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The distribution of electric conductivity on the eastern border of the West African craton (Republic of Niger)

M. Ritz *Centre ORSTOM, Observatoire Geophysique, B.P. 1386 – Dakar, Senegal*

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Summary. Magnetotelluric soundings (MT) were conducted along the 14th parallel on the eastern border of the West African craton in the Republic of Niger.

This profile includes eight sites an average of 30 km apart. We determined the regional structure of electric conductivity and its relation to the various geological belts covered. This study took place within a 15–500 s period band. Two-dimensional modelling suggests that, in the sites located on the sedimentary basin and the mobile belt, there exists a conductive layer in the upper mantle at a depth of 80 km. Within the craton we were unable to prove the existence of this conductive layer.

There also exists another conductive layer at the crust–upper mantle boundary at a depth of 30 km, but this seems to disappear in the cratonic belt.

A significant electric discontinuity is present between the mobile belt and the sedimentary basin, due to a variation in resistivity in the substratum and a thickening in the surface cover.

1 Introduction

During the dry seasons from 1974 January to 1977 June, a two-year magnetotelluric measurement project (MT) was conducted in West Africa, mainly in the Republic of Upper Volta and the Republic of Niger, to determine the electrical properties of the crust and the upper mantle. The purpose of this MT operation was to bring more accurate knowledge to the structural study of the eastern border of the West African craton. In a previous study we focused our attention solely on MT sites in Niger.

In Niger we undertook a profile about 200 km long, including eight sites and extending along the 14th parallel. Fig. 1 represents a geological overview of the region based on the geological map of Niger (Greigert & Pougnet 1965). Table 1 indicates the geographical location of each site.

The area under study is located between the Mali–Upper Volta border on the west and extends beyond the Niger River on the east. The section of this area between the Mali

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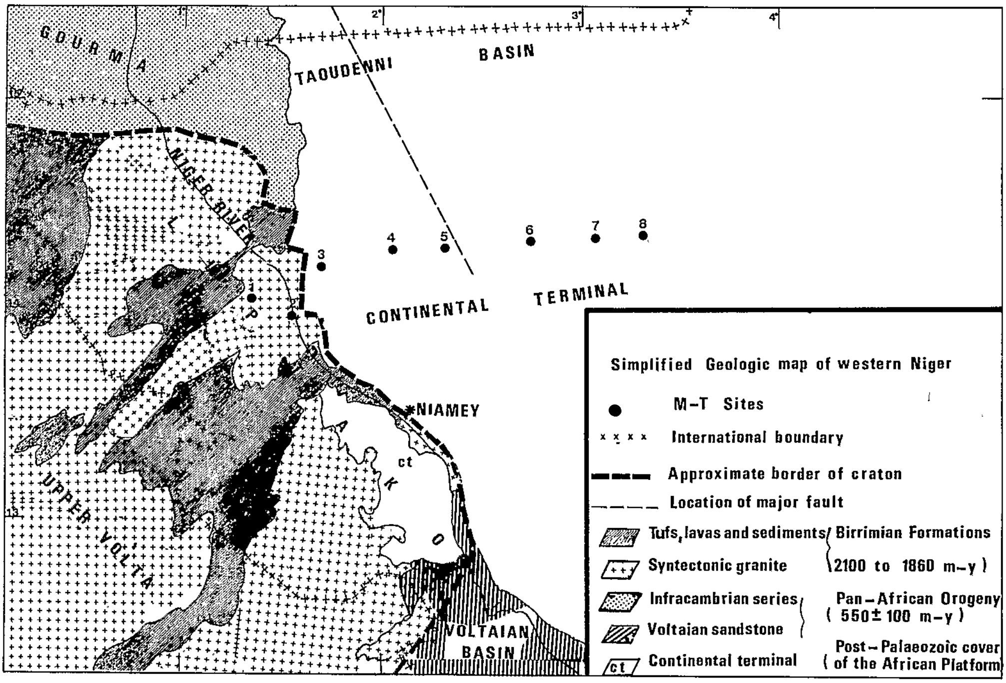

Figure 1. Geological map of the survey area (Western Niger).

Table 1. Magnetotelluric station geographic locations.

Station no.	Station name	Lat. (N)	Long. (W)
1	Doudou	14° 03′	1° 23′
2	Kokomani	14° 01′	1° 32′
3	Barakan	14° 15′	1° 45′
4	Sargan	14° 14′	2° 07′
5	Lahaba	14° 18′	2° 23′
6	Tagasaba	14° 20′	2° 47′
7	Toulou	14° 18′	3° 05′
8	Takawat	14° 18′	3° 22′

border and the Niger River belongs to the West African craton considered to be stable after the final Birrimian folds (2000 Myr). From that time on, the now-rigid basement reacted with tectonic brittleness to subsequent pressure. Sites 1 and 2 are located in this belt on the Pre-Cambrian basement. Significant folding developed in the south-east section of the Taoudenni basin and extends into the eastern section of the Voltaian basin.

The region north and east of the Niger River underwent metamorphism at the time of this folding which was accompanied by granitic intrusions. Age studies using Rb/Sr conducted on the granite have revealed an age of approximately 600 Myr (Machens 1973).

We established three MT sites (sites 3, 4, 5) on the border of the craton. In this transition zone, the Pre-Cambrian basement is hidden by more recent sediment composed of series of the infra-Cambrian age 'Continental Terminal' whose upper level forms the clay-bearing sandstone of Central Niger.

The MT profile along the 14th parallel crosses a significant fault running NNW—SSE. This fault may well be the extension of the western fault of the Sudanese strait, causing the crystalline massif of Gourma to be thrown against the sedimentary basin of Tertiary age (Furon 1950). The electrical soundings of the CGG (1958) show increased electric conductivity east of this fault due to a change in the composition of the basement. To study this phenomenon we set up three sites to the east of the fault (sites 6, 7, 8).

Thus from a geological viewpoint, on the west we have a resistant basement of Pre-Cambrian origin (granite–gneiss) surfacing over the greater part of the region and juxtaposed with a more recent series of low resistivity (clay-bearing sandstone of Central Niger). On the east the basement becomes more conductive.

2 Data acquisition

For our Niger research, we used Mosnier-type sensors, recording respectively the D and the H components of the magnetic field (Mosnier & Yvetot 1972). They are horizontal variometers with a suspended magnet. They possess an independent system of calibration that runs on direct current. The output sensitivity is $10\,\mathrm{mV}\,\gamma^{-1}$. The cut-off period of the low-pass filter is 10 s. For our telluric sensors, we used lead electrodes. These electrodes are made of thin lead plates with a surface of $10 \times 20\,\mathrm{cm}^2$. The number of these plates may vary according to the composition of the soil. In general, we use a sufficient number in order to achieve a grounding resistance of less than 500 ohm. These electrodes are very stable, and spontaneous polarization (constant after a few days) remains at rather low levels.

These plates are buried 1.50 m into the ground with a separation of 500 m along the two orthogonal directions (magnetic NS and EW). The recorders are made up of two 'Servotrace P2V Sefram' of two-track type, one recording NS (electric) and D (magnetic) components, the other EW (electric) and H (magnetic) components of the electromagnetic field.

At first we recorded within a period band of 15–500 s. For each site, the best recordings are chosen and digitized at 3 s intervals (minimum length of record is 3 hr, precision of digitization better than 0.1 mm).

3 Method of analysis

The measurements involve the recording of variations with time of the horizontal components of the electromagnetic field: $Ex(t), Ey(t), Hx(t)$ and $Hy(t)$.

The scalar method devised by Cagniard (1953) is valid for isotropic and homogeneous environments, but it can produce inaccurate results in regions where the Earth has a more complex structure. In general, the calculations given by an impedance tensor are more reliable because they allow us to interpret two-dimensional structures (Cantwell 1960; Vozoff 1972).

A complex impedance tensor is therefore calculated for the different periods.

Starting with Maxwell's equations, we can obtain a tensorial relation between fields E and H such as

$$E = ZH$$

where

$$E = \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}, \qquad H = \begin{bmatrix} H_1 \\ H_2 \end{bmatrix}, \qquad Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$$

where (E_1, E_2) are the components of the electric field along axes x and y; (H_1, H_2) are the components of the magnetic field along axes x and y; Z_{ij} are the complex impedances.

Generally, for two-dimensional environments, the measuring axes are not aligned with the strike of the structure. However, the impedance tensor can be rotated until an angle is found which maximizes $|Z_{12}|^2 + |Z_{21}|^2$ (Swift 1967). Knowledge of the angle of rotation permits an estimate of the direction of the principal impedance axes to be made (Bostick & Smith 1962). On the principal axes Z_{12} and Z_{21} will take on their largest and smallest values respectively and if the structure is reasonably two-dimensional, they should be aligned parallel and perpendicular to the structured strike. It is useful to have some measurement of the degree of two-dimensionality. A skew index, defined by Swift (1967), for any rotation angle is

$$S = \frac{|Z_{11} + Z_{22}|}{|Z_{12} - Z_{21}|} .$$

Small ratios indicate that a two-dimensional or one-dimensional anisotropic model can explain the observations, whereas large ratios would require a three-dimensional model.

A rotation of the impedance tensor from the north–south, east–west observational directions was performed on all of the data in this study, and apparent resistivities ρa (Ωm) and phase ϕ were computed from the principal values of the impedance tensor with the relations

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

and

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

where T is the period in seconds, and Z_{ij} is an off-diagonal element of the rotated impedance tensor.

4 Results and analysis of data

For each site Figs 2–9 show: apparent resistivities, phases, direction of the major axis, skew and the direction in which the telluric currents are polarized. The error bars represent the standard deviation from the average value.

For the sites as a whole, the average degree of skew is less than 0.3. It is, therefore, likely that the distribution of electric conductivity in the area surveyed is quite close to a two-dimensional structure.

At most of the sites along the profile, the horizontal component of the telluric field is more or less polarized. We discovered an average preferential direction, giving the electrical field a greater amplitude (Table 2). This direction may change from one site to another, depending on the presence of small-scale lateral inhomogeneities. These directions are close to the directions of the major axis. In the case of a two-dimensional contact between two structures of different resistivities, the preferential direction is parallel to the contact on the conductive side and perpendicular to the contact on the resistive side. Each site, except sites 6 and 7, is highly anisotropic.

Table 2. The preferred directions of the induced electric field (clockwise from north).

Station	1	2	3	4	5	6	7	8
Orientation	–42°	–45°	36°	42°	57°	–27°	–57°	78°

5 Interpretation

For the sites taken as a whole, the degree of skew is low; the structures can be considered two-dimensional and we can make a quantitative analysis.

To do two-dimensional forward or inverse modelling we begin with pseudo-sections of apparent resistivity and phase, and an initial model. We must decide on an average strike direction for the traverse as indicated by the principal axes. The data have been projected on a traverse in a N 50° E direction, as seemed appropriate from the tectonic map and the principal axes. We used both an inverse program (Jupp & Vozoff 1977) and a direct one (Stodt 1978).

All available geological and geophysical data were used to facilitate the preliminary model, thereby deriving a more realistic model (CGG, 1958).

In Figs 2–9, the unbroken line indicates the results obtained from two-dimensional modelling for apparent resistivities and phases for a profile in a N 50° E direction. The models we obtained were calculated for periods of 30, 100, 300 and 500 s. As for the values of the resistivity along the major axis, the models fit the data rather well. However, it is more difficult to fit the models to reflect the data on the resistivity along the minor axis because of their low value and wider dispersion.

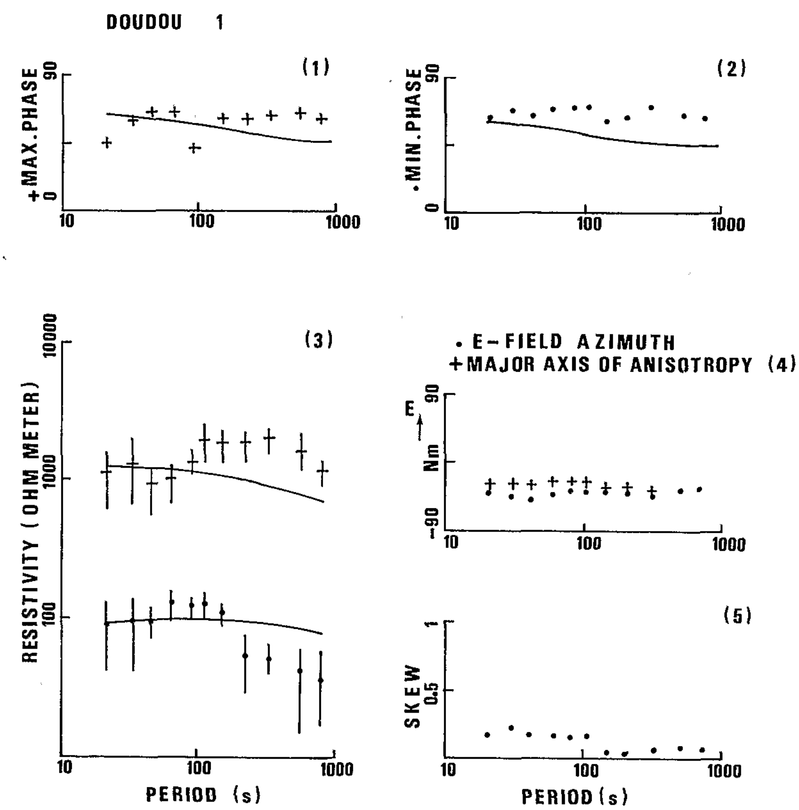

Figure 2. Doudou station. (1) and (2) Crosses and points are the values of the phase which are calculated according to the principal axes. The continuous curve is the result of the two-dimensional modelling. (3) Crosses and points represent the values of the apparent resistivity which are calculated according to the major and minor axis coordinate system. Solid curves are the apparent resistivity plots for two-dimensional models. (4) Points represent the preferred directions of the induced electric field (clockwise from north). Crosses are the orientations of the major axis of anisotropy. (5) Plot of skew values.

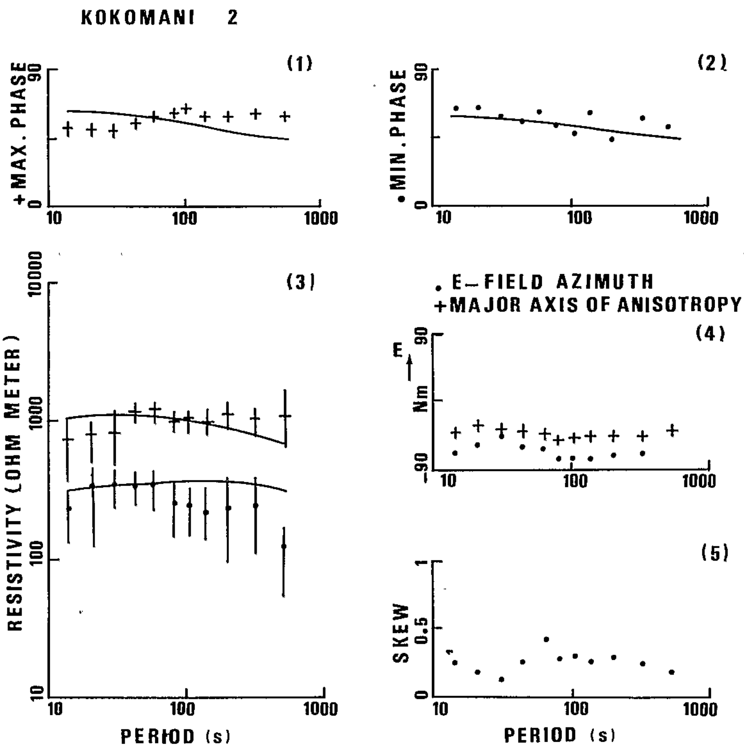

Figure 3. Kokomani station. Same as Fig. 2.

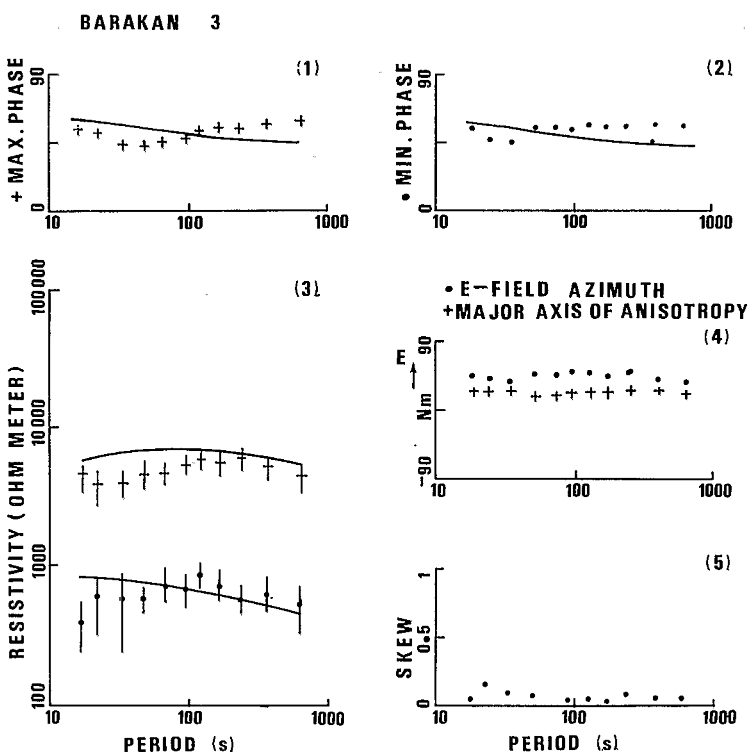

Figure 4. Barakan station. Same as Fig. 2.

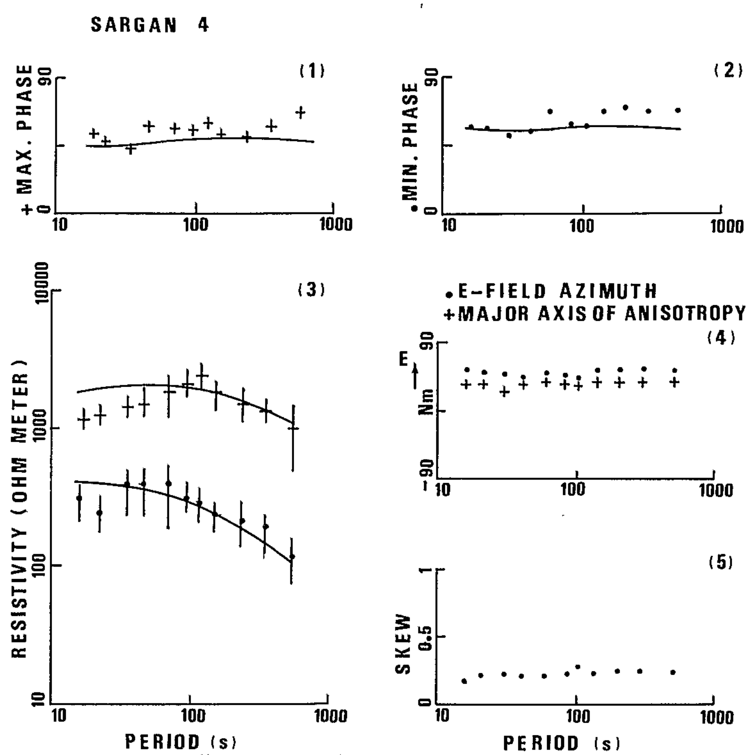

Figure 5. Sargan station. Same as Fig. 2.

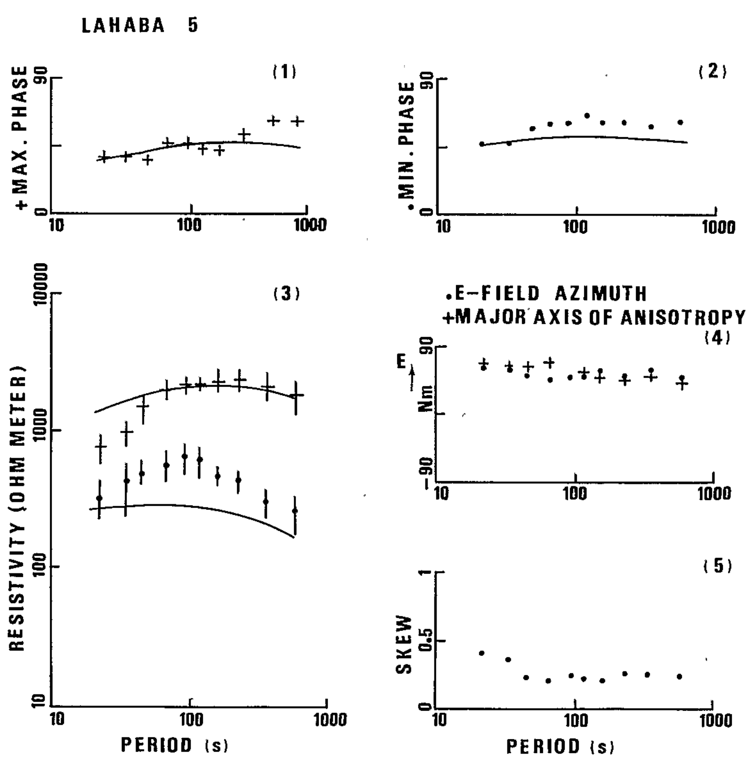

Figure 6. Lahaba station. Same as Fig. 2.

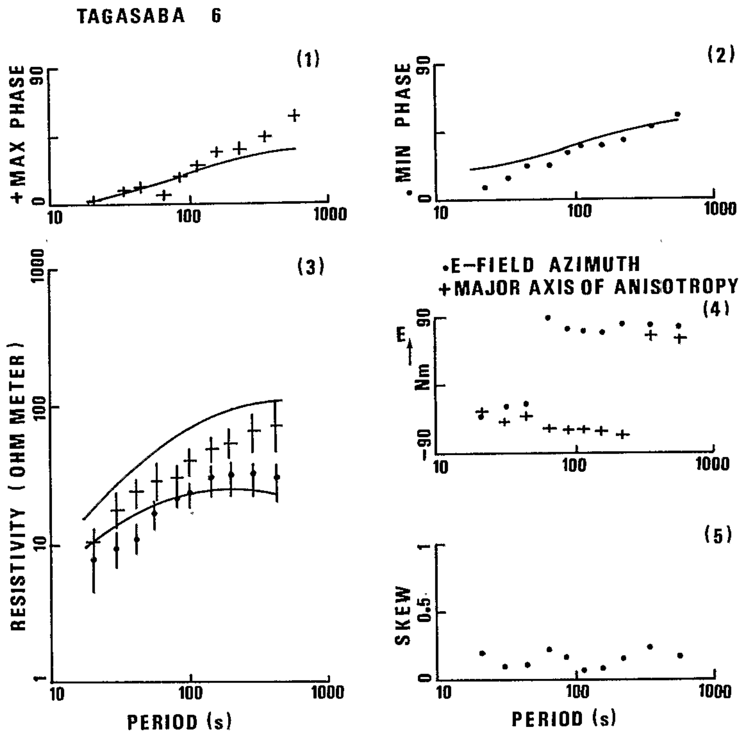

Figure 7. Tagasaba station. Same as Fig. 2.

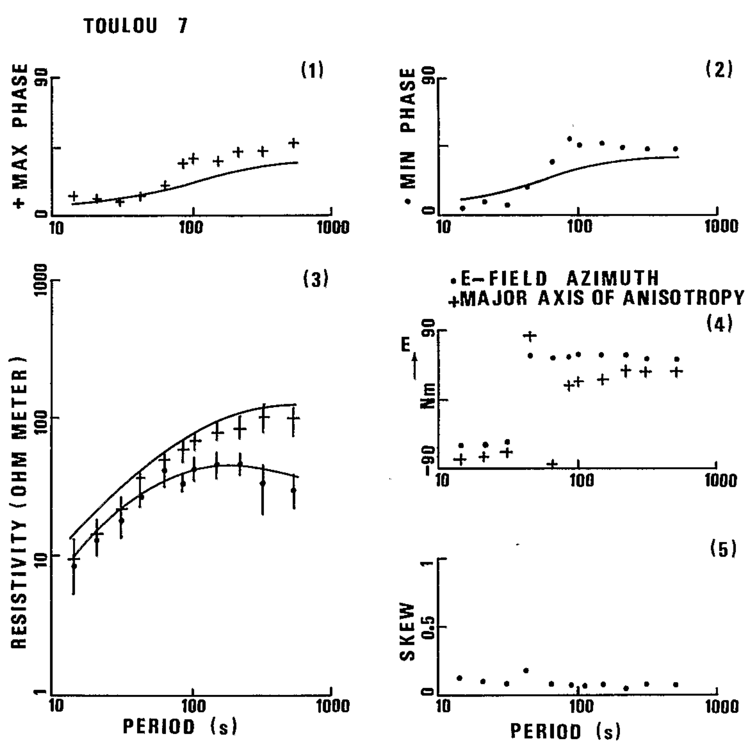

Figure 8. Toulou station. Same as Fig. 2.

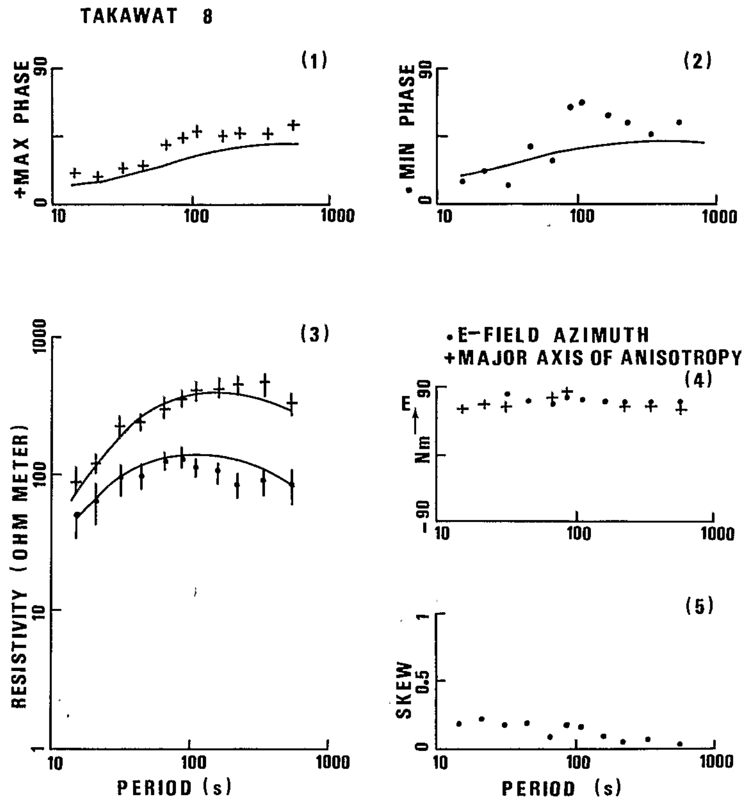

Figure 9. Takawat station. Same as Fig. 2.

The low values of the resistivity on the minor axis can be attributed to three-dimensional structures of finite length. Studies conducted by Ting & Hohmann (1978) show that, when dealing with three-dimensional structures, the TM mode can be used to interpret data without serious error. This is not true for TE mode where the difference between the resistivities calculated on a finite model and a two-dimensional model diverges considerably, particularly at the longer periods. Thus the presence of three-dimensional structures can be anticipated, presenting a problem in fitting the models according to the TE polarization mode.

5.1 STUDY OF THE CRATON–MOBILE BELT

This area is represented by sites 1–5. It is characterized by a significant anisotropy in the apparent resistivities, and the telluric currents show a high degree of polarization (Figs 2–9). The most obvious characteristic of sites 1–5 is the fact that the phases for all periods are above 45°, i.e. that a well-conducting surface cover is missing. We can also see that for each site the direction of the major axis remains virtually unchanged regardless of the period (between 15 and 500 s). Table 2, which represents the preferential direction of the telluric currents (mean over total period band), clearly shows the existence of two different geological entities. Indeed, we note a strong change (approximately 90°) in the azimuth of the telluric currents. It seems probable that the dividing line between the craton and its border is located between sites 2 and 3. On the geological map in Fig. 1, this dividing line has an average direction of N 25° W. In the craton, the telluric currents have an average direction of N 40° W, i.e. they tend to flow approximately along the line of contact. At the border, the

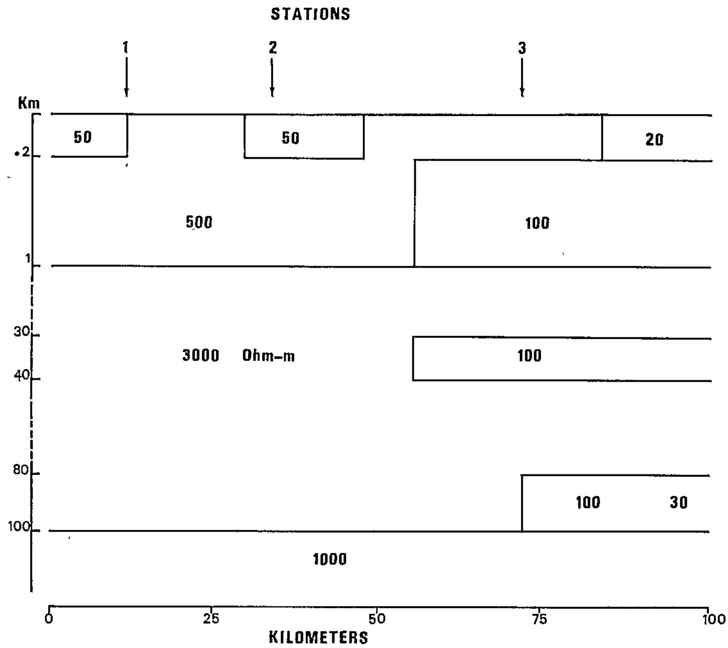

Figure 10. Two-dimensional model resistivity profile across the craton up to its border.

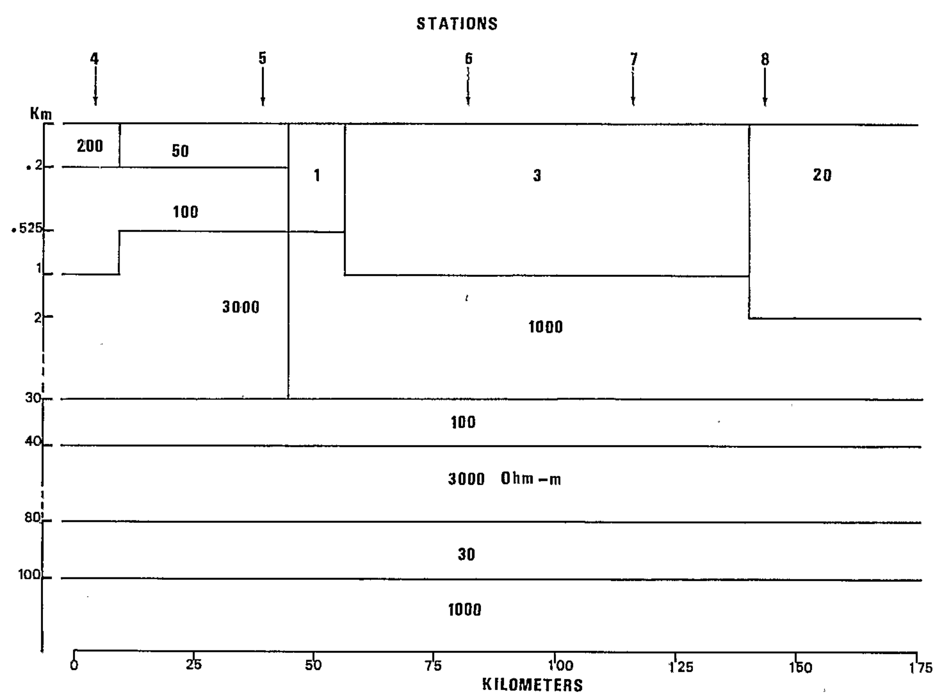

Figure 11. Two-dimensional model resistivity profile across the craton's border on to the sedimentary basin.

telluric currents undergo a significant rotation, causing them to flow perpendicularly to the presumed direction of the craton. The validity of a two-dimensional interpretation, therefore, seems justified: low degree of skew and flow of currents parallel and perpendicular to the geological contact. Figs 10 and 11 represent the final model derived from two-dimensional modelling along the N 50° E direction.

In the area of the craton, sites 1 and 2 are in dune belts dating from the Quaternary era. These dunes generally lie on a more or less modified granite basement. Next comes the unchanged granitic rock of Birrimian origin. The crust of the craton at this point is résistant and corresponds to a stable continental crust. At a depth of 100 km there probably exists a slight decrease in resistivity (ρ = 1000 Ω m).

With a limited recording range of 15–500 s period, we were unable to prove the existence of a conductive layer within the upper mantle. However, deep MT soundings conducted in the Republic of Upper Volta reveal that this conductive layer is probably situated at a depth of 130 km, followed by a resistant layer of 1000 Ω m (Ritz 1982).

A similar distribution for the upper mantle has been discovered by other authors (Tammemagi & Lilley 1972; Reitmayr 1975; Kurtz & Garland 1976; Hutton, Ingham & Mbipom 1980).

The border of the craton (sites 3–5) is characterized by the appearance of the clay-bearing sandstone of Central Niger ('Continental Terminal'). This sandstone disappears on the Pre-Cambrian basement. Drilling activities in this region (CGG, 1958) have shown that the 'Continental Terminal' possesses highly variable resistivities, going from 50 to more than 1000 Ω m with a thickness of 150–200 m near site 4. It seems to lie on a conductive series 200–1000 m thick.

The model we obtained for this region reflects the studies carried out by the CGG (1958). The clay-bearing sandstone is about 200 m thick with resistivities between 30 and 200 Ω m. It lies on a series which, compared to the basement, is fairly conductive. This moderately conductive series is 800 m thick at sites 3 and 4; its thickness decreases at site 5 (325 m).

The substratum may well be the continuation of the craton's Pre-Cambrian basement.

Neither the apparent resistivities nor the phases for sites 3–5 show as function of period any indications for conducting layers and, consequently, we have lengthened the model of the craton in this zone. It is an established fact then at about 100 s there is a divergence between the empirical data and the model values (of the order of 80 per cent for the apparent resistivities in the TM mode). So we have introduced beneath these sites a conducting layer at the crust–upper mantle boundary, improving the model. The interpretation is better shown, but a more important divergence appears at about 300 s for the apparent resistivities between the empirical data and the model values (approximately 100 per cent for the two modes). The introduction of a deep conductive layer permits us finally to fit the data up to 500 s.

In this transition belt, we can explain the results only if we introduce into our model a conductive layer (≃ 100 Ω m) somewhere between 30 and 40 km deep. We can take note of the existence of a conductive layer in the upper mantle at a depth of 80–100 km.

5.2 STUDY OF THE CRATON BORDER–SEDIMENTARY BASIN

This region is represented by sites 5–8. We notice that, for the sites in the sedimentary basin (sites 6–8), the apparent resistivity decreases significantly, compared to the resistivity found in the transition belt. An equally important observation is the phase, starting well below 45° at the short period end, an unambiguous indication for conductive surface cover. The preferential direction of the telluric currents and the direction of the major axis are much more dispersed than at the other sites. This is due to the almost isotropic nature of the apparent resistivities. Table 2 shows the average direction of the currents in the sedimentary basin. We can see that, from one site to another, these directions undergo a slight rotation causing the telluric currents at site 6 to flow parallel to the direction of the geological contact.

Fig. 11 shows the model that best fits the data. This model indicates generally conductive rock at the surface. For site 5 this rock consists of the clay-bearing sandstone of Central Niger; for sites 6–8, clay of Tertiary origin. The thickness of this clay increases regularly towards the east. Oil-drilling activities north of site 7 revealed that at 800 m the rock still contains clay.

Our model clearly shows the fault discovered in 1958 by the CGG. We can see a regular deepening of the basement as it goes from west to east. The CGG discovered a lack of electrical continuity due to a change in substratum resistivity. We seem to go from the resistant Birrimian (site 5) to the relatively conductive Voltaic clay and sandstone (sites 6–8) and also to a fairly large thickening in the cover. The model in Fig. 11 clearly reflects this conclusion. We can see an increase in the cover series and a variation in substratum resistivity. The Birrimian basement may have a resistivity close to 3000 Ω m; and the basement of the sedimentary basin, a resistivity of about 1000 Ω m.

The difference between 3000 and 1000 Ω m basement resistivity can be detected about the 30 s period at site 5 on the TM mode, where an increase of the order of 50 per cent of the apparent resistivity from the model is established, if that of the basement of the sedimentary basin is in the order of 3000 Ω m. The divergence between the empirical data and the model values reaches a maximum about the period 100 s. Likewise, a divergence on the TM mode around 100 s from the side of the sedimentary basin beneath site 6, is noticed and the model values are then found outside the error bars.

At depths of 30 and 80 km, we can see the continuity of the conductive series of the crust and the upper mantle.

We must emphasize that the model presented in this paper is only one of a range of possible models that explain the data derived from our research. It is, however, the model that we prefer, after calculating a certain number of other configurations having varying resistivities and thicknesses. For the surface layers, this model most closely fits the data obtained from electric soundings and oil drilling. For the deeper layers, Schmucker (1970) and Porath & Gough (1971) demonstrate significant geomagnetic anomalies in the upper mantle of the western United States. This anomaly is found at the border between a highly unstable tectonic belt (Rocky Mountains) and a more stable belt (Great Plain) subjected to no volcanic activity since the Pre-Cambrian era. The thickness of the lithosphere seems to be 120 km beneath the Great Plains and 70 km beneath the Southern Rockies.

In Japan, Nishida (1976) showed a geomagnetic anomaly due to a rapid deepening of the conductive level in the upper mantle. The depth of the conductive layer seems to go from 40 km in the east to 180 km in the west.

The model in Fig. 10 shows one possible structure of the upper mantle at the border between two different tectonic regions: the craton, stable for 2000 Myr, and the mobile belt whose last folds occurred 600 Myr ago in the Cambrian era.

In the mobile belt the conductive layer is located at a depth of 80 km on the craton (interpolating the data from Upper Volta), at a depth of 130 km. MT soundings generally imply a decrease in the resistivity of the upper mantle at depths of 60–120 km (Schmucker 1972). It is thought that at this depth, which would coincide with the base of the lithosphere, there is a transition zone of high/low resistivity.

It would seem, therefore, that there is a deepening of the conductive layer in the craton–mobile belt transition zone. This decrease in the thickness of the lithosphere in the mobile belt might be related to a tectonically active mobile upper mantle. Few geophysical studies have been undertaken in this region. Gravity measurements along the perimeter of the craton north-east of our research area show numerous positive anomalies connected with basic intrusions (Crenn, Metzger & Rechenmann 1959). This belt is, moreover, subjected to regular earthquake activity (Gao gorge), and seismic research is scheduled to begin in the near future.

6 Conclusions

One of the features of the cratonic belt seems to be the disappearance of the conductive layer at a depth of 80 km. Research in Senegal and Upper Volta on the western section and in the interior of the craton also seems to demonstrate the disappearance of this layer (Ritz 1982). The resistivity of the crust and the upper mantle is also calculated to be about 3000 Ω m. This resistivity might well be typical of the craton as a whole.

The transition belt shows signs of the 'Continental Terminal' series. Here we find a lack of continuity between the crust and the upper mantle. However, the crust and the upper mantle still have a resistivity comparable to that of the craton ($\rho \approx 3000\ \Omega$ m).

A significant phenomenon in this study is the decrease of apparent resistivities between sites 5 and 6. We can observe along the profile a regular deepening of the basement. We go from the basement surfacing on the western craton to approximately 2000 m of sediment in the east. The significant reduction of the apparent resistivities is connected to the thickening of the cover series as well as to the change in the composition of the substratum: from west to east we go from a crystalline substratum ($\simeq 3000\ \Omega$ m) to lower resistant substratum ($\simeq 1000\ \Omega$ m). This lack of electrical continuity is likewise found in the north and south of our profile (CGG 1958). The throw of the fault exceeds 1000 m in the north, goes less and less deep towards the south, and finally disappears in the Niger Valley as it becomes attached to the border of the Voltaic syncline.

This fault throws the Gourma series and its substratum against the Tertiary and Cretaceous filling of the sedimentary basin.

This magnetotelluric study has demonstrated the existence, from a structural viewpoint, of three clearly defined geological regions, by defining the variation of resistivity with depth:

(1) On the craton, outcrops of the Pre-Cambrian basement, intersected by dunes of Quaternary origin. The conducting layer in the upper mantle could begin at a depth of 100 km. We could not prove this.

(2) The mobile belt is characterized by the appearance of the 'Continental Terminal' series. Modelling suggests that the conductive belt in the crust is located at a depth of 30 km with a resistivity of 100 Ω m. A second conductive layer exists in the upper mantle at a depth of 80 km.

(3) The sedimentary basin shows the continuity of the two preceding conductive series. We can see a significant electrical break at the level of the crust.

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