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Electrical imaging of lateritic weathering mantles over granitic and metamorphic basement of eastern Senegal, West Africa

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Abstract

The electrical properties of several tens of metres of lateritic weathering mantle were investigated by using electrical resistivity tomography •ERT• in two basement areas of eastern Senegal. The field survey was conducted along two profiles providing continuous coverage. Colour-modulated pseudosections of apparent resistivity vs. pseudo-depth were plotted for all survey lines, giving an approximate image of the subsurface structure. In the area underlain by granitic basement, the pseudosection suggests a very inhomogeneous weathered layer in which the apparent resistivity changes more rapidly than thickness. In the second area, underlain by schists, the lateral changes in electrical properties are less pronounced than those of the granitic area. Interpretation of 2D Wenner resistivity data yielded considerable detail about the regolith, even without pit information. In both areas, the near-surface topsoil comprising undersaturated lateritic material is highly resistive. The intermediate layer with low resistivities •e.g., 20–100 • m• contains clays including small quantities of water. The third, highly resistive layer reflects the granitic basement. Comparison of ERT survey results with pit information shows general agreement and suggests that ERT can be used as a fast and efficient exploration tool to map the thick lateritic weathering mantle in tropical basement areas with hard rock geology. • 1999 Elsevier Science B.V. All rights reserved.

Keywords: Electrical imaging; Tropical weathering; Saprolite; Iron crust; Two-dimensional resistivity models; Senegal

1. Introduction

Overburden cover is common in most parts of the world. In eastern Senegal and other tropical regions, the overburden mostly consists of a thick lateritic weathering mantle. The landscape of eastern Senegal is characterized by large flattened surfaces deeply dissected by erosion processes. These surfaces are generally covered by iron crusts under which develop thick clay-rich weathering material. The thickness of these horizons can exceed several tens of meters depending on the nature of the fresh rock and the geomorphological situation •Blot et al., 1976; Leprun, 1979•. A knowledge of the weathering layers and processes is important in groundwater prospecting, evaluation of the mineral poten-

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tial, and geologic mapping (Palacky and Kadekaru, 1979; Hazell et al., 1992). Geophysical surveys can play a major role in the acquisition of such a knowledge. Recent works have shown that the application of direct current (DC) resistivity methods can reveal details of the weathered zone (Robain et al., 1996). In general, DC resistivity soundings in such geological setting show a basic three-layer geoelectrical succession with a low resistive clay-rich saprolite layer sandwiched between much more resistive materials corresponding to the iron crust and basement. However, sampling limitations or incorrect interpretation of data have frequently led to unsatisfactory results because of (i) the presence of lateral resistivity variations within layers which are not horizontally disposed and of (ii) the excessive depth of weathering.

DC surveys are designed to discriminate between anomalies reflecting subsurface electrical resistivity contrasts associated with lithologic and/or hydrologic characteristics. The interpretation of the resistivity sounding data is usually made assuming a stratified earth (Keller and Frischknecht, 1966; Koefoed, 1979) and can only provide the parameters of a horizontally layered model with limited resolution. Spatial variations of earth materials or topographic effects, however, invalidate such assumptions.

In several parts of West Africa (Delaitre, 1993; Tardy, 1993), significant spatial variations have been reported in the lithologic characteristics of weathering profiles. Hence, the highly heterogeneous nature of the overburden implies that situations could arise in which the 1D layered models do not account for realistic geologic structures. This implies that at least 2D information is required.

In areas where complex geology renders conventional DC methods inadequate and where it is necessary to have a continuous cover, the 2D resistivity imaging process can be used for a more accurate delineation of subsurface structures. The electrical resistivity tomography (ERT) method (Griffiths and Barker, 1993) differs from the DC survey in using a multielectrode array system and in recording the maximum number of independent measurements on the array. The purpose of this work was thus to investigate whether ERT could provide accurate information on the weathered layers developed upon the basement in selected areas of eastern Senegal. The surveys were conducted at locations where the geology is well-known from the observation of pits and road cuts, so interpreted data could be compared to this information.

2. Geological and weathering setting of investigated areas

The investigated area is located in eastern Senegal 800 km southeastern of the capital Dakar where two sites have been chosen within lower Proterozoic formations (Fig. 1).

At Tenkoto, a topographic sequence of pits has been set up from a gently sloping plateau covered by an iron crust to a thalweg (Fig. 1a). The geophysical profile is paralleled 30 m from the topographic sequence of pits. The fresh rock is a granite with biotites and amphiboles. The pits were dug to a depth of 7–12 m in a clayey layer including water (Fig. 2a–b). At the bottom of pits, the top of the saprolite contains some decimetric to metric size blocks of unweathered granite which were also observed in the thalweg flats. This saprolite is overlain by a 0.5-m thick mottled clay layer containing many pebbles of angular quartz and round ferruginous nodules. This level actually undergoes further digging for gold artisanal exploration. Above this is the soft iron crust, a low hardened ferruginous level, 2.5 m to 3.5 m thick, which is formed by gravels and ferruginous nodules embedded in a soft matrix. This soft iron crust is covered by a very hardened massive iron crust, 3.5 to 5 m thick (Fig. 2a). The ferruginous levels exhibit rapid lateral variations in hardening and thickness. Locally, the matrix is softer around cracks and fissures that reflects the degradation and the

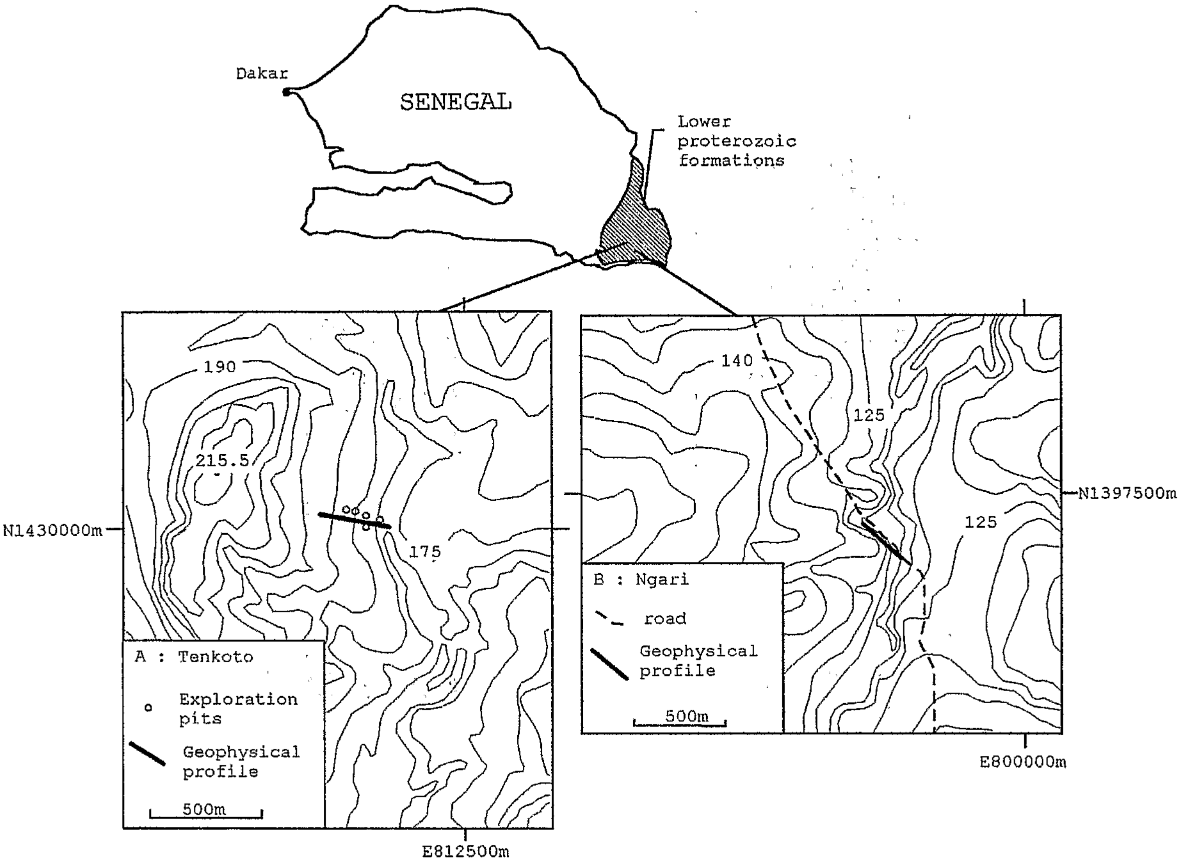

Fig. 1. Topographic location maps of the geophysical profiles (a) at Tenkoto with pits and (b) at Ngari with the road cut. The contour lines are to 5 m intervals. UTM coordinates.

disaggregation of the iron crust whose thickness ranges from 1 to 2.5 m on slopes (Fig. 2b).

At Ngari, a road cuts the lateritic plateau providing an exposure of 12 m thick over a length of 100 m (Fig. 1b). The geophysical profile is paralleled 30 m inside the plateau from the road cut. The weathering process affects schists belonging to a proterozoic metasedimentary series (Birimian). A thick clayey horizon is observed from 6 m to the base of the cut including a saprolite covered by a 1-m thick mottled clay layer (Fig. 2c). A ferruginous horizon is composed of a 2-m thick soft iron crust covered by 4 m of an iron crust which shows marks of dismantling characterized by ferruginous nodules embedded in a clayey–ferruginous soft matrix (Fig. 2c). This disaggregated facies occurs at the base of the iron crust as well as on edges of the plateau where it is often mixed with a linear horizon of pebbles originating from the bending of a quartz vein. Sideways, the ferruginous horizon is cut by the slope of the plateau. The slopes are covered by a colluvial horizon formed by iron crust debris embedded in a clay–ferruginous matrix (Fig. 2c).

The direct observation of pits and road cut does not determine the fresh rock, its topography and the possible geological discontinuity as variations of facies or presence of quartz veins. Such informations are nevertheless of great interest (i) for a better knowledge of the geology, (ii) for understanding the geochemical and physical processes governing the formation of these lateritic weathering profiles, and (iii) for a better

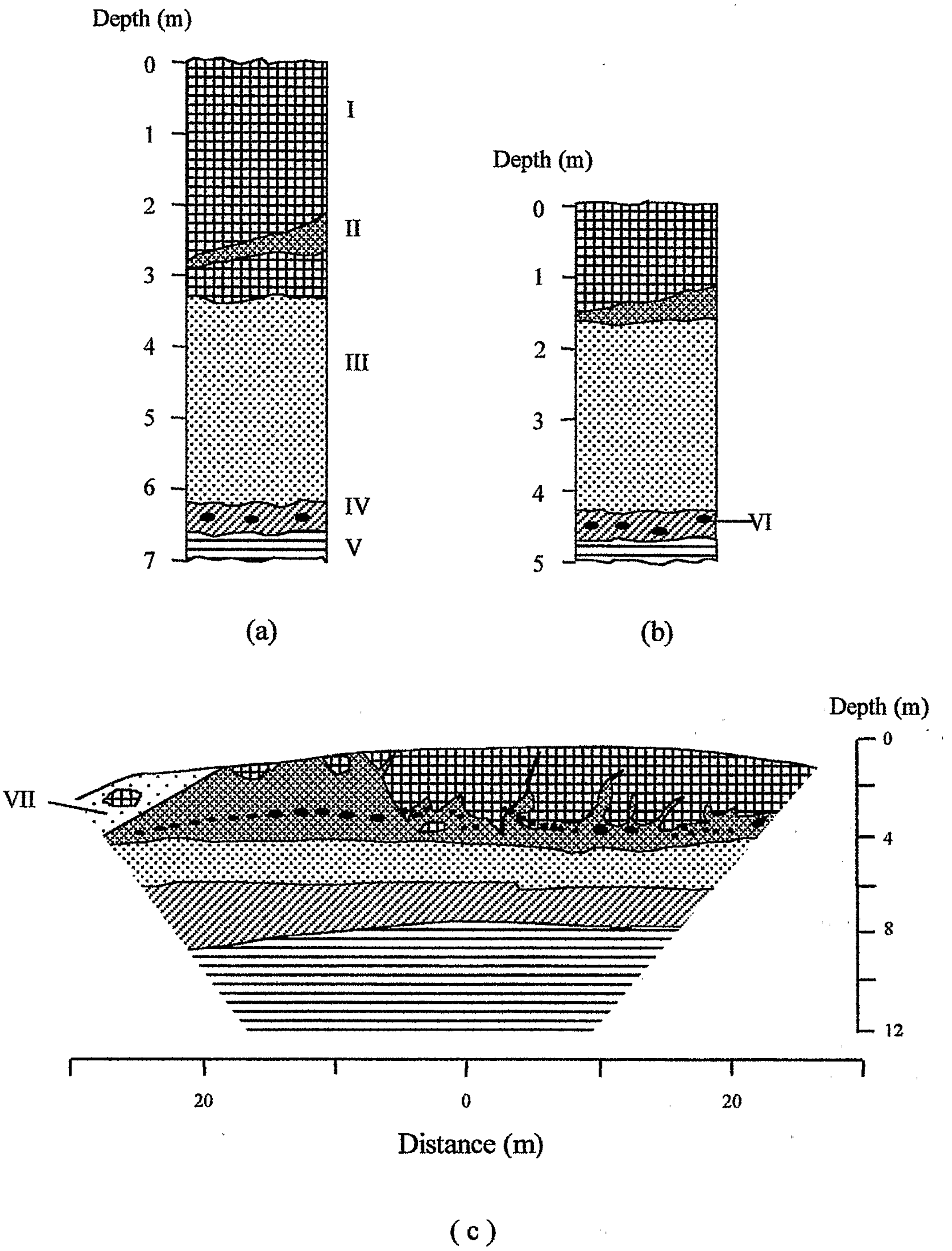

Fig. 2. Lithologic sections of two pits within the Tenkoto area. (a) Weathering profile on the plateau. (b) Weathering profile on the slope. (c) Sketch of the overburden across the Ngari area (I = iron crust; II = disaggregated iron crust; III = soft iron crust; IV = mottled clay layer; V = saprolite; VI = angular quartz and debris of iron crust; VII = colluvial material).

interpretation of the underlying geomorphic processes.

3. Geoelectrical method

The 2D resistivity data were recorded using the ABEM Lund Imaging System with an array of 64 steel electrodes. The survey was carried out along two profiles to examine the ERT response under different geological situations and their effectiveness for providing quantitative information on the weathering mantle. Electrical measurements (Fig. 3) are made on a straight line with a constant spacing using a computer-controlled multichannel resistivitymeter (Griffiths et al., 1990). To obtain good topsoil layer information, it is practice to employ more than one inter-electrode spacing during surveying. The unit electrode spacing determines the length of the profile, the depth of investigation, and the resolution. The short spacing, e.g., 0.5–1 m, will give more detailed information on the upper part of the weathering profile, while the larger spacings, e.g., 3–5 m, have been used to investigate the deeper zones such as the saprolite and the bedrock. A Wenner electrode configuration was employed. The data are classically presented in the form of pseudosections (Edwards, 1977), which give an approximate picture of the subsurface resistivity. Inversion of the data is required to obtain a vertical true resistivity section through the underlying structure (Beard et al., 1996; Loke and Barker, 1996). The field data depicted as contoured pseudoresistivity sections were inverted using the least-squares method as described by Loke (1997). Furthermore, the topographic variations have been incorporated in the inversion processing. The resulting pseudosections of apparent resistivities do not necessarily indicate gradual change of resistivity, implying to carefully compare the resistivity data with the pit observations. Though the inversion method is fast and accurate for simple 2D structures, it does not always give unique and precise limits of bodies of small size.

4. Results and discussion

4.1. Tenkoto profile

Fig. 4 represents the apparent resistivity and the true resistivity images in the upper 5 m of the weathering zone for the granitic area of Tenkoto with an electrode spacing of 0.5 m. Fig. 4b shows a 2-m thick surface layer having resistivities above 10000 Ωm, that corresponds

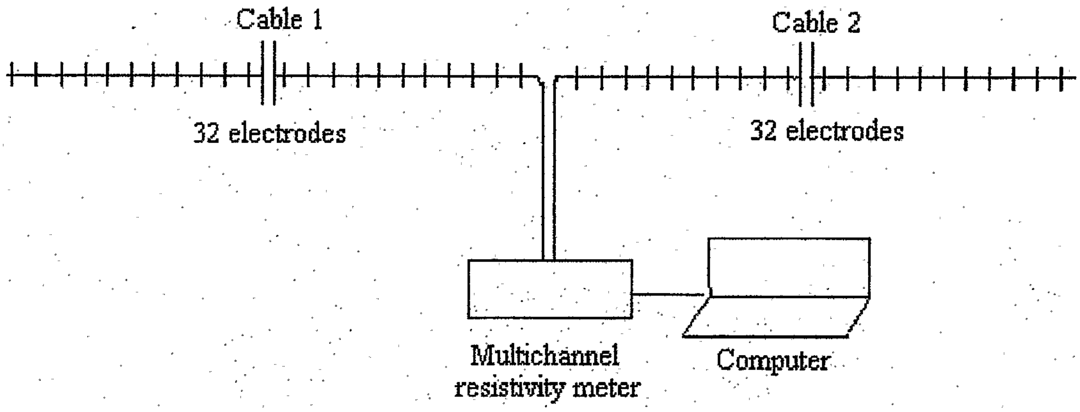

Fig. 3. Schematic layout of the electrical resistivity tomography (ERT) experiment to image the lateritic weathering mantles. Sixty-four electrodes were arranged at equal spacings along a straight line. The cables are connected to a multichannel resistivity meter which is controlled by a computer.

to a very hardened iron crust. The heterogeneity of resistivity is greatest within this layer suggesting lateral variations of hardening and facies.

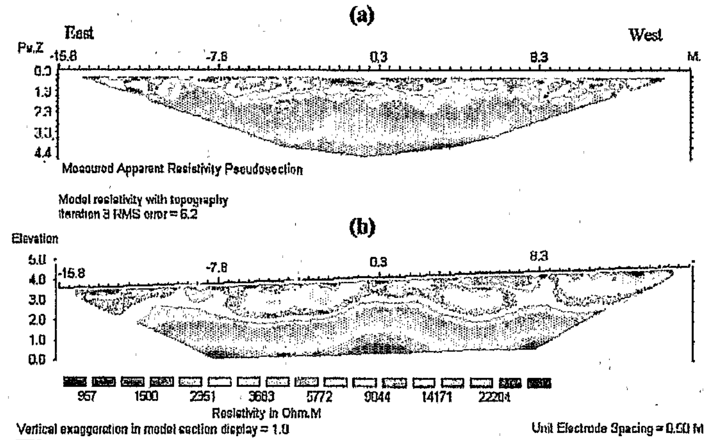

Fig. 4

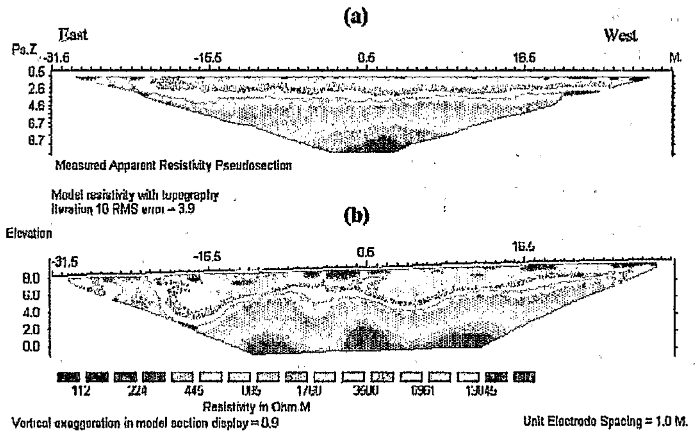

Fig. 5

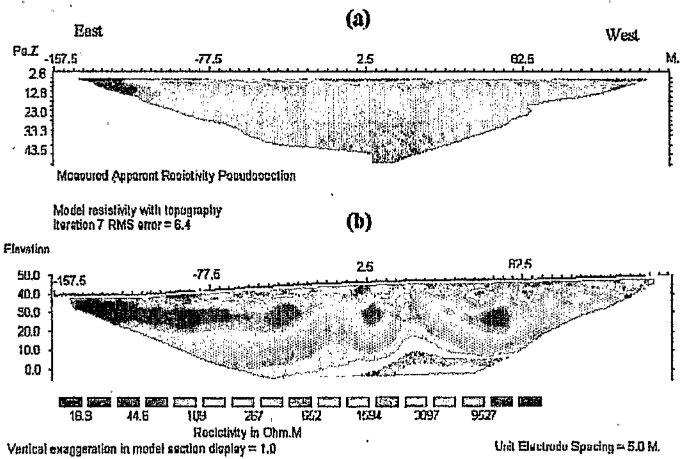

Fig. 6

With an electrode spacing of 1 m (Fig. 5), both depth of investigation and profile length increase, but details of the surface layer are fading compared to the Fig. 4. This section emphasizes even so the heterogeneity of the iron crust. A low resistivity zone of 100 Ωm occurs at depth corresponding to the saprolite. The soft iron crust is characterized by resistivities ranging from 1000 to 3000 Ωm. The scarp underlining the edge of the plateau is marked by a decrease of resistivities between −21 m and −26 m that corresponds to the dismantling of the iron crust (Fig. 5b).

The pseudoresistivity and the inversion for an electrode spacing of 5 m allow a larger view of the weathering mantle (Fig. 6). Fig. 6b shows the high-resistivity surface layer, corresponding to the iron crust. The resistivity, however, decreases of about 10 Ωm in the eastern part of the section. This likely reflects the boundary between the iron crust and the clay-rich weathering material into which freshwater originating from the stream close to the resistivity profiling can infiltrate. At this scale, the geoelectrical distinction between the soft iron crust and the overlying iron crust is not clear. On the other hand, the zone of low resistivity characterizing the saprolite is well-defined, though it seems to be perturbed by a narrow resistivity discontinuity between positions 17.5 and 22.5 m, dividing the area into an eastern and a western zone having similar resistivities. The low resistivities occurring in the eastern zone have been first related to freshwater infiltrations feeding a perched water table which may evaporate during the dry season. Such zones of low resistivity are thus more likely associated with a relatively high clay component. Even a small quantity of water in clay materials increases the cation exchange capacity of clays (Keller and Frischknecht, 1966). As a result, the resistivity of the pore fluid can be significantly lowered. Clays can retain water by capillary action due to their fine-grained texture and this also results in a lowering of the resistivity. Beneath, the saprolite resistivities increase progressively to values above 3000 Ωm. This is likely an indication of a transition from the saprolite to the granitic sand then to the unweathered granite basement. A sharp and narrow high-resistivity area ranging from 650 to 1100 Ωm ascends from the bedrock to the saprolite, that can indicate either a strong irregularity of the bedrock or a geological structure like a quartz vein. The results from the granitic area suggest a lateritic weathering mantle of about 40 m thick from the unweathered bedrock to the surface.

4.2. Ngari profile

Figs. 7 and 8 show the results of 2D resistivity surveying at Ngari with electrode spacings of 0.9 and 3 m, respectively. The pseudosection reveals a decrease of the apparent resistivity with depth (Fig. 7). Fig. 7b shows a well-defined top layer with resistivities above 5000 Ωm corresponding to the iron crust of 2–4 m thick. The lower boundaries of the iron crust and of the soft ferruginous horizon correspond to resistivities of 2500 Ωm and 900 Ωm, respectively. To the west from position 12.1 m, these layers are no longer detected. Fig. 6b suggests that intermediate resistivities below 300 Ωm exist at depth of 7–8 m from position −14 m to position 6.7 m. Westward of the position 6.7, the top of this layer is, however, displaced

Fig. 4. (a) Observed apparent resistivity pseudosection at Tenkoto with an electrode spacing of 0.5 m together with (b) the 2D inversion model section.

Fig. 5. Same as for Fig. 4 with an electrode spacing of 1 m.

Fig. 6. Same as for Fig. 4 with an electrode spacing of 5 m.

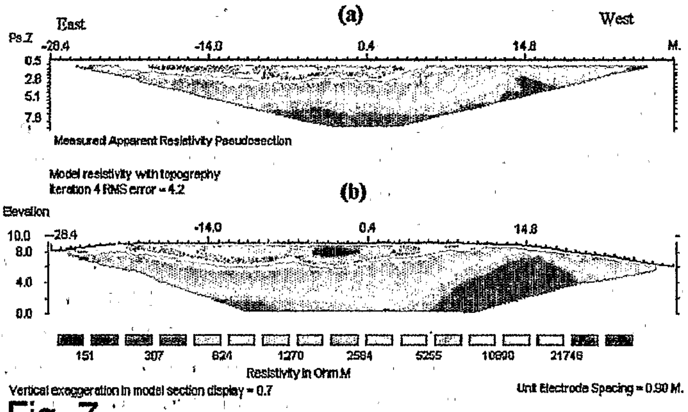

Fig. 7

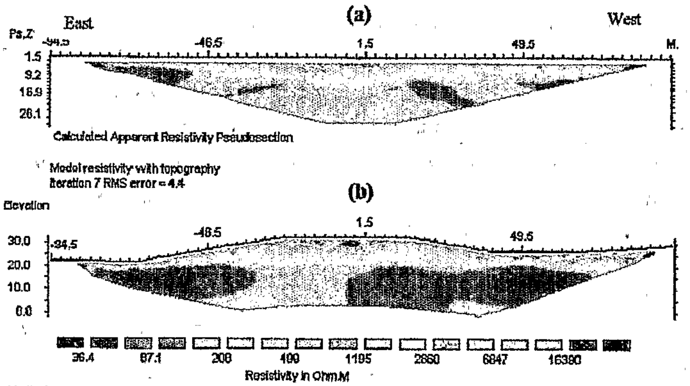

Fig. 8

Fig. 7. (a) Observed apparent resistivity pseudosection at Ngari with an electrode spacing of 0.90 m together with (b) the 2D inversion model section including the topography.

Fig. 8. Same as for Fig. 7 with an electrode spacing of 3 m.

towards the surface, that corresponds to the scarp where the iron crust is disaggregated.

The pseudosection with an electrode spacing of 3 m indicates a nonlayered subsurface electrical structure (Fig. 8). The range of apparent resistivities is comparable with that observed at Tenkoto (Fig. 6), but with a higher limit for the minimum values of apparent resistivities. Fig. 8b shows a thin surface layer with resistivities above 5000 Ωm located at the summit of the plateau, between positions −22 and 10, where the iron crust occurs. The resistivity of that surface layer, however, decreases towards the edges of the section to values of about 2000 Ωm, that characterizes colluvial materials resulting from the destruction of the iron crust in the course of hillslope erosion processes. Below this is a quasi-continuous layer of around 1000 Ωm which could be related to the basis of the ferruginous horizon. A broad zone of 30–200 Ωm, corresponding to the saprolite layer, extends across the entire profile, and becomes more conductive towards the flanks (Fig. 8b). The zones of lowest resistivities can readily be explained by a higher clay content or a higher groundwater content, or any combination of both. The thickness of this layer is not resolved because of the relatively short profile length. At

Ngari, the saprolite layer probably has a thickness of at least 25 m and could be thicker than at Tenkoto.

5. Concluding remarks

The above examples show that the ERT method is well-suited to analyse the inner structure of lateritic overburden, because it gives not only a resistivity value depending on the physical, chemical, and hydrological parameters of the different layers, but it also provides information upon specific geoelectrical heterogeneity of the investigated zone and, thus, upon the lithological variations. Precise identification of the lithology is, however, not possible on the basis of resistivity data alone; correlation with pits is required.

The two study sites present many similarities. The resistivity of the iron crust ranges from 3000 to 30 000 Ωm, indicating lateral variations of facies. Direct field observations allow to correlate zones of very high resistivities to most iron crust facies, while the zones of lower resistivities can be related to the disaggregated iron crust whose matrix is softer. At the two sites, the soft iron crust exhibits comparable resistivities about 1000 Ωm.

In agreement with field observations, variations of resistivity show that the transition from the fresh rock to the saprolite is progressive, while the transition between the saprolite and the ferruginous horizons is more rapid.

The variations of resistivity within each horizon give also interesting indications. The low and variable resistivities in the saprolite may be due to facies changes and/or changes in water content. In fact, the very low resistivity of the saprolite (<30 Ωm) can be interpreted as a fully saturated layer since it is connected to streams, that is confirmed by the presence of water at the bottom of Tenkoto well and at the base of Ngari profiles. Considering the geological context at Tenkoto, two explanations for the increase of resistivity in connection with the fresh rock can be proposed: (i) it is either related to a quartz vein since a layer containing numerous angular quartz debris has been observed beneath the iron crust, or (ii) it indicates a dome of fresh rock which is a structure frequently encountered in granitic areas and, often visible in the thalweg flats. In fact, 3D surveying with multielectrode arrays will be necessary to choose between these two hypotheses. This work is actually under process.

The maximum of detail is obtained for most ferruginous horizons developing between 0 and 5 m which were analyzed with a small electrode spacing of 0.5 or 1 m. Though the dismantling horizon of quartz vein occurs at depth ranging from 3 to 6 m, it is, however, not detected. Instead, it is defined as discontinuous objects of small size (<40 cm) presenting a low contrast of resistivity with the surrounding material.

ERT gives a good image of the main weathering horizons which show similar geoelectrical characteristics in the two studied areas. Our results provide useful indications on the thickness, variations of facies and the nature of contacts between the different formations.

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