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Geoelectrical Deep Soundings in Southern Africa Using the Cabora Bassa Power Line*

Preliminary Results

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Abstract. Geoelectrical deep soundings with electrode spacings between 30 and 1250 km have been carried out from 1973 to 1975 in southern Africa using the Cabora Bassa power line.

At several sounding stations (Schlumberger and bipole-dipole arrays) the electric potential differences have been recorded in different directions. For short current-electrode spacings (< 200 km) the direction of the electric field is nearly perpendicular to the direction between the current electrodes whereas it becomes more or less parallel for large electrode spacings (> 400 km). A possible cause for this rotation of the field may be a dyke system observed in the granitic crust.

The resistivity curve has been interpreted on the basis of a horizontally stratified medium. As a minimum, four layers are necessary for the interpretation of the sounding curve:

Resistivity		50000		50		8000		≦50 Ωm,	
Depth	0		12		30		150		km

Taking into account an intermediate layer in the crust recently proposed by Van Zijl (1976) the following 5-layer model has been derived:

Resistivity		100000		10000		50		8000		≦50 Ωm,	
Depth	0		4		24		42		162		km

Key words: Deep Schlumberger Soundings – Southern Africa – Cabora Bassa power line.

1. Introduction

In recent years many investigations using the magnetotelluric method have been carried out in order to study the electrical resistivity distribution in the crust and the upper mantle. On the other hand, it is very desirable to determine

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the resistivity by independent methods, e.g. by DC resistivity profiling using artificial current sources.

The electrode configuration most commonly used in this wellknown and highly developed method is the Schlumberger quadripole array AMNB (current electrodes A and B, sounding electrodes M and N). The depth of penetration of electric soundings is limited by the maximum AB spacing. Normally this does not exceed a few tens of kilometers (equivalent to a depth of penetration of up to 10 km) because otherwise the logistic effort becomes enormous. Thus ultra-deep electric soundings can only be carried out if already existing transmission lines are available such as overhead telephone lines or electric power lines which are not yet commercially used.

An early investigation of this kind has been carried out by one of the present authors in the Rhine Graben area (West Germany) in 1967 with a maximum AB spacing of 150 km (Blohm and Flathe, 1970; see also Blohm, 1972; Homilius and Blohm, 1973).

Other ultra deep geoelectrical soundings have been done within different tectonic provinces in southern Africa (Van Zijl, 1969; Van Zijl et al., 1970; Van Zijl and Joubert, 1975). The results show that the upper part of the stable granitic crust generally has high resistivities of up to 10^5 Ωm and a depth of about 10 km. The resistivity of the lower crustal layer decreases progressively to a value of about 1000 Ωm at a depth of 16 to 20 km. However, the maximum electrode spacing achieved so far (600 km) did not allow any precise statements about the conductivity within the upper mantle.

For the first time the great length of the Cabora Bassa power line offered the possibility to use electrode spacings of up to 1250 km (Fig. 1), together with an extremely large current of nearly 3000 amp, at least for the maximum AB spacing. Fortunately, this unique opportunity could be seized by a cooperative effort of different scientific institutions. The geoelectrical measurements were organized and carried out from 1973 to 1975 by the following groups:

- Council of Scientific and Industrial Research (CSIR), Pretoria, South Africa;
- University of Rhodesia, Salisbury, Rhodesia;
- Niedersächsisches Landesamt für Bodenforschung (NLfB), Hannover, Federal Republic of Germany;
- Institute of Geophysics, Swiss Federal Institute of Technology Zürich (ETHZ), Switzerland.

The activities of the groups which have carried out the field measurements are summarized in Table 1.

Van Zijl and Joubert (1975) have reported on results which the CSIR obtained in 1973 using the northern part (Mavonde sounding, maximum AB spacing = 450 km) and in 1974 using the southern part (Pietersburg sounding, maximum AB spacing = 400 km) of the Cabora Bassa power line. Though the centres of the soundings have a distance of 800 km, the resistivity curves show the same general characteristics: At first the apparent resistivity increases with increasing electrode spacing and reaches a maximum value for AB spacings between 30 and 50 km. For larger electrode spacings the apparent resistivity continuously decreases.

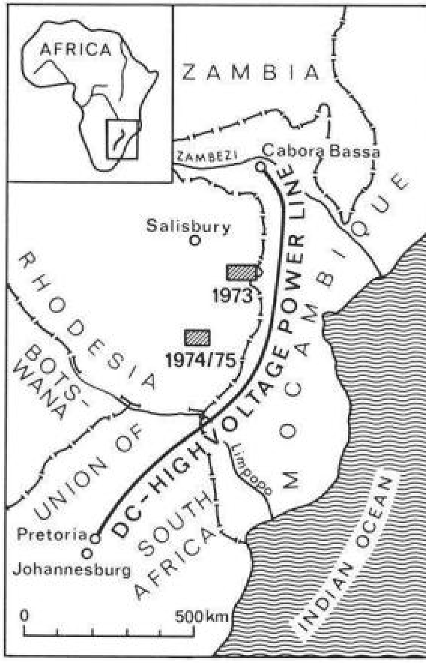

Fig. 1. General map showing the path of the DC high-voltage power line in Moçambique and South Africa. The areas where our sounding stations were situated in 1973 and 1974/75, respectively are marked by oblique hatching

Table 1. Summary of activities of the participating groups

Year	Electrode spacings	Groups	Number of MN stations
1973	30–450 km	CSIR South Africa	5
		NLfB Germany (FRG)	5
1974	420–960 km	CSIR South Africa	5
		Univ. of Rhodesia	1
		NLfB Germany (FRG)	4
1975	1250 km	CSIR South Africa	4
		Univ. of Rhodesia	1
		NLfB Germany (FRG) }	1
		ETHZ Switzerland }	

Very recently, Van Zijl (1976) has presented results of 30 deep electrical soundings (maximum AB spacing = 40 km) which the CSIR team has carried out along the line Umtali-Pietersburg (see Fig. 2). According to Van Zijl the resistivities characterizing the old cratons and the mobile belts are different. He assumes that the resistivity of the material underlying the highly resistant upper layer of the cratons is of the same lower order of magnitude as has been found for the upper layer of the mobile belts.

The present paper reports on the Cabora Bassa measurements of the German group (1973, 1974) and of the German-Swiss group (1975), respectively, and on the preliminary results derived from these measurements.

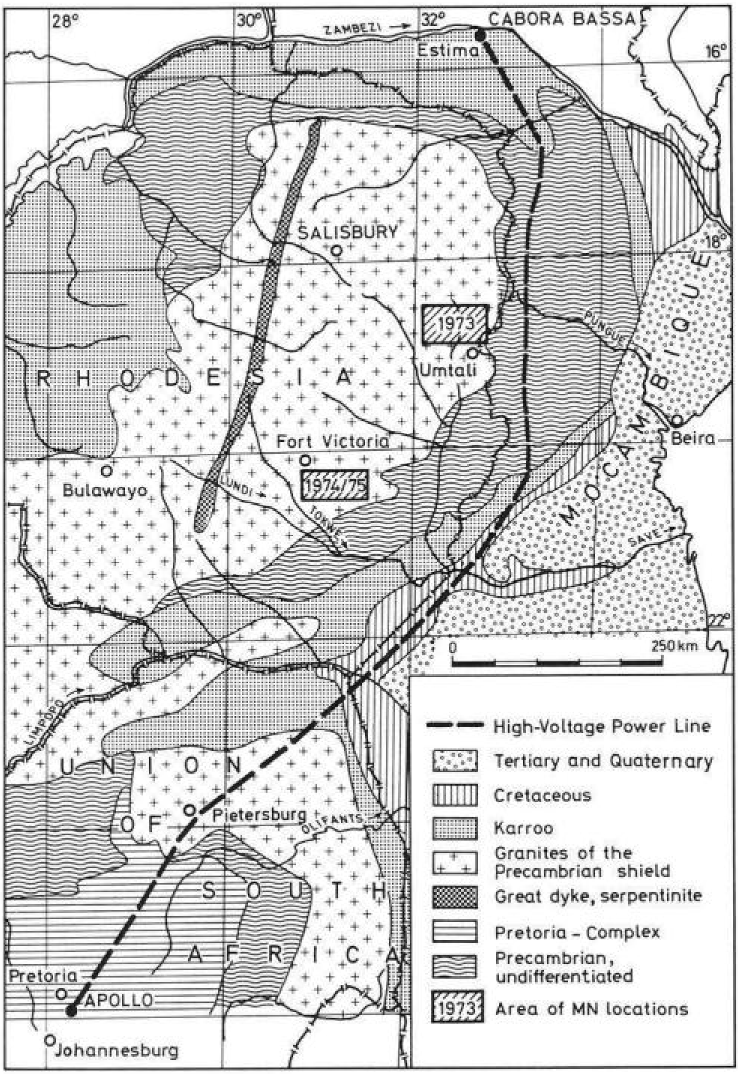

Fig. 2. Simplified geological map of southeastern Africa (after Geological Map of Africa, 1:5000000 Association of African Geological Surveys, 1963, Paris). The path of the power line is indicated by a dashed line. The locations of the sounding stations are shown as in Figure 1

2. Geological Setting

The principal structural units of southeastern Africa are the Rhodesian and the Cape-Vaal cratons, both of Precambrian age. They are surrounded by mobile zones (Limpopo, Moçambique, Zambezi belts). Figure 2 shows a simplified geological map of this area.

The Rhodesian craton consists of rocks with different grades of metamorphism and deformation. In the centre the cristalline basement is nonmetamorphic and either is exposed by erosion or is covered by a thin layer of sediments. The Rhodesian craton is divided into two parts by the Great Dyke consisting of basic and ultrabasic rocks. Furthermore, the northeastern part of the craton is split up by numerous dykes. The craton is surrounded by highly foliated gneisses belonging to the orogenic belts. These gneiss belts are followed by postmetamorphic sediments and lavas of the Karroo formation. On the Moçambique side the Karroo strata are covered by marine sediments of Cretaceous and Tertiary age.

Unfortunately the Cabora Bassa power line does not connect Cabora Bassa and Pretoria in a straight line but follows the Rhodesian-Moçambiquan border a few tens of kilometers east of it (Fig. 2). Thus the line partly touches the sediments of the Moçambique basin which have a higher conductivity than the crystalline basement.

3. Measurements

In 1973 the first geoelectrical soundings were carried out using the northern part of the power line with the centre at Mavonde in Moçambique. A maximum electrode spacing of 450 km was reached. The measurements were continued in 1974 with the centre near the Lundi River and a maximum spacing of 960 km. Finally, in 1975, the soundings were completed using the whole length of the power line ($\overline{AB}=1250$ km).

For the 1973 measurements the nothern part of the power line had been chosen because it was finished at that time and it directly crosses the basement in a straight line from North to South (Fig. 2). The current-electrode (A and B) localities were chosen such that the resistivity in the surroundings was as low as possible. At each locality an array of up to 120 single electrodes with a distance of about 4 m between them was used in order to achieve a very low contact resistance. The current for the electrodes was supplied by the CSIR group and was fed to the power line near Pietersburg in South Africa. A square wave current was used with a period of 4 min. The mean value of the current was 80 Amperes. The inverting of the current was automatically controlled by a quartz clock.

Five sounding stations were set up by the German group north of Umtali in Rhodesia near the border of Moçambique (Fig. 9). Several sounding stations were used in order to get information on lateral inhomogeneities of the crust. The sounding dipoles MN were situated on a straight line intersecting the AB line at a right angle in the centre between A and B (equatorial bipole-dipole configuration). In the case of a horizontal bedding with homogeneous layers the Schlumberger sounding curve is identical with the equatorial bipole-dipole sounding curve, provided that the apparent resistivity is plotted as a function of the effective spacing (see below).

The locations for the MN stations were chosen such that the sedimentary cover over the basement was as thin as possible and the immediate surroundings did not show any marked lateral changes in resistivity. Non polarizable Cu/$CuSO_4$ electrodes were used to measure the potential differences. The distance

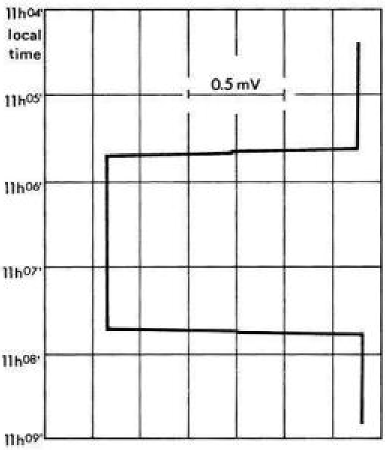

Fig. 3. Reproduction of a typical record of the potential difference ΔV as a function of time for a current-electrode spacing $\overline{AB}=30$ km and a sounding-electrode spacing $\overline{MN}=100$ m. The direction of the sounding dipole MN is N 60° E, applied current ±60 amp, station Umtali farm (FARM) (cf. Fig. 9). Local time = GMT + 2 h

between the MN electrodes was 100 m. At each station up to 15 MN lines were set up at different angles in order to measure the directional dependence of the electrical potential difference △V, i.e. to determine the field vector $\vec{E}$. This was done because $\vec{E}$ is parallel to the AB direction only as long as there are no lateral variations in resistivity (cf. Blohm, 1972).

The total measuring time per AB position ranged between 6 and 7 h. During this period at the different sounding stations 10 to 20 current inversions were recorded for each MN direction. The measured potential difference was amplified by a DC amplifier with high input resistance and recorded on a paper chart recorder. As examples, two recordings are reproduced for AB = 30 km and AB = 300 km in Figures 3 and 4, respectively. The first recording (Fig. 3) shows a nearly undistorted square wave. The small delay to be seen during the inversion phase is caused by a complete swith-off of the current for 2 s. The second curve (Fig. 4, upper part), however, shows two large induction peaks. The first peak results from the swith-off of the current, the second one is caused by the switch-on of the reversed current 2 s later. These inductive effects become more and more important with increasing AB spacing. In addition, the DC offset △V we are interested in, is disturbed by telluric noise. Of course, the accuracy of △V may be improved by stacking (Fig. 4, lower part).

The 1974 program consisted of 4 AB spacings varying between 420 and 960 km. The centre of the AB line had to be shifted southwards compared to the 1973 measurements.

The four German MN stations were situated southeast of Fort Victoria (see Fig. 2). The primary current was generated in the same way as 1973. Again, the mean value of the current was 80 Amperes. The length of the switching period was increased to 15 min to make sure that the field had enough time to settle to the stationary level. Because of the short measuring period – the power line could be used for a period of only 3 weeks – measurements with the smaller AB spacings up to 400 km could not be repeated. However, another sounding using the southern part of the Cabora Bassa power line with the

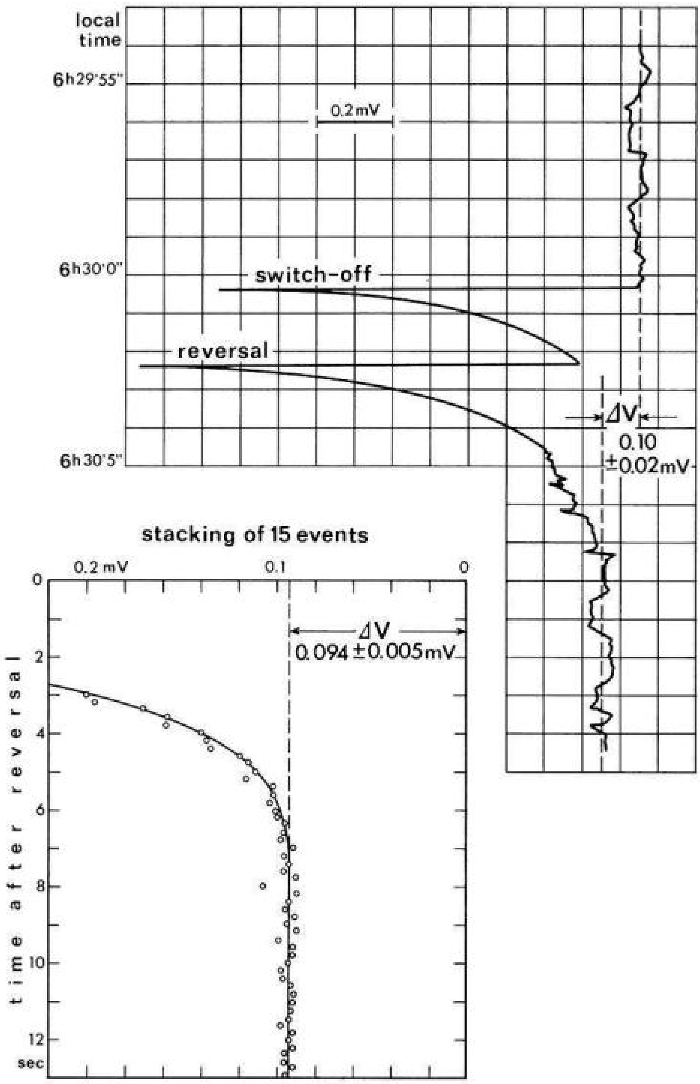

Fig. 4. Same as Figure 3, but $\overline{AB}=300$ km, *MN* direction N 150°E, current ±85 amp. In addition, the stacked signal is shown for time 0–13 s after reversal of current

centre near Pietersburg had been completed in the meantime. It gave a similar sounding curve as the northern sounding carried out in 1973 (Van Zijl and Joubert, 1975). Nevertheless, measurements with the shorter AB spacings within the Limpopo belt would have been desirable because they would have given some information on the resistivity structure of this mobile zone. The Limpopo belt is thought to consist of material coming from the lower part of the crust and which shows a positive Bouguer anomaly (Reeves and Hutchins, 1975).

In 1975 the power line had been completed and was available for final measurements with an AB spacing of 1250 km. They were carried out during

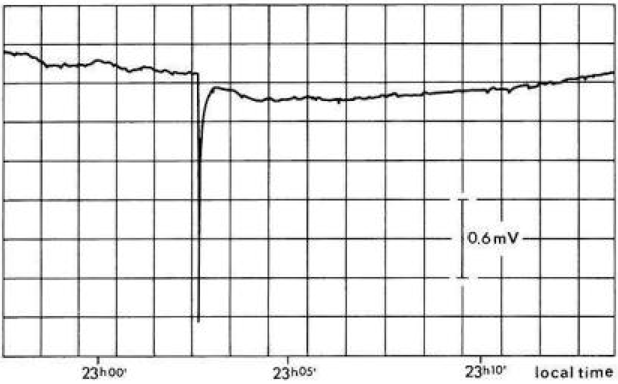

Fig. 5. Similar to Figure 3, but $\overline{AB} = 1250$ km, MN direction parallel to AB direction. A current of 2950 amp was switched off within 20 ms. Station south of Fort Victoria

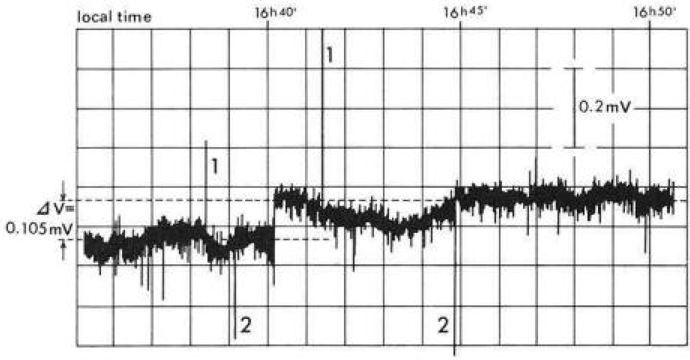

Fig. 6. Same as Figure 5, but swith-off within 10 s and current of 1550 amp. The peaks marked by the numbers *1* and *2* are probably caused by atmospherics

the test phase after start of operation of the Cabora Bassa power plant. The two earth electrodes of the terminal stations Estima (Cabora Bassa) and Apollo (Pretoria) were used as grounding points. These two earth electrodes have been provided for the case that one pole of the power line fails during operation and the earth has to be used as one conductor. Thus the total DC current from the Cabora Bassa power plant was available for the measurements and a maximum value of 2950 Amperes was reached.

The sounding station of the German-Swiss group was located south of Fort Victoria, which is approximately at the centre between the current electrodes. Three MN lines of 100 m length were set up in different directions. The homogeneity of the electric field was examined by an additional MN line of 600 m parallel to the AB direction. Contrary to 1973 and 1974, the four MN lines had to be run simultaneously because the times of the current switch-offs depended on the progress of the test program at Cabora Bassa and could not be predicted. A radio link was installed between the power station at Cabora Bassa and the sounding stations of all participating groups in order to transmit the information on the switching times without delay.

Generally, after switching on, the current increased continuously over some minutes and then remained constant over several hours. Later, the current was switched off again suddenly. Because of the telluric noise the rather slow increase of the current could not be observed. Thus only the switch-off phase could be used for the determination of the potential difference. Figure 5 shows such a switch-off with a switching time of a few milliseconds. Unfortunately a long-period telluric noise is superposed, but the strong induction peak can clearly be seen. In this case it is very difficult to determine a useful value of the potential difference. On the other hand, Figure 6 shows a switch-off with a switching time of 10 s. This time no inductive peak at all is visible. The peaks marked by the numbers 1 and 2 probably caused by atmospherics. Altogether 47 switch-offs have been recorded in 1975.

4. Results

As described in the preceding section nearly all the soundings ($\overline{AB} \leqq 960$ km) were carried out using the equatorial bipole-dipole configuration. Only the last measurement with $\overline{AB} = 1250$ km was a true Schlumberger sounding. However, in case of horizontal stratification the apparent resistivities obtained by the two methods are identical if $\overline{AB}/2$ is substituted by the effective spacing

$$\bar{R} = [(\overline{AB}/2)^2 + R^2]^{1/2}$$

where R is the distance between the sounding dipol MN and the centre of the current-electrode bipole AB (Zohdy, 1970). Accordingly, in Figure 10 the apparent resistivities ϱ_a have been plotted as a function of $\overline{AB}/2$ (Schlumberger configuration) and of $\bar{R}$ (equatorial bipole-dipole configuration), respectively.

The directional dependence of the potential difference ΔV measured at all the sounding stations has been found to be sinusoidal within error bounds. Two examples for an AB spacing of 30 and 300 km, respectively, are shown in Figure 7. The resistivity values used for the sounding curve were computed by selecting the maximum absolute values of the potential difference ΔV at the corresponding sounding stations. However, the directions of the electric field vector deviate considerably from the direction between A and B for small AB spacings. Figure 8 shows the directions of the electric field vector for different AB spacings at the MN station Inyazura II (see Fig. 9). For small spacings ($\overline{AB}/2 \leqq 60$ km) the direction of the field is nearly perpendicular to the direction between A and B, whereas it becomes more or less parallel for large electrode spacings ($\overline{AB}/2 \geqq 125$ km).

Of course, the observed rotation of the electric field vector cannot be explained in terms of a model with horizontal homogeneous layers, because in such a case the field should always be parallel to the direction between A and B. Figure 9 shows the direction of the electric field for all our stations during the investigation in 1973 for AB less than 100 km (solid arrows) and for AB greater than 300 km (dashed arrows). The direction of the field for the smaller AB values is more or less parallel to the strike of most of the

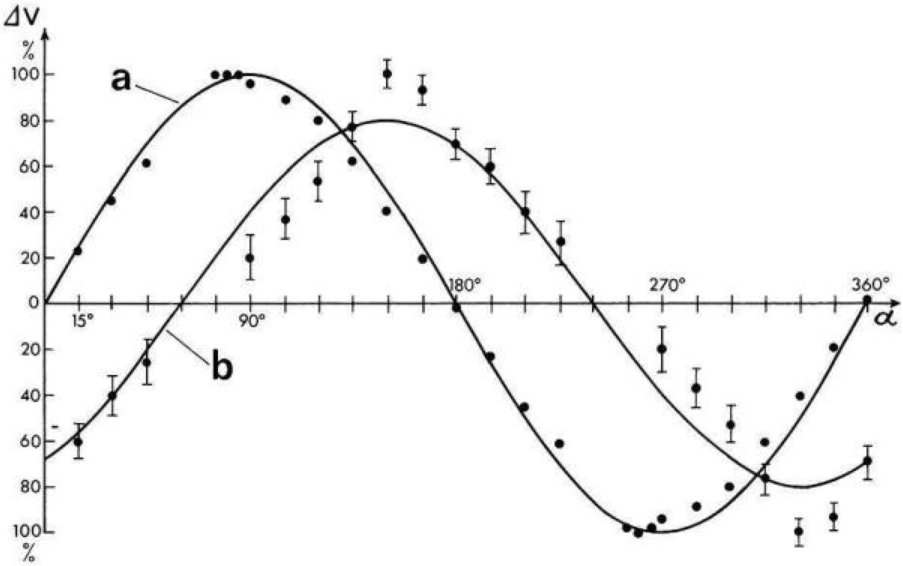

Fig. 7a and b. Plot of normalized potential difference △ V as a function of MN direction (azimuth α = ∢ MN, *AB*), station CAMP (cf. Fig. 9) for **a** $\overline{AB} = 30$ km, **b** $\overline{AB} = 300$ km

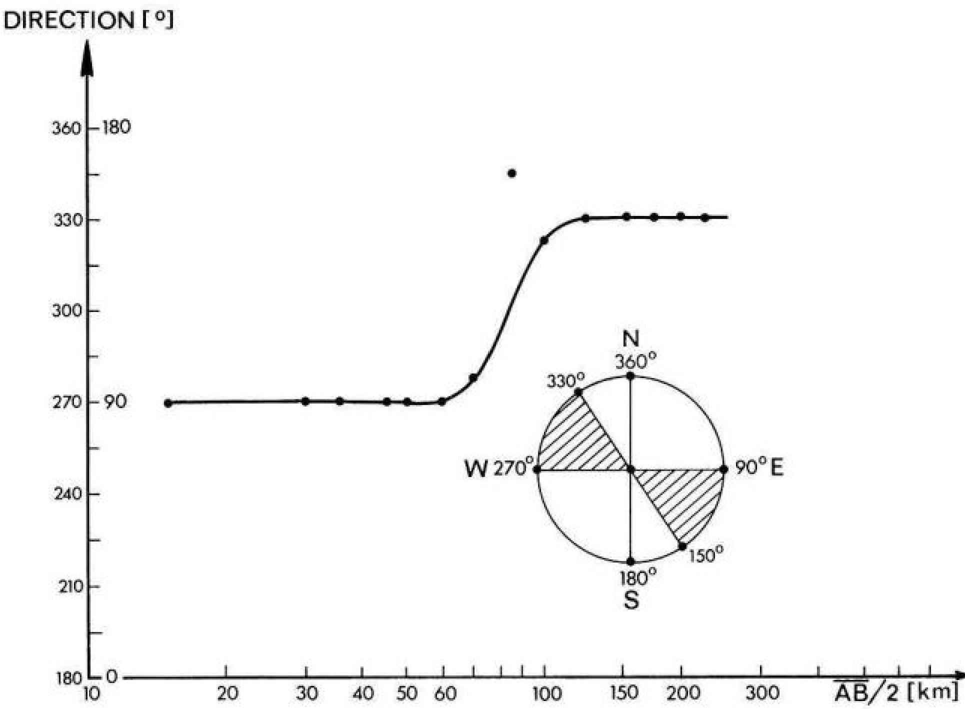

Fig. 8. Direction of the electric field as a function of $\overline{AB}/2$ at the sounding station INY II (cf. Fig. 9). The AB direction varied within ±4 degrees from the NS direction (0°, 180°, respectively)

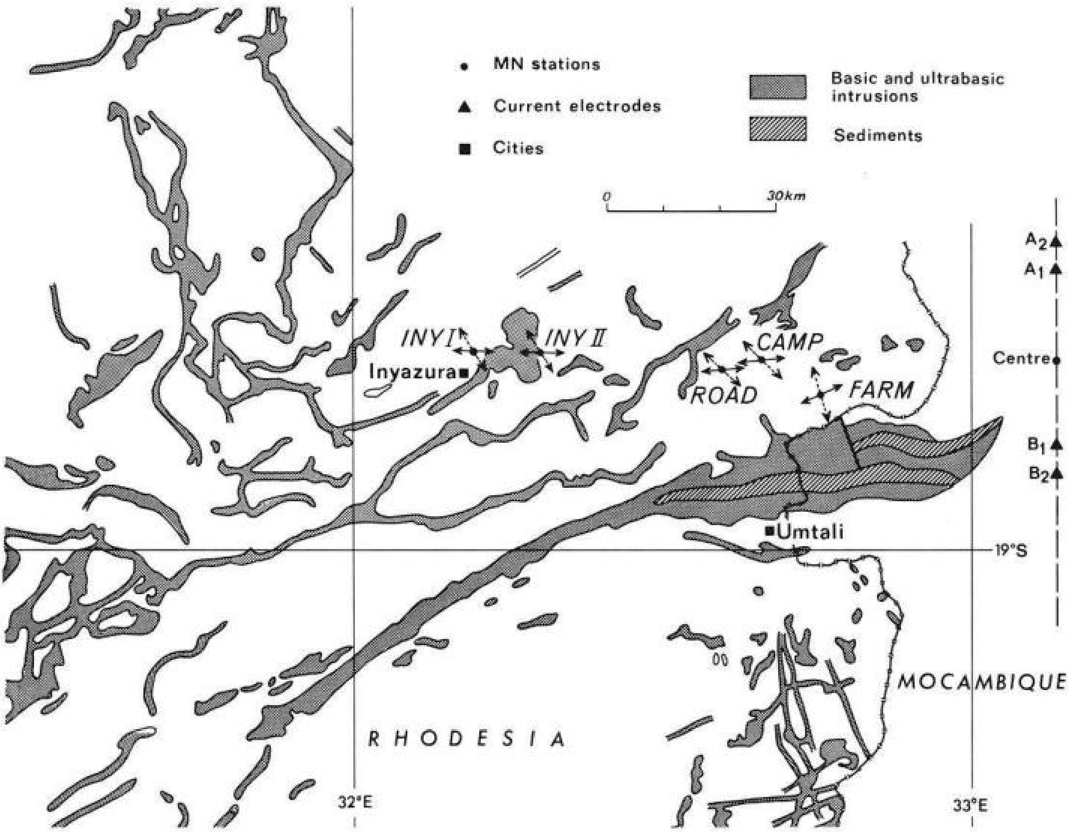

Fig. 9. Geological sketch of the intrusive dykes around the sounding stations near Umtali (after Geological Map of Rhodesia 1:1000000, Rhodesia Geological Survey, 1971, Salisbury, and Carta Geologica de Moçambique 1:2000000, Direcção Provincial dos Serviços de Geologia e Minas, 1968, Lisboa). Solid arrows show the direction of the electric field for AB spacings < 100 km, dashed arrows show the direction of the field for AB spacings > 300 km

basic and ultrabasic intrusions which are very numerous in this region. These dykes appear to have intruded into a preexisting fracture system possessing the same direction. Evidently, the direction of the field and the strike of the dykes must have some connection. The resistivity of the intrusive material has not been measured but is probably different from the surrounding granite. In such a case the current would be channeled in a direction parallel to the dykes. In addition, this fracture system might explain more directly the observed anomalous field distribution if the fractures have a higher water content than the surrounding rock.

The deviation of the direction of the field for larger electrode spacings is relatively small (N 30°W, AB direction NS), but nevertheless significant. This direction is parallel to a possible second fracture system suggested by the strike of some of the intrusions (Fig. 9). This might again provide an explanation for the deviation of the field. These features still are under investigation.

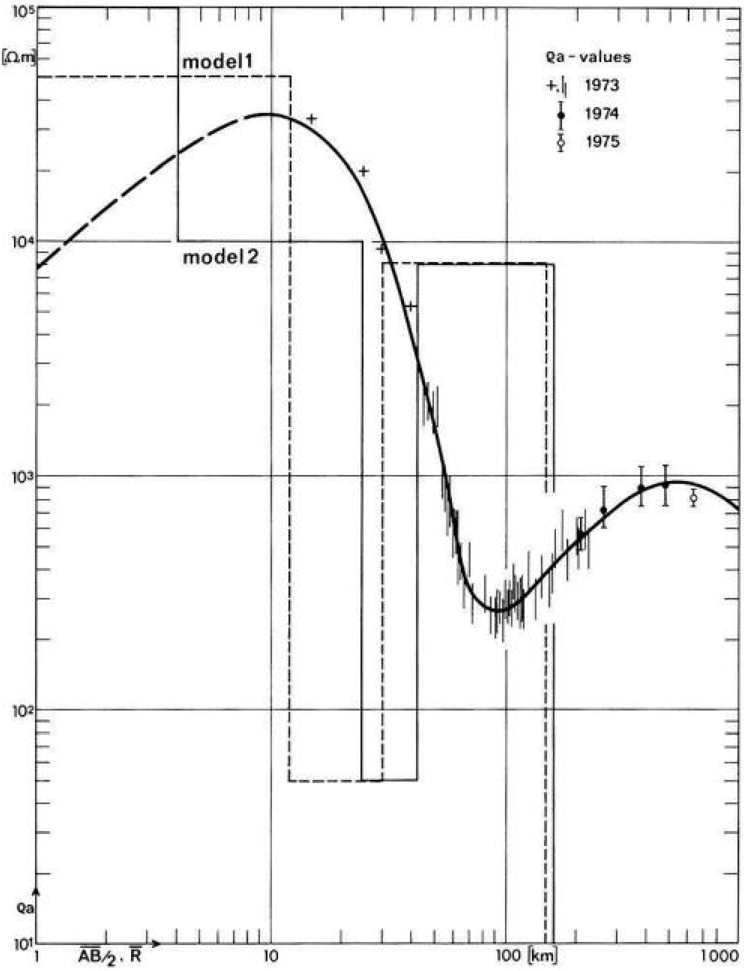

Fig. 10. Values of the apparent resistivity ρ_a as a function of $\overline{AB}/2$ (Schlumberger configuration) and of the effective spacing $\bar{R}$ (bipole-dipole configuration), together with a best fit curve. The ρ_a values marked by + have been computed from ΔV values measured by Van Zijl and his group at the centre position. Dashed portion: Extrapolation from subsidiary measurements carried out by Van Zijl in 1973 (personal communication). Note: The abszissa is the vertical depth scale for the models of four (*dashed line*) and five (*solid line*) layers

On the other hand, the measurements of 1974 and 1975 with AB spacings greater than 420 km showed no anomalous field distribution and the resistivity values agree very well with those from 1973 (see Fig. 10).

Moreover, even for the 1973 measurements which showed the rotation of $\vec{E}$ the scatter of the resistivity values between the different stations is very small (cf. Fig. 10).

Furthermore, Van Zijl (1976) gives a resistivity profile along the line Umtali-Pietersburg showing a nearly horizontal stratification below a depth of 10 km. Considering all these observations an interpretation of the resistivity curve on the basis of a horizontally stratified model appears to be justified although, of course, the geological fine structure of the upper crust might have some influence on the form of the resistivity curve.

The sounding curve derived from all measurements is shown in Figure 10. The resistivity values for $\overline{AB}/2 = 15$, 20, 30, and 40 km measured at the Schlumberger centre have been supplied by the CSIR group (Courtesy Dr. Van Zijl) and have been included in order to complete the curve. The smallest effective spacing $\bar{R}$ realized with our own sounding stations was 44.6 km (station FARM, cf. Fig. 9). For 1973, the resistivity values for the different sounding stations have been plotted seperately for each AB spacing because the effective spacing $\bar{R}$ varied considerably from station to station. The error bars show confidence limits derived from the single ΔV measurements. In 1974, the effective spacings $\bar{R}$ for the individual sounding stations were nearly equal. Therefore only one resistivity value per AB spacing is given. In this case the error bars include both the statistical error of the different ΔV values and the scatter between the results from the individual stations. For 1973 and 1974 the relative error of the apparent resistivity is about 20%, where as for 1975 it amounts to only 7%, mainly due to the high electrode current.

Two best-fit models derived on the basis of a horizontally stratified medium are shown in Figure 10. Of course, due to the principle of equivalence and to error bounds, other interpretations are possible, too. The models have been computed by the NLfB at Hannover (Dennert, 1977).

The first interpretation is a 4-layer case, neglecting a conductive overburden of a few tens of meters:

Resistivity		50000		50		8000		$\leqq 50$ Ωm,
Depth	0		12		30		150	km.

In 1975 subsidiary soundings were carried out by Van Zijl along the path Umtali-Pietersburg using AB spacings of up to 40 km (Van Zijl, 1976). He proposes an intermediate layer between the highly resistive layer of the craton and the conductive layer in the lower crust. Because of the strong resistivity contrast of the neighbouring layers such an intermediate layer is not visible in our sounding curve. Taking into account the results of Van Zijl a second model has been derived:

Resistivity		100000		10000		50		8000		$\leqq 50$ Ωm,
Depth	0		4		24		42		162	km.

The two models given above have the following general characteristics: A resistive zone with a maximal thickness of 24 km is followed by an intermediate conductive layer having a thickness of about 18 km. The next layer has a high resistivity again and a thickness of 120 km. The resistivity of the last layer is not defined very well, but is definitely lower.

The resistivity of the upper crustal layer seems to be rather high ($\geqq 50000$ Ωm), but the resistivity near the surface is high too. For instance, the resistivity of the nonmetamorphic granite at the MN station near Zimbabwe (south of Fort Victoria) was 20000 Ωm. This high-resistivity layer probably consists of unfractured granites with a very low porosity. Possibly, this first layer must be subdivided into two layers with 100000 Ωm and 10000 Ωm, respectively (model 2).

These zones of high resistivity are followed by an intermediate conductive layer. The extremely low resistivity of 50 Ωm might be caused by hydrated rocks in the lower part of the crust. Although this resistivity corresponds to the best-fit curve shown in Figure 10, it has to be kept in mind that other models leading to the same longitudinal conductance are possible within error bounds.

A conductive layer within the lower crust has also been found by many investigators using the magnetotelluric method. These studies have been summarized by Keller (1971). Further material can be found in chapter 5 of the comprehensive monograph edited by Adam (1976).

Moreover, this zone might be correlated with low-velocity zones observed by Bloch et al. (1969). These authors suggest a model with two low-velocity layers with a thickness of 2 km at a depth of 12 and 24 km which is consistent with dispersion studies of surface waves along the line Pretoria-Bulawayo.

The resistivity of the upper mantle (8000 Ωm) is in reasonable correspondence with results from laboratory models (Brace, 1971). The depth of about 160 km can be associated with the thickness of the lithosphere. It agrees surprisingly well with the values of 150–175 km derived by Fairhead & Reeves (1976) from teleseismic delay times.

The last two values of the apparent resistivity curve indicate that the final layer has a low resistivity. Of course, even the great AB spacing of 1250 km has not been large enough for a precise evaluation of the resistivity of this layer. In accordance with results from magnetic deep soundings its resistivity has been assumed to be $\leqq 50$ Ωm (Schmucker, 1974).

5. Discussion

The interpretation given above is based on the assumption that lateral variations of the resistivity are negligible. However, such variations do exist and are clearly demonstrated by the observed rotation of the electric field vector. Apparently the direction of the field vector can be correlated with the geological fine structure observed in the northeastern part of the Rhodesian craton. Moreover, other geological features resulting in a lateral variation of resistivity have to be considered, e.g. the sediments of the Moçambique basin and the Indian Ocean. Although detailed computations taking these effects into account have not yet been finished, the small scatter of the resistivity between the different stations indicates that lateral effects are small and can be neglected. This is further confirmed by the good agreement between the 1973 and 1974 sounding data (AB$\approx$400 km) where the centre between A and B was shifted southwards by about 400 km and the direction between A and B changed by about 40°.

Unfortunately no magnetotelluric data are available for this part of Africa, with the exception of a study on the conductivity anomaly in South-West Africa (De Beer et al., 1975). Thus one has to look at far-away data for comparison. Therefore, a magnotelluric survey within Rhodesia would be very desirable.

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