
Multi-electrode resistivity survey for groundwater exploration in the Harare greenstone belt, Zimbabwe

R. J. Owen · O. Gwavava · P. Gwaze

Abstract A multi-electrode resistivity survey, carried out over metasedimentary strata and metavolcanics in the Harare greenstone belt in northeastern Zimbabwe as part of a groundwater resources investigation, illustrates the ability of this technique to produce high-resolution images of the subsurface, which are useful for groundwater resources assessment. The resistivity results provide a clear view of the thickness of the weathered regolith and of the distribution of the various lithological units. Using a combination of apparent formation resistivity and inferred depth of weathering, it is possible to characterize the various lithologies on the geophysical profiles. These assigned lithologies show excellent correlation with the mapped geology, and the main lithologies, metabasalt, meta-arenite, granodiorite and banded iron formation can be clearly identified. The banded iron formation is characterized by low resistivity values, while a combination of the depth of weathering and resistivity values are used to distinguish between the meta-arenite on one hand and the metabasalt and granodiorite on the other. The multi-electrode method is successful in identifying potentially favourable zones for obtaining groundwater, such as areas with a maximum depth of weathered regolith, zones of fracturing and faulting, and high porosity and permeability zones associated with lithological contacts.

Résumé La prospection électrique par la méthode de multiélectrodes, effectuée pour l'investigation des eaux

souterraines cantonnés dans des roches métamorphiques d'origine sédimentaire et volcanique de la ceinture de Harare-Zimbabwe a mis en évidence les possibilités de cette technique de réaliser des images à grande résolution du sous-sol qui sont très utiles pour l'évaluation de la ressource en eaux souterraines. D'après la distribution de la résistance il résulte une image très claire de l'épaisseur des regolithes altérés ainsi que de la distribution des différentes unités lithologiques. D'après les profils géophysiques on peut caractériser les différents lithologies en utilisant les résistivités apparentes de la formation respective et les informations sur la profondeur de la zone altérée. Les lithologies ainsi déterminées montrent une excellente corrélation avec les cartes géologiques et on peut très bien identifier les lithologies principales comme les metabasaltes et les meta-arenites, les granodiorites et les formations de fer rubanées. Celles dernières sont caractérisées par des faibles valeurs de la résistivité, tandis que en utilisant les résistivité et la profondeur de la zone altérée on peut distinguer les meta-arenites de granodiorites et des metabasaltes. La méthode des multiélectrodes est donc capable d'identifier des formations favorables à l'accumulation en eau comme les zones de faille et des fractures, ainsi que les zones à grande porosité et perméabilité, associées aux contacts lithologiques.

Resumen Un estudio de resistividad multi-electrodo que se llevó a cabo en estratos meta sedimentarios y metavolcánicos en el cinturón de rocas verdes de Harare, en la parte noreste de Zimbabwe, como parte de una investigación de recursos de agua subterránea, ilustra la capacidad de esta técnica para producir imágenes de alta resolución de la subsuperficie, las cuales son útiles para la evaluación de los recursos de agua subterránea. Los resultados de resistividad suministran una visión clara el espesor del regolito meteorizado y de la distribución de varias unidades litológicas. Mediante el uso de una combinación de resistividad aparente de formación y de una profundidad inferida de meteorización, es posible caracterizar las diferentes litologías en los perfiles geofísicos. Estas litologías asignadas muestran una excelente correlación con la cartografía geológica y se pueden identificar las litologías predominantes como metabasalto, meta-arenita, granodiorita y formación de hierro bandeado. Esta última se caracteriza por valores bajos de resistividad, mientras

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que se utiliza una combinación de profundidad de meteorización y valores de resistividad, para distinguir entre meta-arenita por un lado y metabasalto y granodiorita por el otro. El método multi-electrodo es exitoso para identificar zonas potencialmente favorables para captar agua subterránea, las cuales pueden ser áreas con una profundidad máxima de regolito meteorizado, o bien zonas de fracturamiento y fallamiento, o también zonas de porosidad y permeabilidad altas asociadas con contactos litológicos.

Keywords Zimbabwe · Groundwater surveying · Multi-electrode resistivity · Crystalline basement aquifers · Drilling site selection

Introduction

The multi-electrode resistivity technique is now fairly well established with respect to theory, practical application and interpretation techniques (e.g. Barker 1981; Dahlin 1993; Loke and Barker 1996a, b). The aim of this paper is to create an awareness of some of the values and benefits of using multi-electrode resistivity for groundwater exploration.

Resistivity methods are very sensitive to variations in earth resistivity, and are therefore useful for identifying lithological units and variations within lithological units. Such features and changes are usually highly significant with respect to groundwater occurrence. Conventional DC resistivity sounding and profiling has successfully capitalised on this aspect of resistivity surveying but is weak in respect of spatial coverage. By utilising microcomputer control, the multielectrode resistivity method has overcome this weakness in resistivity surveying.

In this case study the multi-electrode resistivity method has been used to assess the groundwater potential in a valley at Rudolphia farm, which lies approximately 40 km ENE of Harare in the Harare greenstone belt, northeastern Zimbabwe, centred at 31° 24.6' E and 17° 45.2' S (Fig. 1a).

Locality and geology

Rudolphia farm lies towards the eastern edge of the Harare greenstone belt, on a sequence of metabasalts and meta-arenites, striking ENE WSW to EW, and intruded locally by younger granitic rocks. The central portion of the geological map (Fig. 1b) is underlain by meta-arenites, with subordinate banded iron formation and talc schist, and these formations are flanked both to the north and south by metabasalt. The central area, underlain by meta-arenite, forms an open EW trending valley, which is occupied by a small stream draining eastwards. Soft talc schists occur as an outcrop preserved between two ridges of banded iron formation on the southern valley flank, but are not observed downslope in the valley floor, although they are presumed to occur under a cover of soil and colluvium. Small outcrops of intrusive granodiorite are observed both at the eastern and the western ends of the surveyed area, and are shown on the generalized geological map of the

farm (Fig. 1b), which is based on the 1:100,000 geological map of the area by the Zimbabwe Geological Survey (Baldock 1991). Where observed, the dip of the strata is subvertical. Based on the distribution of the lithological units and the dip directions and angles, it is possible that the central meta-arenites may be the core of an antiform that has been exposed by erosion, but there is insufficient field evidence to conclusively prove this.

Resistivity survey

Basic principles

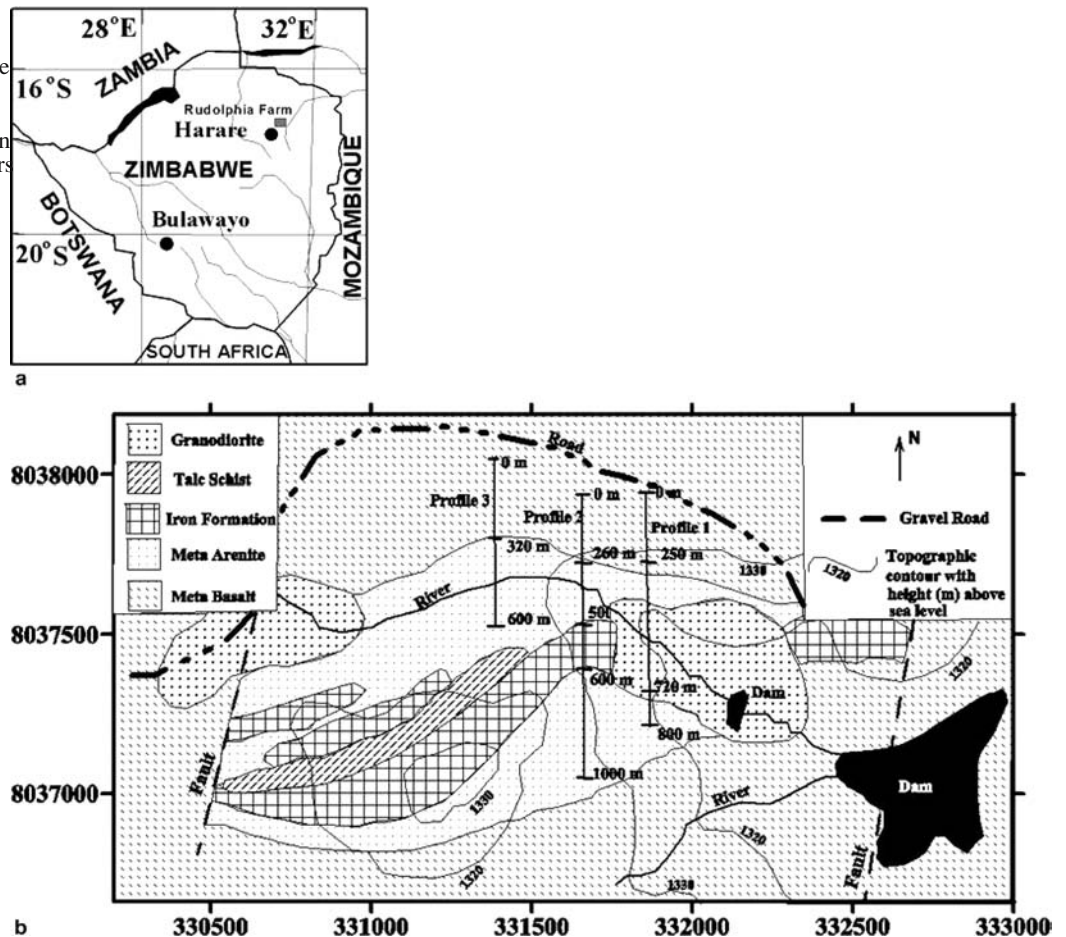
Electrical sounding (1D vertical) and electrical profiling (1D horizontal) are routinely used for groundwater, and are well described in standard geophysical texts such as Parasnis (1986). A detailed picture of the subsurface can be obtained by combining the sounding and profiling data to give two-dimensional (2D) cross sections, which can in turn be combined to give a 3D model of the ground. However, to carry out such investigations manually is both time consuming and labour intensive. This has led to the development of computer-controlled multielectrode resistivity systems (Dahlin 1993), which entails the use of multiple electrodes, connected via multicore cables to a switching box, which in turn is connected to a DC resistivity meter. A computer protocol file instructs the switching box to automatically select combinations of four electrodes at a time according to the survey design, and the resistivity meter takes readings for each set of selected electrodes, thus producing a 2D data set.

Data acquisition and processing

The resistivity system used for data acquisition was a modified version of the ABEM Lund Imaging System. It consists of six main elements: a high-resolution voltmeter (Terraohm AD201) which is a 24 bit analogue/digital converter; a portable field computer with two serial ports and one parallel port (e.g. Husky FC486) that controls data acquisition; 4×64 channel relay switching unit (ABEM Electro Selector ES464); a current amplifier (ABEM Booster SAS 2000) and an active booster interface; four 100-m multiconductor cables with 21 takeouts at 5-m spacing; steel rod electrodes of different lengths (0.6–1.2 m) and cable jumpers for connecting the electrodes to the takeouts. This system uses the data acquisition software Eric_ad developed by Dr T. Dahlin, Lund Institute of Geotechnology, Sweden. A detailed explanation of how the instrument is setup and data is collected is given by Dahlin (1993). The program allows the user to set the minimum and maximum current, and to select electrode configurations through protocol files, e.g. Wenner, dipole-dipole, pole-pole, Schlumberger, etc. or a combination of these and others. After the system is setup, the software checks for sufficient ground contact across the entire electrode spread.

Three nearly parallel profiles (Fig. 1b), trending NS across the valley, were surveyed in three days by a crew of four using the Wenner array configuration, an electrode

Fig. 1 a Location of Rudolphia farm; b General geology and locations of three NS profile—Rudolphia. Topographic contour interval 10 m; the UTM coordinates in metres. Rudolphia farm covers the whole area



spacing of 5 m and the rollalong technique. In the rollalong technique, measurements are done on a spread of say four cables linked together and then the first cable is moved to the upper end of the spread and measurements are taken for the second setup. This procedure is repeated until the whole profile length is covered. Profile lengths range from 600–1,000 m and all cross the central WE drainage line. A total of 483 electrodes were implanted along the three profiles. On average, a current of 20–50 mA (milliampere) was injected into the ground. The profiles were levelled and the profile topography has been incorporated in the inverted models.

The data was modelled using RES2DINV (ver3.42d) developed by Dr M. H. Loke. The inversion routine used by RES2DINV is based on the smoothness constrained least-squares technique (deGroot-Hedlin and Constable 1990; Sasaki 1992) and offers three options, namely a very fast quasi Newton method (Loke and Barker 1996a), a slow but more accurate conventional Gauss Newton method, and a hybrid of the quasi Newton and Gauss Newton methods. The program automatically creates a 2D model by dividing the subsurface into rectangular blocks and chooses optimum inversion parameters for the data which include the damping factor, vertical to horizontal flatness filter ratio, convergence limit and number of iterations. The user can modify the inversion parameters to suit different data types.

The program calculates the apparent resistivity values of the model blocks using either a finite difference or finite element method and compares these to measured data. The resistivity of the model blocks is adjusted iteratively until the calculated apparent resistivity values of the model agree with the actual measurements.

A Gauss Newton inversion method with smooth constraint parameters was applied to all the profiles. Using a Pentium III laptop computer with 64 MB RAM, it took about 4 min to get an inverted model for the shortest profile (600 m) with 121 electrodes and 543 data points, whereas the 1,000-m profile with 201 electrodes and 1,326 data points required about 25 min. Inversion of 2D and 3D data sets is an active area of research with faster and more accurate algorithms being developed.

The final output from RES2DINV displays three sections, i.e. measured and calculated apparent resistivity pseudosections, and the inverse model resistivity section. The pseudosections are a qualitative way of presenting the spatial variation of the measured or calculated apparent resistivity in cross section and do not reflect the true depth. The inverse model section shows the true depth and true formation resistivity. The location of the data points and the isopleths of resistivity values together with a series of grey shades can be shown on all three sections. The topography can only be included on the inverse model section.

Goelectrical expectation model

It is useful to construct a hydrogeological “expectation” model for the area within the resistivity survey domain, based on the distribution of the various lithological units and the anticipated weathering profiles associated with each unit. Such a model can be used to produce a theoretical goelectrical model based on the expected goelectric signatures for the various hydrogeological units. This model can be used to assist with the interpretation of the actual resistivity profile data, giving rise to a more realistic interpretation of the earth model.

In this survey area, five lithological units have been identified by field mapping (Baldock 1991), and these are tabulated in Table 1, together with the anticipated depth and nature of their various weathered regoliths, and the expected resistivity signature range for each of these units.

The groundwater potential, as identified in Table 1, is estimated based on the lithology. The permeability and porosity values that occur in the profile are closely linked to the depth of weathering and fracturing in the subsurface, and to the degree of alteration and type of weathered products that are developed. Acworth (1987) carried out detailed studies on the weathered regolith, as developed in a tropical environment, of crystalline basement rocks, and estimated the variation of permeability and porosity down the profile (Fig. 2).

The potential for obtaining groundwater and the well yields are closely linked to the nature of the regolith profile, with the saturated thickness of the high porosity upper saprolite, and the development of a high permeability transition zone between regolith and bedrock being the two key factors controlling respectively the aquifer storage capacity and the well yield potential. One of the principal advantages of using multielectrode resistivity surveying is

that the technique affords the user a view of the goelectrical changes within the regolith, which can be readily related to the changes in the porosity and permeability values anticipated in a typical vertical profile through the regolith in crystalline rocks.

Results and interpretation

Results of resistivity Profiles 1 to 3 are presented below together with a correlation of the results with the mapped geology. It is interesting to note that the vertical profile changes may be readily interpreted in light of the model profiles proposed by Acworth (1987, Fig. 2). Three resistivity sections, as outlined above, are presented for each profile.

Figure 3 shows the three sections of Profile 1. The overburden along the profile is conductive as expected for weathered greenstone lithologies. The northern valley flank from 0–240 m is underlain by metabasalt, which due to the presence of labile minerals, weathers relatively easily to smectite type clays. This is clearly shown by the surficial low resistivity zone (20–50 Ω m) around 20 m thick and is interpreted as weathered regolith. Another zone of low resistivity values is seen from 480–800 m. The depth of weathering is around 20 m, with a deeper section from 500–720 m indicating weathered regolith up to 30 m depth, further increasing to 40 m at 630 m along the profile. This part corresponds with the granodiorite as mapped in the 1:100,000 geological map (Fig. 1b). The final section of the profile from 720–800 m exhibits shallow weathering, and corresponds to meta-arenite on the geological map. Below the weathered regolith, the resistivity values increase, suggesting that the rock becomes less weathered, grading

Table 1 Lithology and potential for obtaining groundwater in the study area

Lithological unit	Weathered regolith: nature and thickness	Potential for obtaining groundwater	Resistivity range in Ω m	Fresh rock	Regolith
Metabasalt	Deep weathered regolith (20–40 m). Clay with thick transition zone	Moderate to very good	>400		10–50
Meta-arenite	Shallow weathering (2–20 m). Clays absent due to lack labile grains in sedimentary formations	Poor to moderate	>600		40–100
Granite/granodiorite	Moderate to deep weathering (10–40 m). Clay with residual mica and quartz	Moderate to low	>400		25–100
Banded iron formation	Very limited weathering but fractured to moderate depth (20–30 m). Intact rock conducts current	Moderate to very good	<10		10–100
Talc schist	Clay weathering, moderate to very shallow depths	Poor to moderate	>200		20–100

*Data from Interconsult (1987). National master water plan for rural water supply and sanitation; vol 2.2. Hydrogeology. Department of Water Resources, Government of Zimbabwe

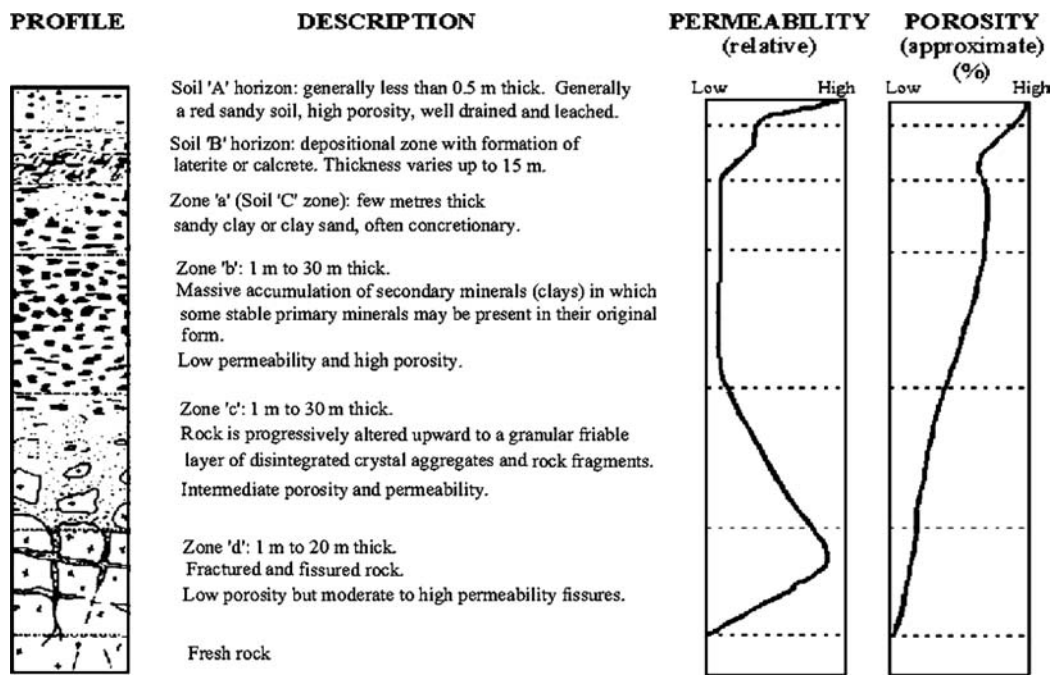


Fig. 2 Typical vertical regolith profile for crystalline rocks in a tropical environment . Copied from Acworth (1987)

into fresh rock. The central part of the profile from 240–500 m exhibits very high resistivity values ($>630 \Omega \text{ m}$) at shallow depth, indicating a very limited depth of weathering. This correlates well with the mapped meta-arenites, which are known to be resistant to weathering (Interconsult 1987). There is a narrow vertical feature, with slightly lower resistivity values, in the middle of the meta-arenite at approximately 350 m, which may be an unmapped fault zone. This resistivity profile shows a good correlation with the mapped geology.

Figure 4 shows the three sections of resistivity Profile 2. From 0–260 m, there is a thick (20–60 m) low resistivity (20–80 $\Omega \text{ m}$) upper zone, interpreted as weathered regolith overlying meta basalt. The depth of weathering becomes significantly less in the valley floor from 260–500 m, while the resistivity of fresh bedrock increases ($>600 \Omega \text{ m}$); this section corresponds with the meta-arenite on the geological map (Fig. 1b). From 460–660 m in the valley floor, a striking feature, with very low resistivity ($<20 \Omega \text{ m}$), has been interpreted as banded iron formation, which, when intact, is known to be an excellent electrical conductor. The inverted cone shape of this low resistivity feature is suggestive of an antiformal fold axis, but there is insufficient evidence to substantiate this interpretation. Overlying this low resistivity feature between 500–600 m, there is a high resistivity surface, which corresponds to an outcrop of granodiorite boulders. The resistivity profile shows that there is no root to this outcrop, suggesting that it is either float or the remnant of a former granodiorite sill, which has been almost entirely eroded away. To the south, from 600–1,000 m, the resistivity of the weathered regolith increases to between 40–150 $\Omega \text{ m}$, and the depth of weathering is moderate to shallow at 20–30 m depth. This section of the profile corresponds well with the mapped meta-arenite. The

geology along this profile shows a striking agreement with the resistivity interpretations.

Figure 5 shows the three sections of Profile 3. As in the other profiles, the beginning of the profile from 0–280 m is more deeply weathered, with a depth of weathering up to 40 m. This corresponds well with the mapped distribution of the metabasalt. From about 280–600 m at the end of the profile, the depth of weathering is significantly less, around 15–20 m thick. This has been interpreted as the weathered regolith overlying meta-arenite. This corresponds well with the geological map, and the resistivity profile has been able to easily distinguish the boundary between metabasalt and the meta-arenite, based on the difference in the depth of weathering, and the higher resistivity values associated with the meta-arenite.

Discussion

Due to the high spatial resolution, and the ability to map resistivity contrasts, the multielectrode resistivity technique has shown that it is very capable of differentiating geological strata, and can be a valuable tool for mapping the subsurface geology. In addition, the technique is capable of mapping changes in the vertical profile that may be highly significant with regards to the hydrogeological potential of the area (Acworth 1987; Interconsult 1987). Where there are few outcrops, such as in valley floors covered by alluvial fill and deep soil profiles, resistivity sounding can be useful for making a preliminary interpretation of the subsurface geology.

>In the case study presented, it has been possible to differentiate between the two major lithologic types, the metabasalt and the meta-arenite, principally due to the

difference in thickness of the weathered regolith that develops above these two, but also by the higher resistivity values associated with the fresh meta-arenite. Clastic sedimentary formations typically tend to be less susceptible to chemical weathering, resulting in thin weathered profiles, in contrast to igneous rocks, particularly those of mafic composition, which may be weathered to considerable depth.

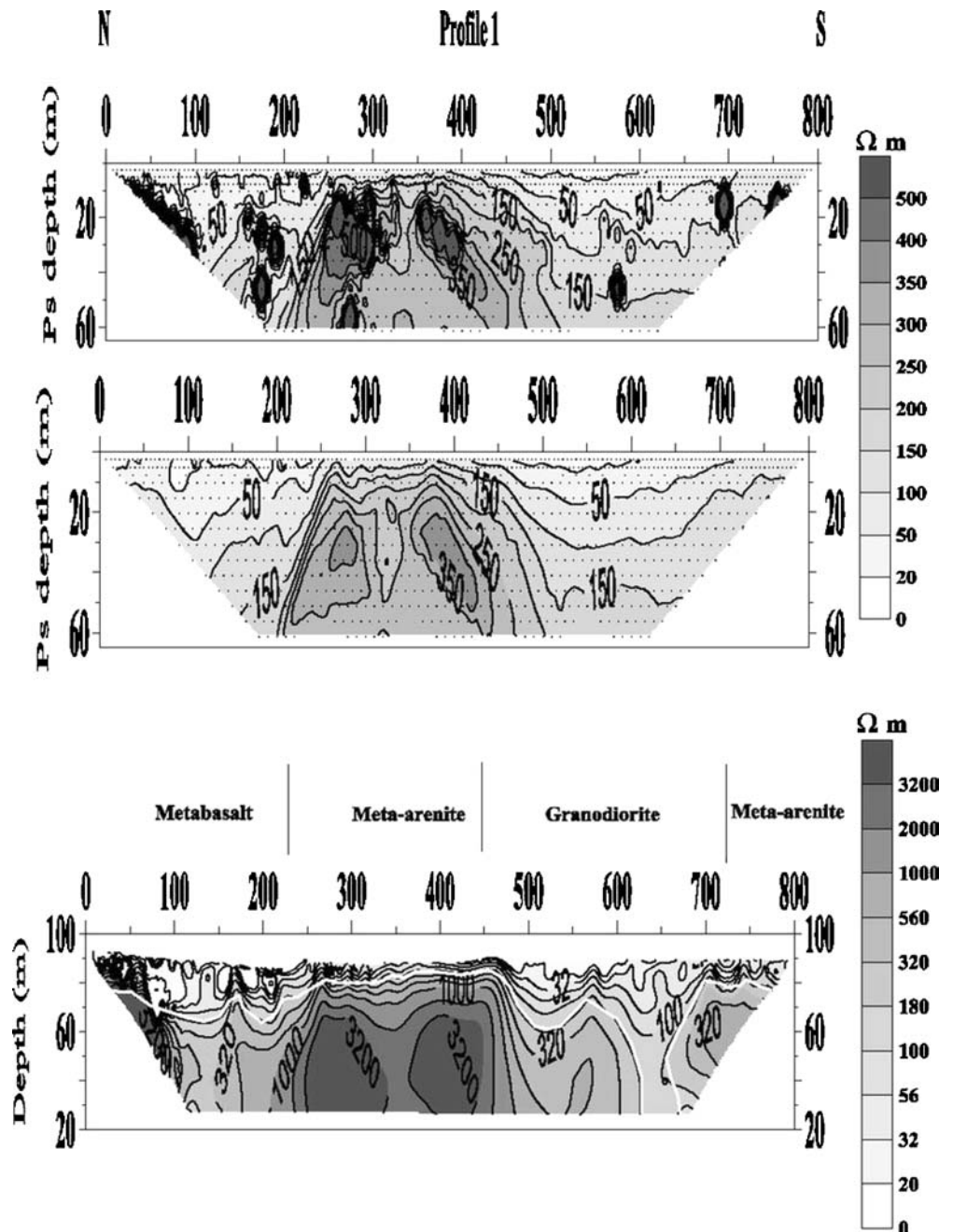
In Profile 1, the granodiorite, though it has a broadly similar resistivity range, can be distinguished from the meta-arenite by the depth of the weathered profile. In Profile 2, a very low resistivity vertical feature corresponds with a mapped outcrop of banded iron formation. Banded iron formation has the ability to conduct electrical current due to the presence of iron in the formation and registers low to

very low resistivity values. Fractured and weathered banded iron formation, which may be expected in the near surface environment, is less able to conduct electrical current due to the air and soil between the conductive ironstone material, and tends to register higher apparent resistivity values.

Potential for obtaining groundwater

The results from the multielectrode resistivity survey are useful in estimating the potential for obtaining groundwater, and in particular for locating drilling sites. Drilling site selection may be based on an understanding of the hydrogeological properties of the various lithologies (Table 1), but

Fig. 3 Sections for Profile 1. The top pseudosection is for the measured apparent resistivities with the data points shown as dots; the middle pseudosection is for the calculated apparent resistivities with the data points shown as dots; the bottom section is for the inverse model with topography included and the white line marks the inferred boundary of weathered regolith and freshrock. Ps depth means pseudo depth. Resistivity isopleth values are in Ω m



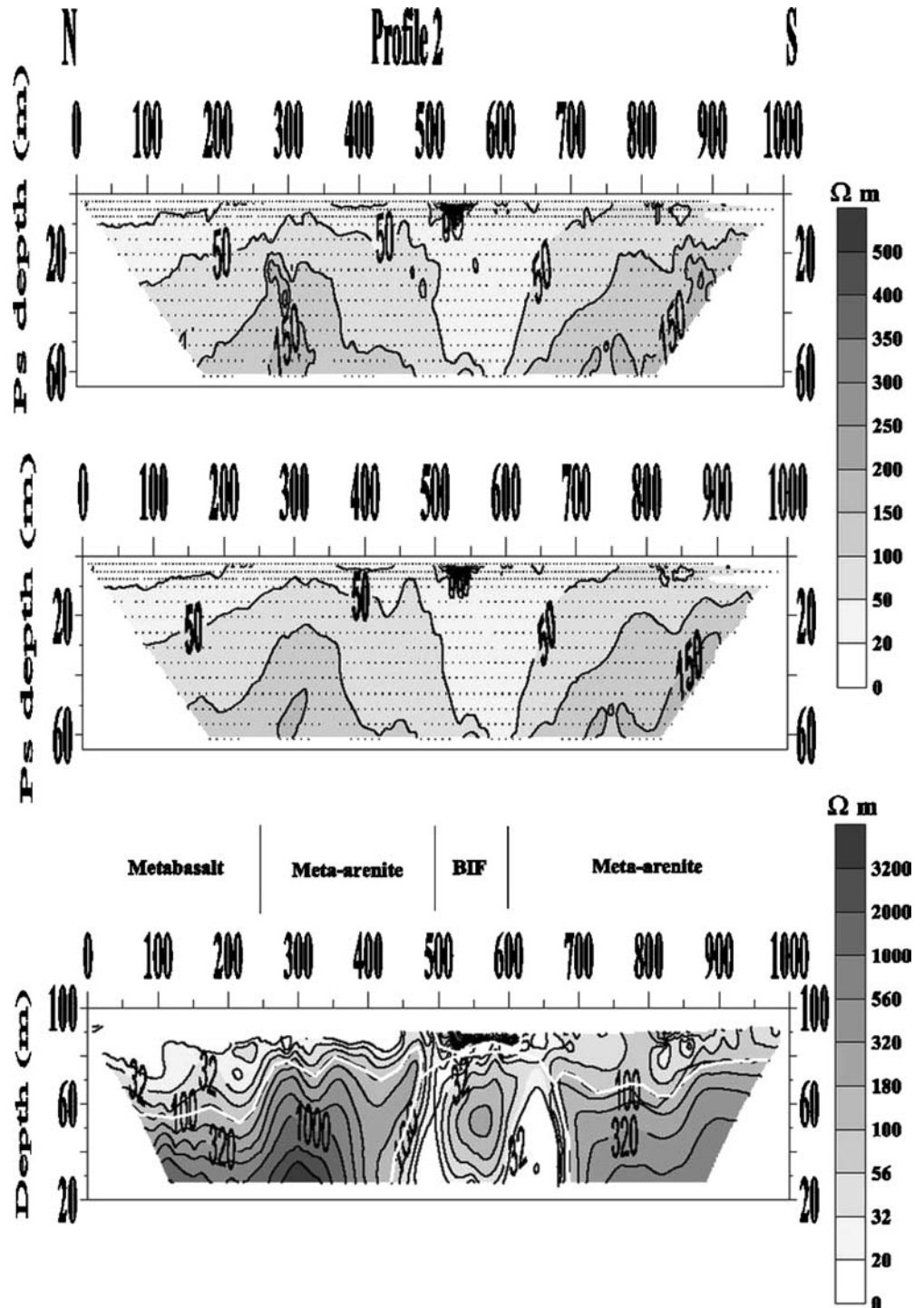
knowledge of the saturated thickness of the weathered and fractured regolith as inferred from the resistivity sections will greatly enhance the success of drilling site selection.

All the profiles show that the meta-arenite has a limited thickness of weathered regolith, ranging from 10 to 20 m, and is therefore not a good source of groundwater. Both the metabasalt and the granodiorite exhibit considerably thicker weathered regolith profiles, ranging from 20 to 50 m depth, and the deeper regolith sections are identified as the

better sources of groundwater. In addition to evaluating potential sources of groundwater based on regolith thickness, there are specific features on the profiles associated with linear features, such as faulting, jointing and lithological contacts, which are also useful in the evaluation.

Profile 1 at 350 m has a thin vertical feature of relatively low resistivity within the meta-arenite, which may be a fault, and thus indicative of a potential source of groundwater. Profile 2 holds the most promise for groundwater

Fig. 4 Sections for Profile 2. The top pseudosection is for the measured apparent resistivities with the data points shown as *dots*; the middle pseudosection is for the calculated apparent resistivities with the data points shown as *dots*; the bottom section is for the inverse model with topography included and the *white line* marks the inferred boundaries. *BIF* means Banded Iron Formation. *Ps depth* means pseudo depth. Resistivity isopleth values are in Ωm



development. In addition to reasonably deep weathering over the metabasalt, this profile is characterized by a major break with low to very low resistivities in the central part of the profile between 460 and 660 m, which coincides with the mapped banded iron formation. Due to its brittle nature and its resistance to chemical weathering, banded iron formation tends to provide a highly permeable, fractured rock mass, particularly at moderate depths, and at contacts with the country rock where the degree of fracturing is greatest. The banded iron formation shows high resistivity values in the centre of the zone at 550 m, and this is tentatively interpreted as the development of quartz fill migrating into the zone of fold closure of a subvertical antiformal fold. The more fractured banded iron formation, located near

the surface and along the contacts with the meta-arenite, exhibits relatively low resistivity values. Profile 3 clearly distinguishes the difference in the depth of weathering between the metabasalt and the meta-arenite and offers some prospects for obtaining groundwater based on the deeper weathering developed over the metabasalts.

Potentially favourable drilling sites have been selected based on the resistivity profiles and are tabulated below (Table 2), together with an indication of the hydrogeological nature of the sites. The sites are ranked in order of preference based on the estimated relative well yields. The deeply fractured contact zones between the banded iron formation and the meta-arenite are considered to be the most favourable drilling sites.

Fig. 5 Sections for Profile 3. The top pseudosection is for the measured apparent resistivities with the data points shown as *dots*; the middle pseudosection is for the calculated apparent resistivities with the data points shown as *dots*; the bottom section is for the inverse model with topography included and the *white line* marks the inferred boundary of weathered regolith and fresh rock. *Ps* depth means pseudo depth. Resistivity isopleth values are in Ωm

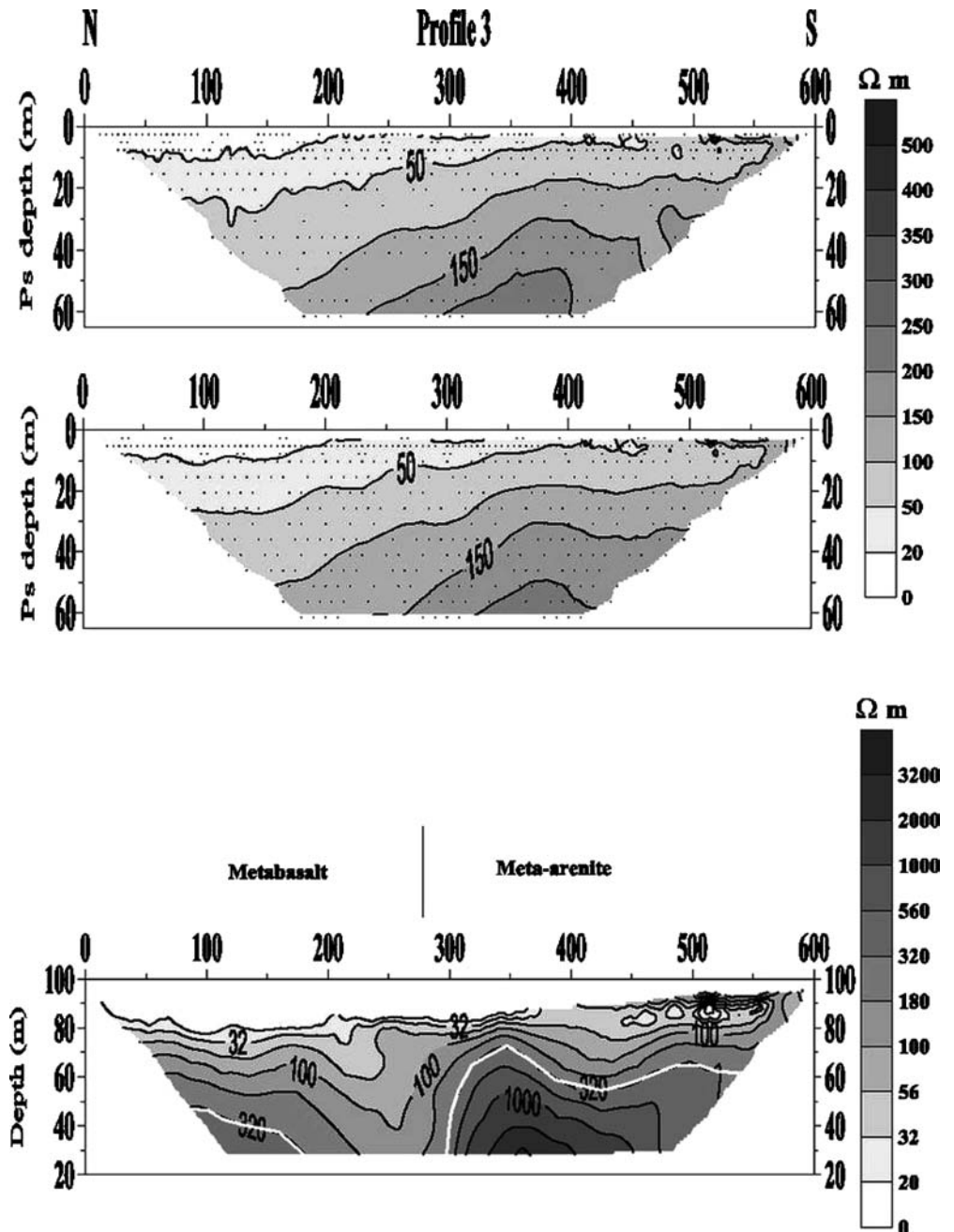


Table 2 Features of selected drilling sites

Position	Lithology	Topography	Hydrogeological feature	Rank
Profile 1: 130 m	Metabasalt	Valley slope	±30 m weathered regolith	6
Profile 1: 350 m	Meta-arenite	Valley flat	Narrow fracture zone	7
Profile 1: 630 m	Granodiorite	Flat upland	±40 m weathered regolith	5
Profile 2: 0–220 m	Metabasalt	Valley slope	±50 m weathered regolith	3
Profile 2: 500 m	BIF/Arenite	Valley floor	Contact zone with fractured and weathered rock to >60 m depth	1
Profile 2: 630 m	BIF/Arenite	Valley floor	Contact zone with fractured and weathered rock to >60 m depth	2
Profile 3: 210–280 m	Metabasalt	Valley slope	±40 m weathered regolith	4

Conclusions

Metabasalt, meta-arenite, granodiorite and banded iron formation can be identified by the resistivity data, based principally on the depth of weathering, but also partly on the relative resistivity values. Meta-arenite exhibits the least depth of weathering and the highest resistivity values. Metabasalt and granodiorite are more deeply weathered than meta-arenite, and exhibit slightly lower resistivity values (e.g. Profile 1). Metabasalt can be distinguished from granodiorite by its lower surficial resistivity values, which are a result of the clay rich nature of basaltic soils (e.g. Profile 1). The occurrence of deeper weathering may also be used to distinguish the metabasalt from the granodiorite (e.g. Profiles 2 and 1). The resistivity values of these three lithologies all increase with depth. Banded iron formation may be distinguished by very low resistivity values, which tend to decrease with depth as the formation becomes more intact. In profile 2, the resistivity in the centre of the banded iron formation zone is relatively high, possibly due to quartz infill in a fault.

The ability of multi-electrode resistivity profiling to provide a detailed continuous 2D map of the subsurface, identifying the different lithologies, delineating contact zones and faults, and measuring the thickness of the weathered regolith, makes this technique a very useful tool for groundwater investigations, both for locating drilling sites and for obtaining an assessment of the general extent of the depth of weathering and the location of fractured zones, which are the principal groundwater reservoirs. The method appears to be particularly well suited to the characterization of crystalline basement rocks and their weathered regolith profiles.

The multi-electrode resistivity technique is more expensive than traditional DC resistivity surveying, but the additional cost may be justified where the demand for groundwater is relatively high, such as for municipal or irrigation development.

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