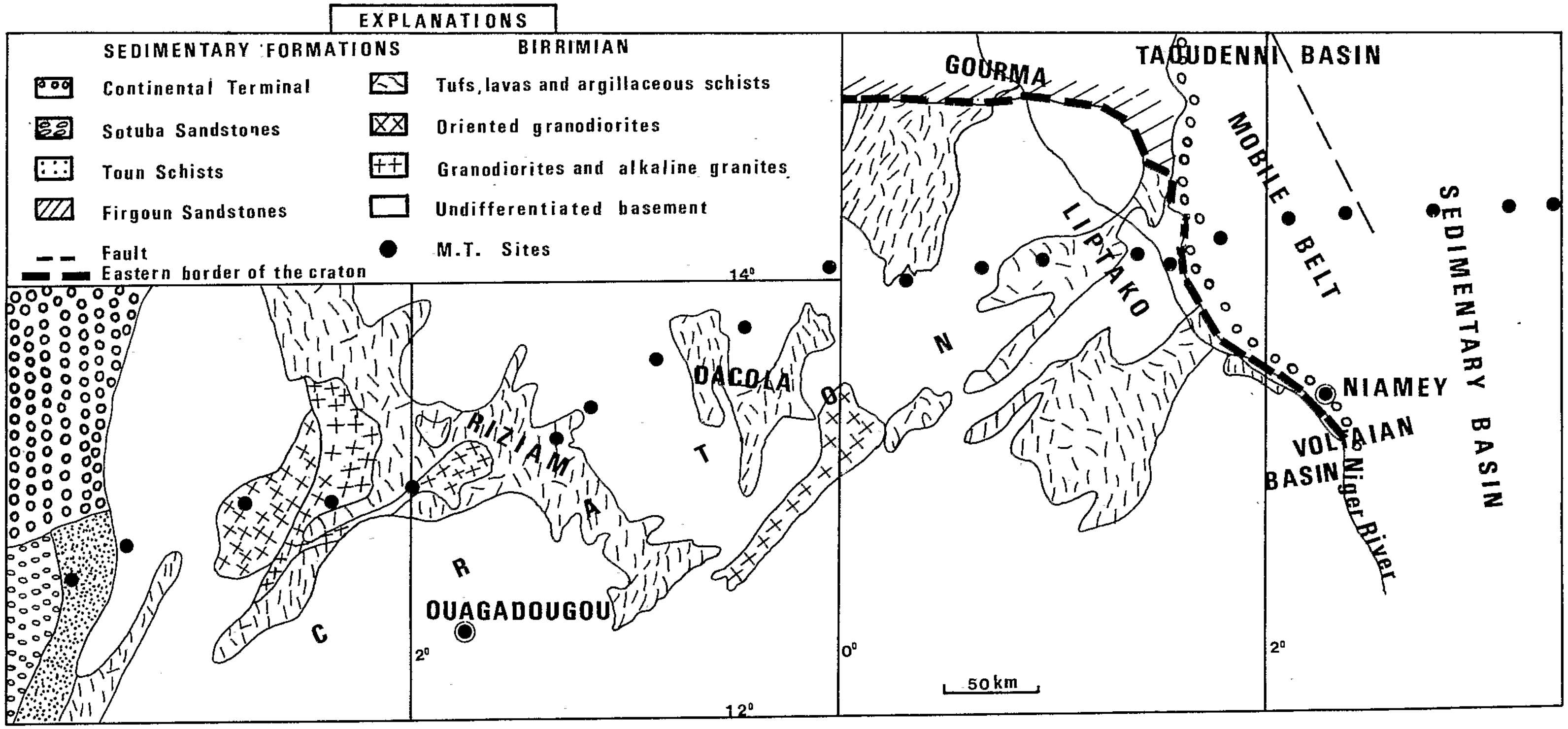

Fig. 2. Sketch map of Niger-Upper Volta area showing the essentials of the geology and location of MT sites (from Bessoles, 1977).

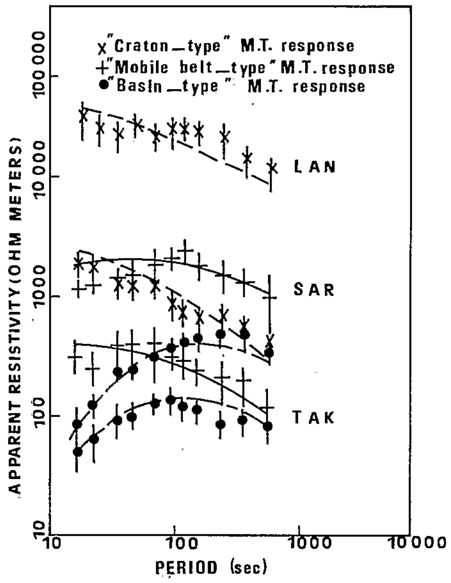

Fig. 3. Apparent resistivities as function of the period calculated into principal axes, site LAN (crosses), site SAR (pluses), site TAK (dots). The superimposed solid curves represent theoretical curves calculated from the model, site LAN (dashed curve), site SAR (solid curve), site TAK (dot-dashed 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 anisotropic 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 minimum 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 magnetotellurics by inversion of observed apparent resistivity (and phase) results for each sounding to obtain a one-dimensional resistivity distribution (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 structure. 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 representative 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 modeling 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 approximates 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 dimensional, 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 resistivities, 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 evidence 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 profile a sedimentary cover appears, composed es-

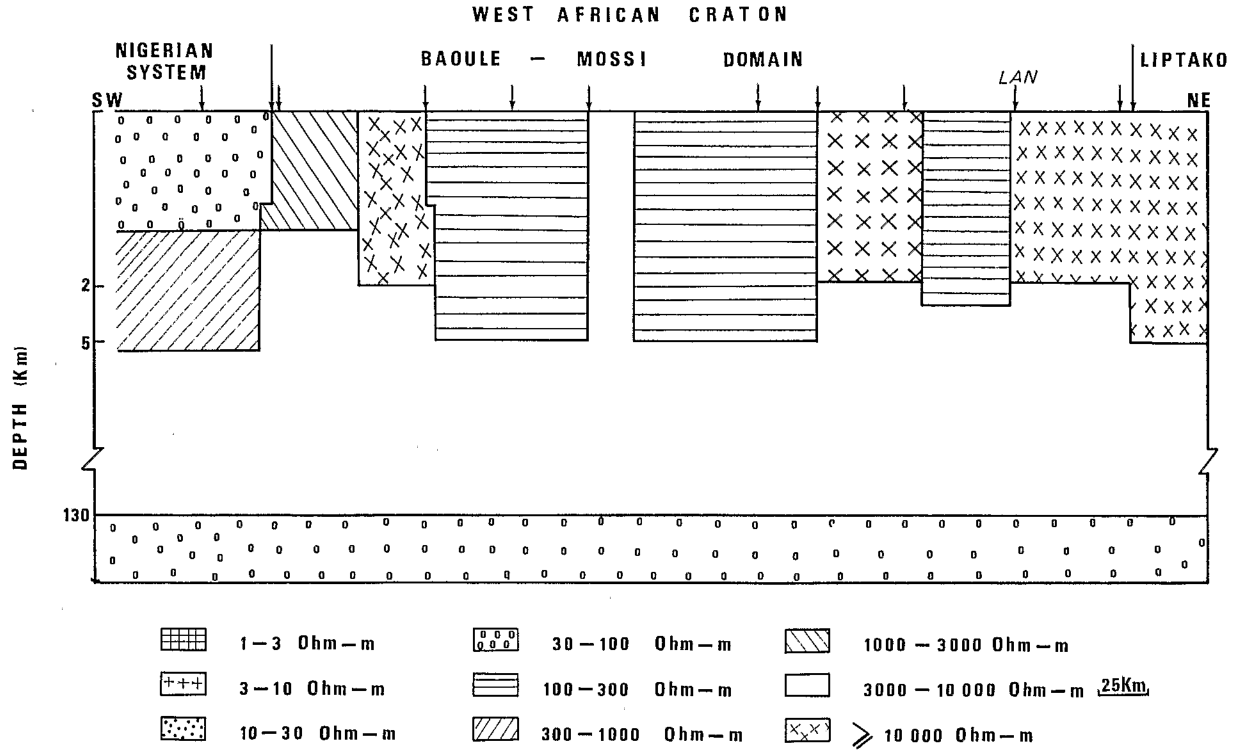

Fig. 4. A model displaying the distribution of the resistivity from two-dimensional model calculations for profile A. The little arrows show locations of MT measuring sites. Note the nonlinear depth scale.

sentially of subhorizontal layers of sandstone and of clastic rocks. Beneath these Birrimian

of the "resistive crust" which we find under the West African craton is not unusual. It is com-

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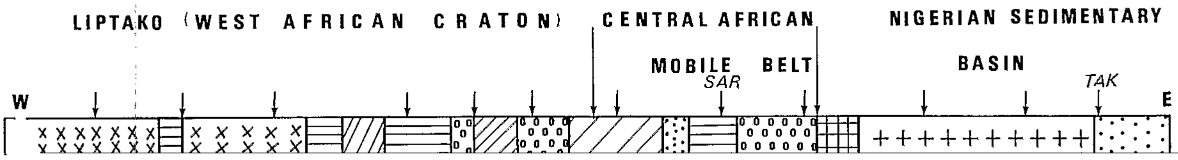
LIPTAKO (WEST AFRICAN CRATON)
CENTRAL AFRICAN
MOBILE BELT
NIGERIAN SEDIMENTARY
BASIN
SAR
TAK
W
E

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

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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