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Geophysical and hydrogeologic investigation of groundwater in the Karoo stratigraphic sequence at Sawmills in northern Matabeleland, Zimbabwe: a case history

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Abstract Geophysical and hydrogeological investigations have been carried out around Sawmills in Zimbabwe, Africa. The investigations are components of a larger investigation to assess the groundwater potential of the Karoo sedimentary basin with regards to supplying water to Bulawayo City. The Sawmills area was selected due to the availability of borehole logs indicating favourable stratigraphy for groundwater availability and due to the high yields from the aquifers measured from these boreholes. Data collected using two geophysical methods are presented here: transient electromagnetic (TEM) and continuous vertical electrical sounding (CVES) data. The data have also been processed using laterally constrained inversion (LCI). Because the CVES provides greater detail in the shallow subsurface, whereas TEM is more effective at depth, a more accurate image of the entire subsurface profile is provided based on using both methods. The results suggest that LCI of CVES and TEM data, in the subsurface at the required depths at Sawmills, is able to provide a substantially more accurate image of the subsurface than either method alone. The hydrogeological interpretation of the geophysical data is valuable for determining the depth to and thickness of the potential aquifer horizon(s) and for identifying the position of potential recharge zones.

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Résumé Des investigations géophysiques et hydrogéologiques ont été menées aux alentours de Sawmills au Zimbabwe en Afrique. Celles-ci font partie d'une campagne d'investigation plus large concernant le bassin sédimentaire du Karoo, dans le cadre d'une évaluation du potentiel des eaux souterraines de cette région afin d'alimenter en eau la ville de Bulawayo. La zone de Sawmills a été sélectionnée à cause des logs de forages qui présentaient une stratigraphie favorable à la présence d'eau et des débits important mesurés lors de pompages dans ces puits. Les deux méthodes géophysiques ayant permis de collecter des données sont: la prospection électromagnétique en transitoire (TEM en anglais) et la prospection électrique verticale en continu (CVES en anglais). Les données ont également été traitées suivant l'inversion en contraintes latérales (LCI en anglais). La méthode CVES fournit plus de détails en subsurface tandis que la méthode TEM est plus efficace en profondeur; ainsi, l'utilisation combinée des deux méthodes permet une image plus précise sur tout le profil souterrain. Les résultats suggèrent que faire une LCI des données CVES et TEM, des surfaces souterraines aux profondeurs requises dans la zone de Sawmills, permet d'obtenir une image considérablement plus précise de ces zones souterraines que l'utilisation d'une de ces méthodes seule. L'interprétation hydrogéologique des données géophysiques est utile pour déterminer la profondeur et l'épaisseur du ou des horizons aquifères potentiels et pour identifier la position des zones de recharge potentielles.

Resumen En los alrededores de Sawmills en Zimbabwe, Africa, se han llevado a cabo investigaciones geofísicas e hidrogeológicas. Estas investigaciones forman parte de una investigación más amplia sobre la Cuenca Sedimentaria de Karoo, para estudiar el potencial de aguas subterráneas de esta zona con vistas al suministro de agua a Bulawayo City. El área de Sawmills fue seleccionada debido a la disponibilidad de registros de sondeos que indicaban una estratigrafía favorable para la existencia de aguas subterráneas y a las altas productividades de los acuíferos medidos en estos sondeos. Se presenta aquí la toma de datos usando dos métodos geofísicos: Sistema Electromagnético Transitorio (TEM) y Sondeos Eléctricos Verticales Continuos (CVES). Los datos han sido procesados mediante Inversión lateralmente constreñida (LCI). Debido a que CVES proporciona un mayor detalle en el

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subsuelo poco profundo mientras que TEM es más efectivo en profundidad, se obtiene una imagen más precisa del total del subsuelo basada en el uso de los dos métodos. Los resultados sugieren que LCI de los datos de CVES y TEM es capaz de proporcionar una imagen más precisa del subsuelo en las profundidades necesarias en Sawmills que el uso de cada método por separado. La interpretación hidrogeológica de los datos geofísicos es valiosa para determinar la profundidad y el espesor de los horizontes acuíferos potenciales y para identificar la posición de las potenciales zonas de recarga.

Keywords Groundwater exploration · Geophysical methods · Karoo aquifers · Joint inversion · Zimbabwe

Introduction

Zimbabwe is a landlocked country in the south-central part of Africa. Zimbabwe covers an area of 390,000 km^2 and is bordered by South Africa, Botswana, Zambia, and Mozambique. The average annual rainfall is 675 mm, whereas the average annual potential evaporation is around 1,800 mm. The southern and western parts of the country are considerably drier than the northern and eastern parts, and large areas of Zimbabwe are considered to be semi-arid where water is sparse. Rain falls in a unimodal rainy season extending from November to March. In addition to the limited amount of rainfall, annual rainfall variability is high and characterized by mid-season droughts.

During the 1991–1992 wet season, the most severe drought "in living memory" resulted throughout the country. In the most affected areas, 45% of the primary water resources became dry and water quality degraded appreciably (Ohlsson 1995). From an economic basis, agricultural production was reduced by 40% during the drought period; 600,000 cattle were put down or died from starvation, and the gross national product decreased by 12% from the previous year (Nilsson and Hammer 1996).

The drought defined the fragility of the water supply throughout Zimbabwe, especially for densely populated urban centres such as Bulawayo (Fig. 1), the capital city of the Matabeleland provinces. Stringent water rationing was introduced in Bulawayo but this rationing was insufficient to alleviate drought conditions. In order to provide a supplementary water supply for the estimated 1,000,000 Bulawayo city residents, an emergency well field was established during the height of the drought, when the surface-water resources for Bulawayo had almost entirely dried up. The well field consists of approximately 60 deep boreholes drilled into the "Nyamandhlovu aquifer" around the small farming town of Nyamandhlovu, approximately 45 km northwest of the city. Artesian groundwater has been known for many years to be present in this area. This groundwater source was developed for irrigation in the 1960s.

The established capacity of the emergency well field is 27,000 m^3/day. This capacity represents about 20% of Bulawayo's daily water demand (SWECO 1996), but this resource has only been pumped during water-critical periods and is not part of Bulawayo's regular daily water supply. Anecdotal reports from farmers utilizing irrigation in the Nyamandhlovu area indicate declining groundwater levels and increasing water salinity during periods when the well field is operating. The well field is operated by the Bulawayo City Council only during water-critical periods.

In an attempt to find a long-term solution to the water-supply problems in Bulawayo, the Swedish International Development Agency (SIDA) and the Government of Zimbabwe, represented by the Ministry of Local Government, financed an analysis of the established water supply, as well as the development of a water-resource plan to cover the next 25 years (SWECO 1996). The key focus of this plan was an investigation into the feasibility of constructing and maintaining a pipeline from Bulawayo to the Zambezi River. This pipeline has been sought for many years by the residents of Bulawayo. The pipeline would be 330 km long to the planned Gwayi-Shangani Dam and then to the Zambezi River; an alternate pipeline route would be 400 km long directly to the Zambezi River.

The SWECO study recommended a full investigation into the feasibility of the possible incremental exploitation of groundwater resources along the planned pipeline route. Earlier investigations of the sedimentary basin to the northwest of Bulawayo had shown the possible presence of groundwater sources (Bond and MacDonald 1962; Dennis and Hineson 1964; MacDonald 1970; Beasley 1987). Because of the controversy surrounding the use of the Nyamandhlovu well field by Bulawayo, it was decided to focus the investigations further to the northwest and avoid the problems of overpumping of groundwater from the Nyamandhlovu well field. The SWECO study confirmed that substantial groundwater potential is present along the pipeline route and the initial option of utilizing groundwater was expected to be considerably less expensive than the option of constructing and maintaining a pipeline, particularly concerning the initial capital outlays (SWECO 1995; Mkandla 2003).

In order to further investigate the groundwater resource, research funding was made available to carry out a limited geophysical/hydrogeological study to investigate the nature, extent, and potential of utilizing groundwater in the sedimentary basin for supply to the city of Bulawayo. For practical reasons, the groundwater sources closest to the city of Bulawayo, excluding Nyamandhlovu, were to be investigated first.

The overall aims of the full geophysical study were as follows:

- To create preliminary hydrogeological/geophysical expectation models for these pre-selected areas
- To use a variety of geophysical techniques to generate data that could provide answers to the key hydro-

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geological questions developed for each of the target sites
- To establish the depth to, thickness and sequence of geological units at each of these sites
- To identify exploration drilling targets that can be used to calibrate the geophysical data
- To integrate all the data and use the data to upgrade and re-interpret the hydrogeological expectation model
- To identify a limited number of high potential groundwater target areas based on available groundwater information, drilling data, and previous studies

The purpose of this report is to present the results of the survey at the Sawmills site. Specifically, the detailed geophysical results will be interpreted with regards to the available data from the surface geological map and the subsurface geological data obtained from borehole logs at the Sawmills site. This interpretation can then be used elsewhere to provide a control on the geological interpretation of other geophysical data obtained during the geophysical study.

Geophysical surveying was carried out using several different methods including direct current (DC) continuous vertical electrical sounding (CVES), transient electromagnetics (TEM), slingram, magnetics, gravity, and seismic refraction and reflection. Different geophysical methods were used in different areas extending along the railway line, including Nyamandhlovu, Igusi, Sawmills, Gwaai, Ngamo, and Intundlha (Fig. 1), depending on the local geology and on the type of information required. This report presents parts of the CVES and TEM results from this work from the area around the railway siding at Sawmills. The preliminary SIDA groundwater study (SWECO 1995) identified the village of Sawmills as an area with potential groundwater resources based on aquifer-test data obtained from two deep production boreholes (G3/378-331 m and G3/463-413 m) and one observation well (O3/117-284 m) drilled in the 1960s by the National Railways of Zimbabwe.

During 1997–1999, geophysical measurements were performed to map the subsurface around Sawmills and to relate the data to the lithologies obtained from the deep drill holes, and, thereby, to gain information about the extent, depth, and thickness of the potential aquifers in the area. The geophysical methods used were primarily the CVES and the TEM methods. In total, 31 km of CVES profiling and 309 TEM soundings were completed over two field seasons.

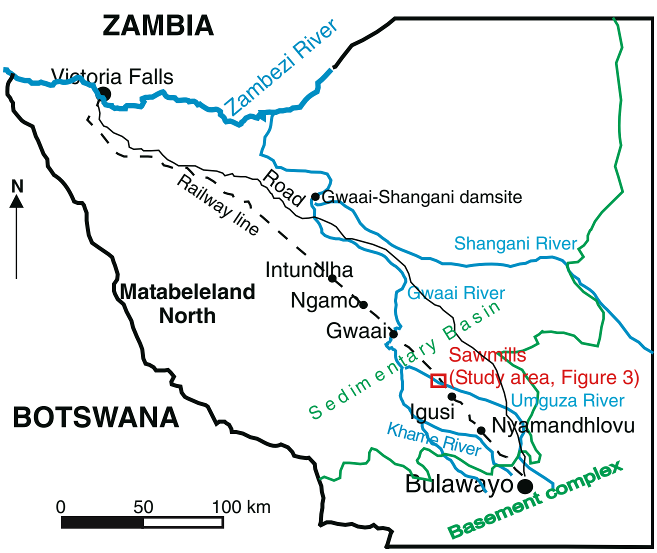

Fig. 1 The western part of Zimbabwe. The study presented here focuses on the Sawmills area

Area description

Geology

The study area is in northwestern Zimbabwe, extending from Bulawayo in the south to Victoria Falls in the north. A map is shown in Fig. 1. In the southern part of the area, granite and greenstone belt crystalline basement rocks outcrop. To the northwest, overlying the basement, an extensional sedimentary basin has been developed by rifting along the Zambezi Valley. This basin has been filled by a thick sedimentary sequence, known as the Karoo Supergroup. The Karoo Supergroup hosts the various sandstone horizons that are the potential aquifers discussed in this report. Overlying the Karoo Supergroup is the Kalahari Group, a sequence of unconsolidated aeolian and fluvial sands and silts.

In Zimbabwe, the Karoo Supergroup is deposited directly on the pre-existing crystalline basement, and consists of two main groups, the Lower and the Upper Karoo Groups, separated by an angular unconformity. Initial deposition commenced into a developing tectonic basin in the late Permian Period with the deposition of glacial sediments such as varved clays and glacial tills in the Lower Karoo Group. These glacial deposits are succeeded by a number of pulses of fining-upwards terrestrial-clastic sediments, ranging in composition from coarse grits and sandstones to coal measures and mudstones. By the late Triassic Period, due to plate movement, the local climate had become warmer and more arid, and the resulting Upper Karoo Group sediments are dominated by terrigenous and aeolian sandstones.

The Karoo sedimentary basin in this area is known as the mid-Zambezi Basin. The basin is a half graben, with the major fault margin boundary located to the north along the Zambezi Valley, whereas the southern boundary is a gentle lobate margin overstepping onto the basement. At its maximum, the Karoo Supergroup reaches a thickness of 4 km near the northern margin of the middle Zambezi basin (Orpen et al. 1989), but because Sawmills is located close to the southern margin of this sedimentary basin, the thickness of the sediments here does not exceed 400 m in the study area. Karoo Era terrestrial sedimentary deposition was terminated by onset of rifting and the separation of Africa and South America that initiated the widespread eruption of flood basalts in the Lower Jurassic Period (Bond and MacDonald 1962). A sketch of the Karoo sedimentary basin is shown in Fig. 2.

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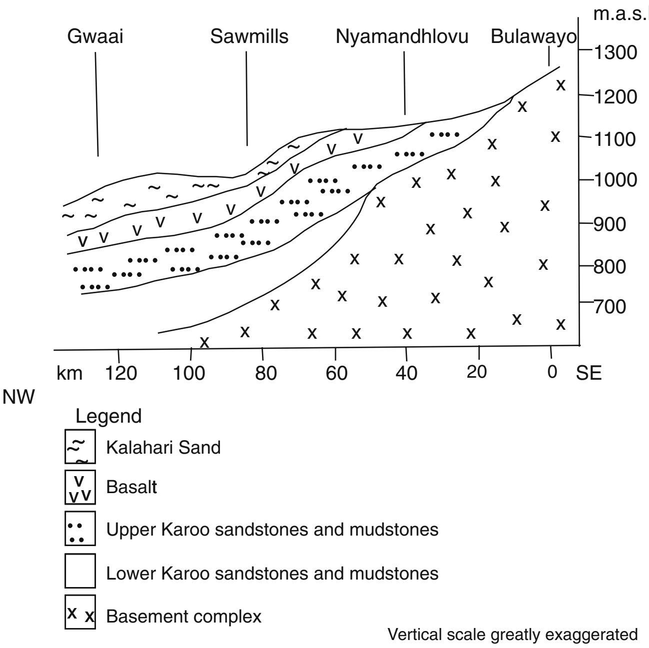

Fig. 2 The cross section of the Karoo sedimentary basin as interpolated from borehole data (after Bond and MacDonald 1962). The drill hole shown in Fig. 4 penetrates the Karoo Supergroup at Sawmills

The Karoo Supergroup is overlain by the Kalahari Group, consisting of unconsolidated, structureless aeolian sands with subordinate fluvial sediments occupying 44,000 km^2 in western Zimbabwe. The Kalahari Group is considered to extend from the Tertiary Period to the present (Stagman 1978). Because of their lack of consolidation, the sands have been remobilized and redeposited various times, and in some localities they have been found overlying gravel carrying artifacts from Stone Age cultures. These deposits are regarded as part of the Kalahari Group based on their similarity to other deposits that fill a depression extending from about 1°N to more than 20°S. The deposits found in western part Zimbabwe mostly belong to the main phase of the Kalahari Group that occurred in the Tertiary Period (Stagman 1978).

The regional geology for the Sawmills area is presented in Fig. 3. The Umguza River drains towards the northwest, and this has exposed Karoo basalt in the floor of the river valley. Karoo sandstones are also exposed in the valley floor towards the northwest where they have been faulted up by a northeastern trending fault. Other smaller northeastern trending faults are mapped in the exposed basalt. A small outcrop of pepperite is exposed on the southern side of the valley.

The valley flanks are mantled with unconsolidated Kalahari Sand, and the contact between the basalt and the Kalahari Sand, particularly in the north, is marked by an extensive outcrop of ferricrete. To the south, the ferricrete is much less prominent. The exposure pattern of the ferricrete at the Kalahari Sand/ basalt contact suggests that the groundwater drainage in the Kalahari Sand has been towards the south. Where groundwater has seeped out of the Kalahari Sand and evaporated ferricrete has been precipitated, thus, producing the large ferricrete body north of the river.

Hydrogeology

This report considers the groundwater resources located specifically in the Karoo Supergroup found at Sawmills. The Karoo stratigraphy in Zimbabwe has been discussed in detail by Barber (2003), and although there are variations both within individual Karoo basins and also between different Karoo basins, there are a number of units that may be considered as potential aquifers.

From the base upwards, these aquifer units are listed below:

1. Lower and Upper Wankie Sandstones. These units are at the base of the Lower Karoo Group immediately above the glacial sediments and are widely distributed throughout all the Karoo basins in Zimbabwe. These units are usually highly productive aquifers.
2. The Escarpment Grit. This normally very thin unit is at the base of the Upper Karoo Group, and where present, this unit constitutes a productive aquifer.
3. The Forest Sandstone. The climate became drier during the deposition of the Upper Karoo Group, resulting in widespread aeolian conditions. The Forest Sandstone is the uppermost sedimentary unit in the Karoo Supergroup and it consists of fine-grained aeolian sandstones and silts interbedded with fluvial sediments. The Forest Sandstone is considered to be an important regional aquifer of moderate permeability (e.g. Beasley 1987), and it has been significantly developed for irrigation around the town of Nyamandhlovu since the 1960s. Artesian and sub-artesian streamflow has been recorded in the Umgusa and Khame Rivers in this area since the early 1900s and the Forest Sandstone has been referred to locally as the Nyamandhlovu aquifer. However, at Sawmills, this aquifer appears to be a minor contributor to borehole yield.

At Sawmills, the Karoo Basalt and the Upper Karoo Group Sandstone (Forest Sandstone) are exposed in the river valley. Borehole logs indicate that the Lower Karoo Group strata are also present at depth. The geological surface mapping and SPOT image analysis have identified a number of NE–SW trending fault zones that intersect and displace the Karoo strata (see Fig. 3). In addition to their effect on the deposition of the Karoo strata, these fault zones are also likely to be sites of enhanced secondary permeability.

It is important to note that the Karoo Supergroup covers large parts of southern Africa. The main Karoo basin in South Africa extends over 400,000 km^2, and a second major Karoo basin of similar size extends from south-central Namibia, through central Botswana, across northern Zimbabwe and into north-central Mozambique. The extensive sandstone units present in both the Upper

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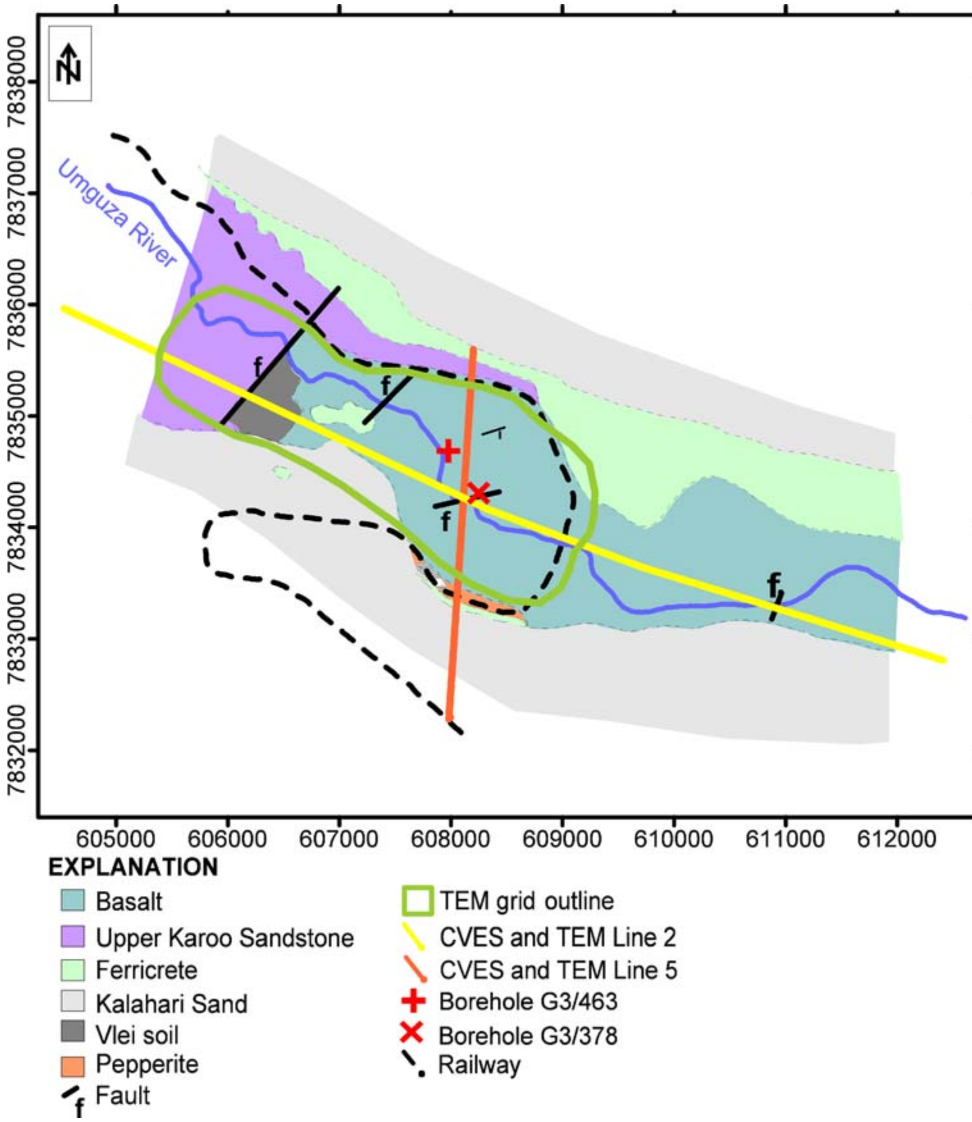

Fig. 3 Field and regional geology map of the Sawmills area, also showing the transient electromagnetic (TEM) grid outline and CVES sounding profiles (*lines 2 and 5*). The *tick marks* delineate 1 km

and Lower Karoo Groups are potentially important regional aquifers that have been widely exploited particularly in Botswana and South Africa. The Water Research Commission of South Africa (WRC) has identified the Karoo Supergroup as an important groundwater resource and has recommended further research into the potential for aquifer development. Furthermore, the Karoo Sandstone constitutes a major regional aquifer in Brazil. Hence, it is envisioned that the results presented here also may be applicable to areas outside of Zimbabwe.

The Sawmills boreholes

The small hamlet of Sawmills lies in the Umguza River Valley approximately 85 km northwest of the provincial capital Bulawayo. Three boreholes, two production wells, and one observation well were drilled at Sawmills in the late 1960s in order to find a water supply for the coal-fired steam trains on this railway route. Groundwater under artesian pressure was encountered in these boreholes.

A composite lithological/geophysical/hydrologeological log of the deepest borehole (G3/463-413 m) drilled at Sawmills shows that there is a complete sequence of Lower and Upper Karoo Group strata at this site, extending from the crystalline basement through to the overlying Batoka Basalts (Fig. 4). The lithologic sequence in this borehole is almost identical to the lithologic sequence in the borehole for the other production well (G3/378-331 m), which is less than 1 km away.

The hydrologic log, based on a 28-hour aquifer test performed by MacDonald (1970) shows that the first subartesian water was encountered in the sandstones of the Upper Karoo Group, and artesian water was encountered at the contact between the Upper and Lower Karoo Groups at an elevation of 850 m. Additional artesian inflow zones were encountered in the Lower Karoo Group down to an elevation of 760 m. MacDonald (1970) describes six major inflow zones in the borehole, where the lowermost zones had the largest flows. MacDonald (1970) gives no direct indication of the water flow directly

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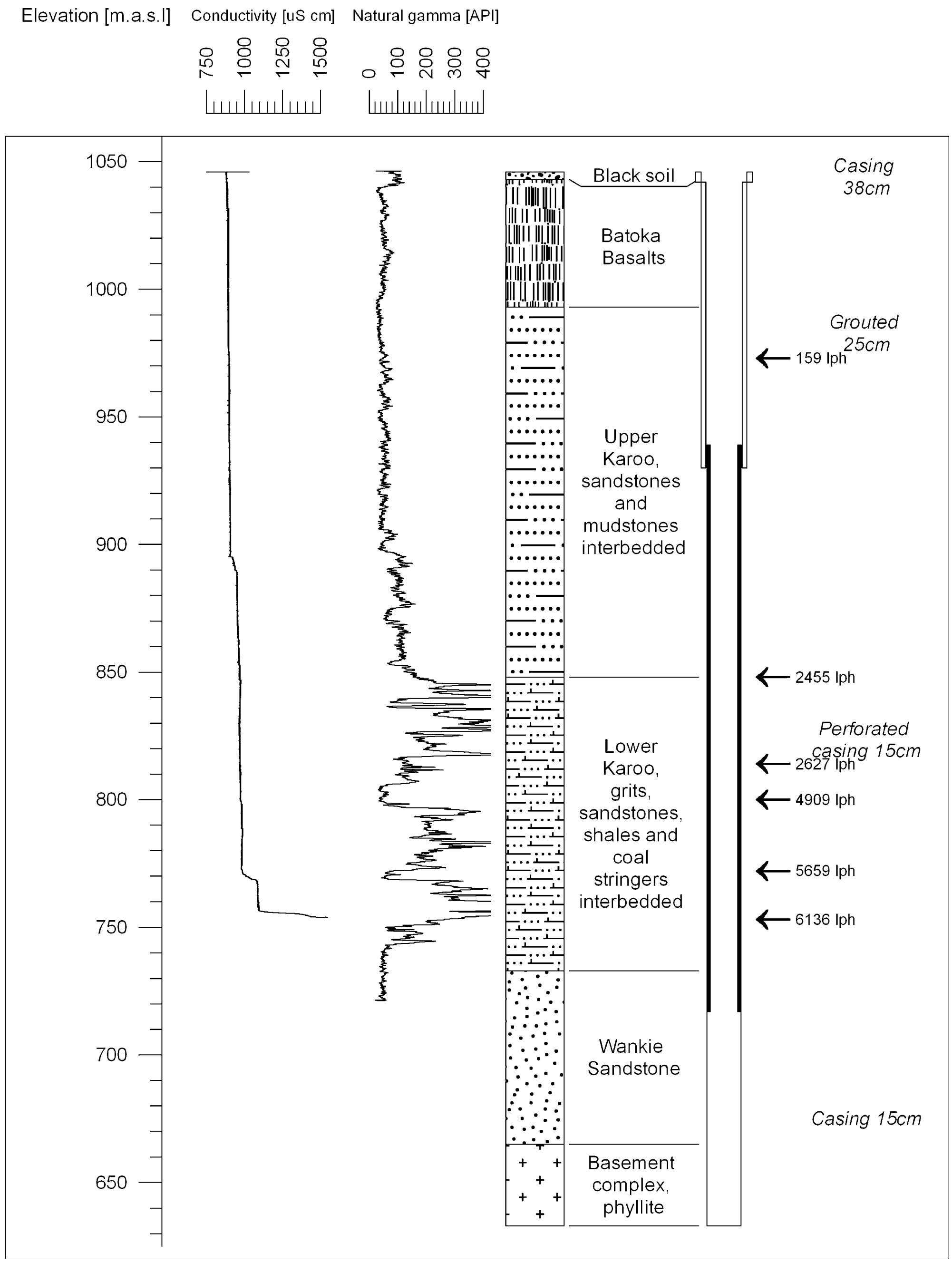

Fig. 4 Conductivity and natural gamma (Mangeya 2003) and summarized lithologic logs (MacDonald 1970) at borehole G3/463. The vertical scale is elevation in metres. To the *right*, the measured inflows from MacDonald (1970) are stated in litres per hour (lph). The location of the borehole is shown on Fig. 3

from the Wankie Sandstone below 740 m at the base of the sedimentary pile. However, this borehole yielded 50 m^3/h during the pumping test and the borehole log shows discharges through the casing of approximately 22 m^3/h. The balance of 28 m^3/h must, therefore, have come from the underlying Wankie Sandstone. In 1995, SWECO, carried out a step drawdown test in the deep borehole at G3/463 using Atlas Copco Well Monitor software and established a 5-year pumping discharge rate of 80 m^3/h, or 52 m^3/h with a calculated safety factor designed to reduce the possibility of over-exploitation of the aquifer (SWECO 1995). The average calculated transmissivity for all the pumping steps was 11 m^2/day and the specific capacity was 0.729 m^3/h/m of drawdown.

The lithologic log for G3/463 indicates that the Lower Karoo Group consists of the coarse Wankie Sandstone units at the base, grading upwards into coal, shales and mudstones. The Upper Karoo Group is described by MacDonald (1970) as sandstone with some clay bands, and by Bond and MacDonald (1962) as interbedded sandstone and mudstone. The Karoo Basalt cap the Karoo Supergroup and consists of at least three flows that are compact at the base and in the middle and vesicular, and, thus, probably more weathered at their upper surfaces.

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Two other deep boreholes at Sawmills were documented by MacDonald (1970) showing a consistent stratigraphy down to their maximum depths of 285 m (O3/117) and 322 m (G3/378). The thickness of the basalt varies in the three Sawmills boreholes: 39 m (G3/378), 48 m (G3/463), and 85 m (O3/117), indicating faulting and vertical movement between the two production wells and the observation well.

The conductivity log shows fairly high values that appear to be related to the groundwater conductivity rather than formation conductivity; formation conductivity is expected to be lower. The conductivity of a mixed water sample from the borehole was measured in the laboratory as 975 μS/cm (SWECO 1995). The conductivity log shows small but distinct changes at 975, 895, 850, 800, 770, and 755 m above sea level (masl). Apart from the changes at 895 m, all the other changes can be related to inflow zones identified in the hydrogeologic log. This result indicates that the downhole conductivity log is a useful tool for identifying groundwater inflow zones. The 850 m elevation is the interface between the Lower and the Upper Karoo Groups.

The gamma log correlates very well with the lithology and, to some extent, with the inflow zones. The gamma log shows a change to slightly higher counts between 900 and 850 masl. These higher counts represent the depth interval from the first inflow zone down to the inflow zone at the Upper/Lower Karoo Group boundary. Between 850 and 750 m, the gamma signature is dramatic and appears to change at water interflow zones. The lithology in this zone has been logged as Lower Karoo Group grits, sandstones, shales, and coal stringers. Below 740 masl, the lithology is the Wankie Sandstone and the gamma signature changes markedly to a lower more stable signature.

Geophysical data acquisition methods

Two geophysical methods proved especially useful for surface geophysical mapping: continuous vertical electrical sounding (CVES) and transient electromagnetic sounding (TEM). CVES was used to delineate the near-surface geological structures, whereas TEM was used to delineate the deeper structures.

The transient electromagnetic (TEM) sounding method

The TEM method has been used in hydrogeologic studies over the last 15 years. The usage of the method is described by e.g. Fitterman and Stewart (1986); Danielsen et al. (2003). The TEM method makes use of a direct current transmitted into the transmitter loop lying on the ground. The current creates a primary, stationary magnetic field. The direct current is switched off which induces an eddy current system in the ground. Due to ohmic resistance of the subsurface, the current system will decay and further induce a secondary magnetic field that is measured in an induction coil (the receiver coil). The decay rate of the electromagnetic field depends on the resistivity distribution of the subsurface. The field decays slower in a conductive rather than in a resistive medium. Consequently, the TEM method has excellent resolution of conductive layers at depth, whereas the resolution of resistive layers is limited (Christensen and Sørensen 1998).

TEM soundings are usually made with spacing between 150 and 250 m, depending on the exploration target. The penetration depth is dependent on the magnetic moment of the equipment (i.e. transmitter loop size and number of turns and the transmitted current), the resistivity of the ground, and the magnitude of electromagnetic background noise (Macnae et al. 1984; McCracken et al. 1986).

Advantages of the TEM method are its sensitivity to conductors at great depths and the lightweight equipment compared to CVES. Drawbacks of the TEM method are low resolution of resistive layers, relatively low lateral resolution in general, high degree of coupling to man-made conductors (Danielsen et al. 2003), and that the method is conceptually advanced.

The continuous vertical electrical sounding (CVES) method

The CVES method has been extensively used for groundwater investigations over the past decades (Olayinka and Weller 1997; Rühlow et al. 1999; Sørensen et al. 2001) and for various other purposes by e.g. Bernstone and Dahlin (1999); Beresnev et al. (2002), and Wisén et al. (2004). The popularity of the CVES method is closely connected to its wide applicability, its robustness, and the availability of numerous two-dimensional (2-D) and three-dimensional (3-D) inversion programs, e.g. Loke and Barker (1996a, b); Oldenburg and Li (1994), and Li and Oldenburg (2000).

A number of electrodes secured into the ground and connected by electrode cables are used with the method. A switching unit connected to a computer controls the transmission of current into ground through two of the electrodes, while potentials are measured over other electrode pairs. In this way, measurements are performed for various electrode spacings along a profile line. The array configuration and the electrode spacings are dependent on the target of a given exploration (Dahlin and Zhou 2004).

The CVES method provides high data density and it has a superior near-surface, horizontal resolution in comparison to e.g. the TEM method. The data are robust, as they are not appreciably affected by coupling to man-made conductors and electromagnetic noise. The main drawbacks of the method are the limited penetration depth and the dependency on galvanic contact to the ground. Galvanic contact is a problem particularly in dry areas.

Data acquisition, processing, and interpretation

Of the 31 km of CVES profiling and 309 TEM soundings collected around Sawmills, data presentation is limited here to the TEM soundings and CVES profiles of

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geophysical profile lines 2 and 5 (marked in Fig. 3), and the area covered by TEM soundings inside the U-shaped bend of the railway.

TEM

The TEM soundings were collected using the Geonics Limited PROTEM 57 and 47 systems for line 2 and line 5, respectively. A single turn, 80×80 m transmitter loop was used to gain sufficient penetration depth. The receiver coil was placed in the centre of the transmitter loop.

The PROTEM 57 system transmits 12.5 Ampere (A), yielding a magnetic moment of 80,000 Am^2. Data are measured in the time range of 0.1 to 70 ms after turn-off. However, usable data were only measured until approximately 7 ms. This resolution lies within the capacity of the far more mobile PROTEM 47 system, which also has a higher resolution of the near-surface formations. The system measures in the range from 0.007 to 7 ms after turn-off. The PROTEM 47 transmits a maximum of 3 A, yielding a magnetic moment of 19,200 Am^2. In the application of the PROTEM 47 at Sawmills—here represented by line 5—the receiver coil of the PROTEM 57 system was used. The PROTEM 57 system has a narrow bandwidth reducing the background noise, i.e. data are usable to later times, but it also distorts the early time gates (Effersø et al. 1999). The mixed PROTEM 47 system allowed the field crew to perform around 15 soundings per day, corresponding from 2.5 to 3 profile kilometres. This number of soundings should be compared to 10 soundings per day using the heavier PROTEM 57 equipment. As opposed to the CVES method, the TEM method has the same production in the Kalahari Sand, as galvanic contact to the ground is not a problem.

Outlying data points were removed with the SiTEM software (HydroGeophysics Group 2007). Standard deviations on the individual data points have been estimated from the noise measurements performed on the sounding site. When the level of the induced response from the earth approaches the noise level, the standard deviations of the data points are increased. In this way, the noisier data points at late times are assigned less weight in the inversion. The low occurrence of man-made conductors makes the use of the TEM method favourable in this application.

The inversion program SELMA (Christensen and Auken 1992) was used for the individual inversion of the TEM data. The program does one-dimensional inversion and model analysis of TEM data. The underlying model is one-dimensional, but may be a parameterized model or a multi-layer model. The TEM data were interpreted using a multi-layer model with 19 layers, where the layer thicknesses increase with depth to reflect the resolution capacity of the method (Constable et al. 1987).

CVES

The CVES were mainly carried out in areas with a top cover of weathered basalt as this provided good electrode contact compared to the high resistivity Kalahari sands. For the CVES data presented here, only the southern part of line 5 is measured in Kalahari sands.

Local workers were hired to cut the lines through the bush. The starting points of the lines were measured by Differential Global Positioning System (DGPS) and from there directional bearings were taken using a compass and ranging rods. The length along the profile (x-coordinate) was determined with a measuring tape and the stations were marked with wooden pegs. The line topography was obtained by levelling with a dummy level in reference to the starting points.

The CVES surveying was carried out using an ABEM Lund Imaging System (Dahlin 1996). A total layout length of 800 m was used with a 10-m minimum electrode interval. Line 5 was measured using Wenner protocols providing 16 different a-spacings from 10 to 240 m. On line 2, the Wenner protocols were complemented by Schlumberger protocols. Schlumberger protocols include a higher data density at great depth, but these data are generally noisier than data collected with Wenner protocols (Dahlin and Zhou 2004).

The CVES data were measured transmitting currents in the range 50–200 milliamperes (mA). However, the Kalahari sands required considerable efforts in watering and hammering the electrodes, and the current had to be lowered to 20 mA in some cases. A mixture of salt and starch based gel intended for rotary mud drilling with water helped to improve contact in the highly permeable sand. The productivity during fieldwork ranged mostly between 800 and 1,000 m per day, depending on the galvanic contact of the ground.

The CVES data are generally of good quality. The most noise affected profiles have a Kalahari sands top cover, e.g. from 0 to 1,000 m on line 5. The data were inverted using the Res2dinv program, where approaches described by Loke and Dahlin (2002) and Loke et al. (2003) are used. The underlying model is a two-dimensional finite element model that accounts for topography. The inversions were carried out using the L1-like minimization of the error function. Together with a horizontal flatness filter, these settings create models with sharper boundaries than the default least squares approach. A sharp boundary model was considered to be a better representation of the layered geology underlying the Sawmills area.

Mutually and laterally constrained inversion

The TEM and geoelectrical methods are complementary in many ways making them ideal methods for joint inversion. Both methods measure the electrical resistivity (or conductivity) of the subsurface, but they have different sampling volumes and sensitivities. Joint inversion of data sets resolving the ground resistivity has been presented by e.g. Gómez-Treviño and Edwards (1983); Raiche et al. (1985); Yang et al. (1999), and Albouy et al. (2001).

In this study, the mutually and laterally constrained inversion (LCI) of Christiansen et al. (2007) for joint inversion of TEM and geoelectrical data is used. A

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parameterized inversion of several one-dimensional models on a profile is used minimizing the same objective function. The model parameters of adjacent soundings are laterally constrained to claim identity between the neighbouring models. The lateral constraints can be considered as prior information of the geological variability as seen by the method along the profile. The resulting model has sharp layer boundaries, but a smooth lateral development.

It was expected that the consecutive basalt flows in the survey area can create electrical anisotropy (Christensen 2000) because the flow surfaces are weathered before they are overlain by a new flow. Also, the upper portion of the flows are enriched by fluids and volatiles derived from basalt degassing due to pressure changes that occur after extrusion. The benefit of joint inversion schemes in an anisotropic environment is exemplified by the model analysis shown in Fig. 5.

Synthetic TEM and DC geoelectrical data sets for the model shown in Fig. 5a are generated by EMMA (Auken et al. 2002). These synthetic data sets are inverted individually, and the resulting models are shown in Fig. 5b and c, respectively. The TEM model does not reproduce the first two layers correctly, but the depth to and resistivity of the bottom layer and the thickness of the anisotropic layer are correctly reproduced. The Schlumberger sounding recovers the upper part of the model, but the thickness of the anisotropic layer is exaggerated. However, the joint inversion of both data sets shown in Fig. 5d reproduces the true model, apart from the actual anisotropy that is beyond the resolution capabilities of any surface-geophysical method.

Constraint set-up

The set-up of the constraints is crucial for the inversion result. To evaluate different constraints, a test profile, from 1,000 to 2,500 on profile line 2 (see Fig. 3), was set up with different constraints.

The Res2dinv inversion result of CVES data for the test profile is shown in Fig. 6a. The upper 30 m are low resistive, but at profile coordinates 1,600 and 1,800 m, small resistive bodies are located close to the surface. A resistive layer is encountered below a depth of 50 m.

Initially, reproduction of the two-dimensional inversion result was sought by one-dimensional LCI of the CVES data alone. This reproduction is shown in Fig. 6b. The upper 50 m of both profiles are similar. The lateral constraints are looser in the upper two layers of the underlying four-layer model compared to the lower two layers. Loosening the constraints corresponds to weighting the data more in the upper part of the model than in the lower part. This approach is reasonable as the sensitivity of the method decreases with depth. A looser constraint factor between neighbouring resistivities in the top layer allows the models to account for near-surface resistivity variations caused by the so-called static shift problems (Li and Oldenburg 2000 and Spitzer 2001). The LCI shows continuity in the 20–40-Ωm shallow layer stretching through the entire profile, even if the LCI, occasionally, jumps between neighbouring layers. The shallow layer is generally thinner than in the two-dimensional inversion. This result is explained by the nature of the smooth inversion; the inversion has to incorporate a transition from the shallow conductive structure to the resistive

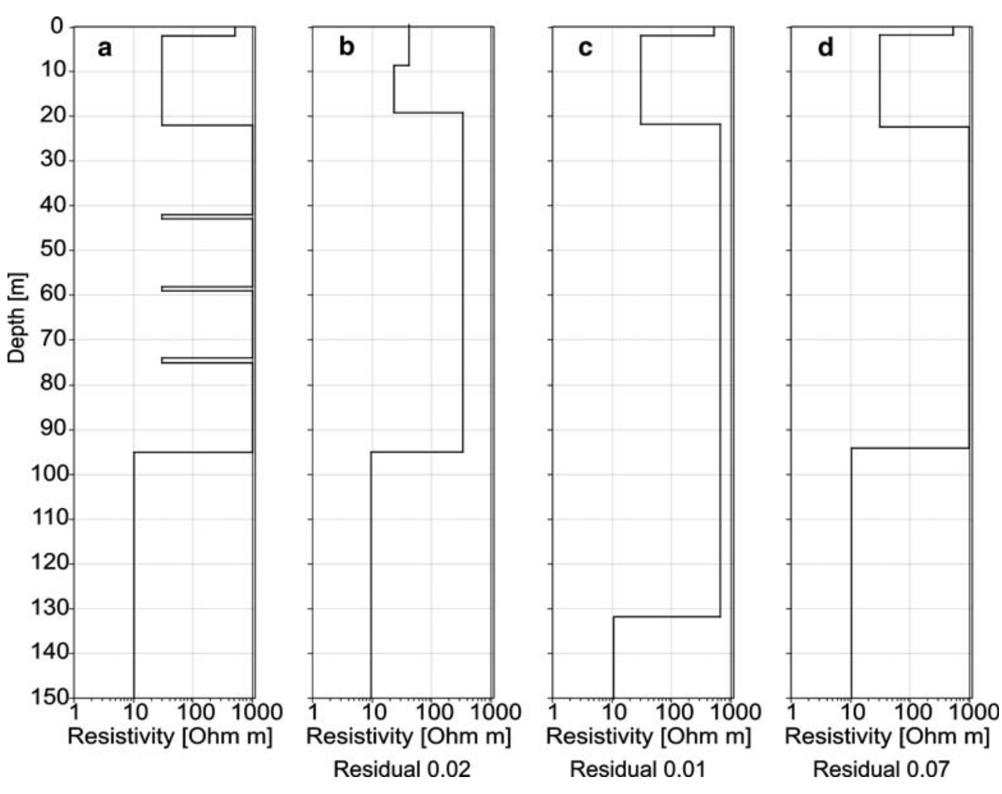

Fig. 5 Model analyses: **a** the true model, **b** the TEM inverted model, **c** the DC inverted model, and **d** the constrained inverted model. The anisotropy is modeled as three 30Ωm layers, 1m thick, interbedded in a 1,000Ωm layer. Data residuals from the inversion are stated below the models. A residual of 1 corresponds to the data uncertainty. Hence, the synthetic data are well-fitted for all three inversions

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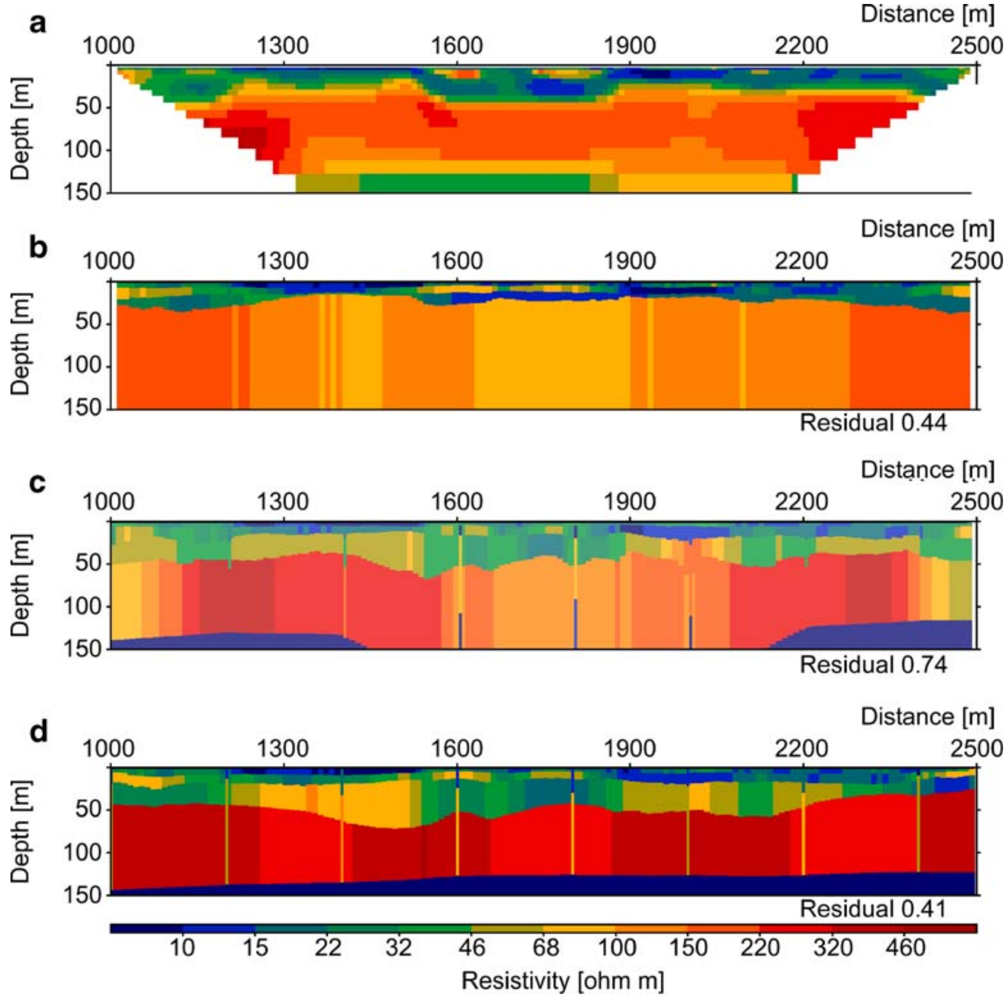

Fig. 6 Test profile used to determine the set-up of constraints. In **a** it is the two-dimensional inversion of CVES data by Res2dinv is shown, in **b** it is the one-dimensional LCI of CVES data, in **c** it is an abandoned attempt of LCI of TEM and CVES data, whereas **d** is the LCI with the model as chosen. A residual of 1 corresponds to a fit at the uncertainty applied to the data. Hence, data are fitted within the data uncertainty

structure below. At depths greater than 50 m, Res2dinv shows vertical variations in resistivity, where the LCI varies laterally with similar variations to obtain the same integrated resistivity.

The TEM data are added to the LCI system in Fig. 6c. The conductive layer at great depth is severely constrained from model to model. To ensure continuity from TEM model to TEM model, the constraint needs to be narrow, as 20 CVES models are present between two TEM models. The CVES models have a tendency to increase the resistivity and push the layer down (not shown). This result may be due to anisotropy as discussed above.

Based on the results shown in Fig. 6c, it was decided to constrain the TEM models to the CVES models only by the bottom layer boundary, as the CVES data have the higher surface-near resolution. The resulting model is seen in Fig. 6d. This model has the near-surface resolution of the two-dimensional CVES interpretation, e.g. note the shallow resistive bodies at 1,600 and 1,800 m. The low-resistive bottom layer is necessary to explain the TEM data and it confines the lower boundary of the anisotropic basalts. The bottom layer prevents the overshoot of thickness and undershoot of resistivity due to electrical anisotropy (Fig. 6a and b). It is believed that the LCI provides a better estimate of the properties of the basalt and can be used for assessing the degree of fracturing and weathering that are important for recharging underlying aquifers.

Measured and model data for three soundings along the profile are shown in Fig. 7. Measured data are represented by error bars, whereas the model data are presented by dots. For large electrode spacing, two data points are present for the same electrode spacing. This result is due to the presence of both Wenner and Schlumberger data with the same array midpoint. Considering a one-dimensional earth, the two data points would coincide. Because the two data points do not coincide, the inadequacy of the one-dimensional model is realized. Generally the fit to data is acceptable for both DC and TEM.

Results and interpretation

Line 2

The inversion results of line 2 are given in Fig. 8. The model sections are described below. A model section of one-dimensional inversions of line 2 TEM data down to an approximate depth of 200 m using a multi-layer model

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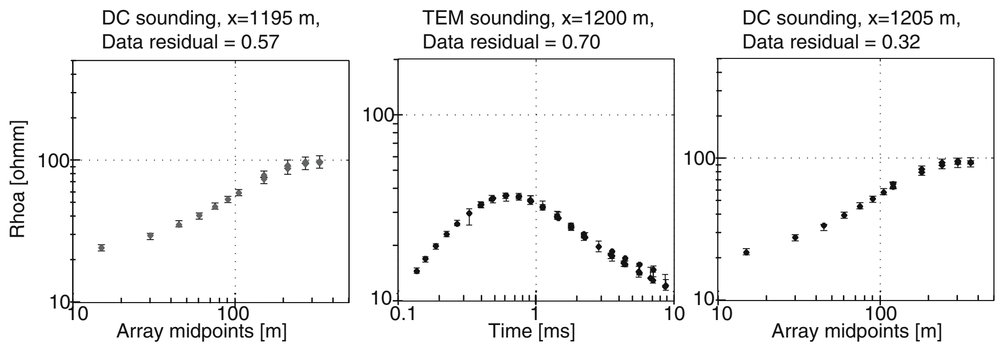

Fig. 7 Measured and model data for three soundings on the test profile. *Error bars* mark the measured data and the applied data uncertainty, whereas the *dots* are the model data. Note the good data fit

is shown in Fig. 8a. The model section shows a highly conductive bottom layer with resistivities around 10 Ωm at depths varying along the profile from 60 to 150 m with the minimum depths in the centre, between 4,400 and 5,100 m. Above a depth of 4,400 m, at least two layers of higher (a few hundred Ωm) and intermediate (a few tens of Ωm) resistivity can be found. The major units deduced from the inversion results are, pending additional drilling information, attributed to weathered basalt (intermediate resistivity: a few tens of Ωm), fresh basalt (high resistivity: a few hundred of Ωm), and Karoo sediments (10–15 Ωm).

In the left third of the profile (Fig. 8a), the top layer has an intermediate resistivity, and corresponds to an area where surface observation has identified soils derived from the weathering of basalt and sandstone (see the local geologic map in Fig. 3). Gradually higher resistivity appears in the interval from about 3,000 to 5,200 m. The higher resistivity corresponds partially to outcrops of fresh basalt observed in the interval from 4,300 to 5,300 m.

From profile coordinates above 5,500 m, at least four layers can be distinguished. The top high resistivity layer (a few hundred Ωm) is followed by an intermediate resistivity layer (a few tens of Ωm) and then to a high-resistivity third layer (a few hundred Ωm) to a low resistivity basal layer (around 10 Ωm). The geological interpretation for these results is the presence of fresh basalt at the surface, confirmed by outcrop evidence in the river bed, then weathered basalt and/or sandstone, a second flow of fresh basalt and, lastly, Upper Karoo Group sediments at the base of the profile. The low resistivity of the Upper Karoo Group sediments is due to the interbedded layers of mudstones, and the presence of conductive groundwater (Fig. 4). Between 4,000 and 5,500 m, the Karoo Supergroup sediments dome towards the surface, and this result is interpreted as an upfaulted block.

The Lower Karoo Group, consisting of mudstone, shale, and coal overlying coarser basal sandstone units at the bottom, is likely to be more conductive than the predominantly sandstone units that compose the Upper Karoo Group. Moreover, the groundwater in the Lower Karoo Group has a significantly higher conductivity than the more readily recharged groundwater in the Upper Karoo Group. Hence, a layer of lower resistivity likely is present below the Upper Karoo Group, but cannot be

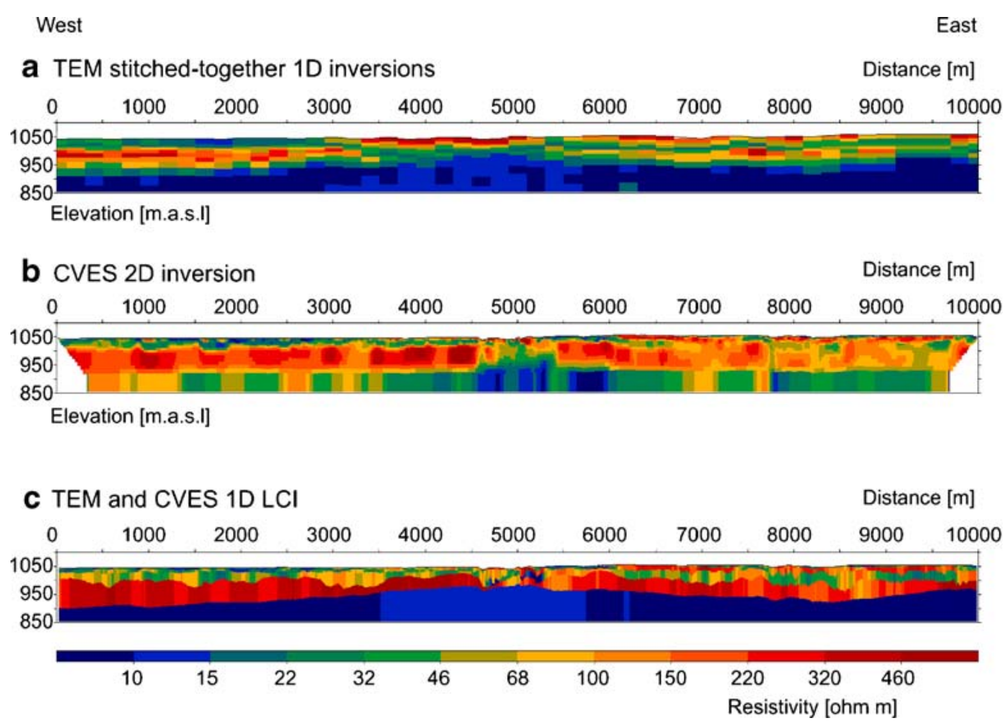

Fig. 8 Inverted model sections from line 2 at Sawmills: **a** is the one-dimensional multi-layer inversion based on TEM data, **b** is the two-dimensional robust inversion of CVES data, **c** is the one-dimensional mutually constrained inversion of TEM and CVES data

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clearly identified because of the great depth of burial. In the borehole log for G3/463, the depth to the upfaulted Lower Karoo Group is 200 m, and it must lie deeper outside this upfaulted block.

The CVES inversion result from line 2 is presented in Fig. 8b. The first section of the line (from 0 to 4,600 m) shows essentially a three-layer structure. A 30-m-thick relatively conductive top layer (a few tens of Ωm) overlies a 100-m-thick resistive layer (some hundred Ωm), which in turn overlies a lower resistivity base (a few tens of Ωm). This interpretation agrees with the TEM model.

Supported by outcrop information and borehole data, the three layers are interpreted as conductive weathered basalts interbedded with sandstones, underlain by resistive fresh basalts, followed by the relatively conductive Upper Karoo Group sediments. The high resistivity basalt layer varies significantly in resistivity along this section of the profile, indicating variations in electrical properties probably due to variation in joint spacing and associated weathering on joint surfaces. The thickness of the fresh basalt layer is expected to be exaggerated due to electrical anisotropy. There are small highly resistive spots in the shallow parts of the model, which may be explained by local deposits of coarse-grained alluvium.

From 3,500 to 4,600 m, there is a thin high resistivity surface layer associated with exposures of fresh basalt. Between 4,600 and 5,400 m, the low resistivity bottom layer, interpreted as Upper Karoo Group sediments, has been vertically uplifted closer to the surface. The high resistivity layer has been largely displaced, and where it persists, it is thinner and fragmented. Where this layer reaches the surface, it coincides with the exposed basalt. The thickness of the high resistivity layer in this interval also agrees with the thickness of the basalt recorded in boreholes G3/378 (48 m) and G3/463 (50 m; MacDonald 1970).

Similar interpretations as described above can be made for the rest of the profile from 5,400 m eastwards to the end of the line. The basal layer has low resistivity and is overlain by a high resistivity layer representing Upper Karoo Group sediments and fresh basalt, respectively. The top section indicates slightly greater complexity, and may be either a single low-resistivity surface layer or a double layer with a thin high-resistivity surface layer followed by a low-resistivity layer. This result has been interpreted as either weathered basalt or an upper flow of fresh basalt overlying the weathered basalt.

Another distinctive feature of this end of the profile is that the main zone of high-resistivity fresh basalts is more broken by vertical zones of low resistivity, as compared to the western section. The vertical breaks may be due to block faulting or to variations in the spacing of the joints. This pattern can also be derived from the joint inverted profile in shown in Fig. 8c. The joint inversion gives a better estimate of the thickness and resistivity of the basalt layer. This better estimate particularly applies to the west in the profile, where the basalt/Karoo Group boundary supposedly is deep and well below the penetration depth determined with the CVES method. To the east, above 9,000 m, the Upper Karoo Group comes closer to the surface. The first yielding horizon in the borehole in Fig. 4 correlates well with the conductive layer at the borehole site at an elevation of 975 m in the joint inverted geophysical profile. This horizon (below the basalt/Karoo Group interface) is apparently shallower in this part of the profile and, presumably, less costly to drill. Optimization of the depth to the water-yielding horizons is of major importance in such a geophysical survey. This horizon is too deep to be consistently determined by the CVES method alone, whereas the stand-alone interpretation of the TEM data shown in Fig. 8a lacks the detail in the near-surface.

One limitation to the interpretation described above is that the underlying model assumption is one-dimensional. In areas with clear two-dimensional (or even three-dimensional) structure, the two-dimensional inversion of CVES is better equipped to show the structure. This result happens e.g. at the fault zone between 4,600 and 5,400 m. Luckily, the conductive layer in this area is closer to the surface and it is picked up on the CVES profile. In this particular region, more confidence should be placed in the structure shown by the CVES model. All in all, it is convenient to have several model displays and data representations, as no one representation is best in all respects.

Line 5

The inversion results of line 5, which strikes line 2 at right angles at the fault zone, are shown in Fig. 9. The TEM inverted multi-layer model shown in Fig. 9a appears able to differentiate between the Lower and Upper Karoo Groups. Below the high-resistivity layer, interpreted as fresh basalt, a 50-m-thick layer with a conductivity of 15-20 Ωm is located above a 10-Ωm layer. The 15–20 Ωm layer may be interpreted as the Lower Karoo Group. This interpretation is not supported by the CVES in Fig. 9b, and the inclusion of the CVES data in the joint inversion (Fig. 9c) scheme subdues this feature. Also, the great depth of the Lower Karoo Group at borehole G3/463 makes this interpretation uncertain.

The Kalahari Sand is clearly seen as the top high-resistivity layer in the CVES and the LCI profiles from 0 to 1,000 m. The TEM one-dimensional profile gives evidence of the presence of the Kalahari Sand until it becomes too thin at 800 m. It is well-known that the strength of the method is the detection of buried, conductive layers. At greater depth, coordinates from 0 to 1,000 m are the most resistive part on line 5, suggesting that the basalt here is fresh and intact. This fresh and intact basalt is likely to reduce recharge to the underlying Karoo Supergroup sediments. Similarly, on line 2 (Fig. 8), resistivity values from coordinates from 0 to 1,000 also indicate fresh intact basalt.

In the interval from 1,300 to 2,700 m, the fault zone is recognized. Line 5 strikes almost perpendicular to line 2; therefore, line 5 provides an image of the fault zone in the N–S direction. Again, the fault zone is most clearly recognized in the CVES two-dimensional profile. The TEM one-dimensional profile contains a bad sounding at 1,200 m that was skipped. Skipping this sounding lowered

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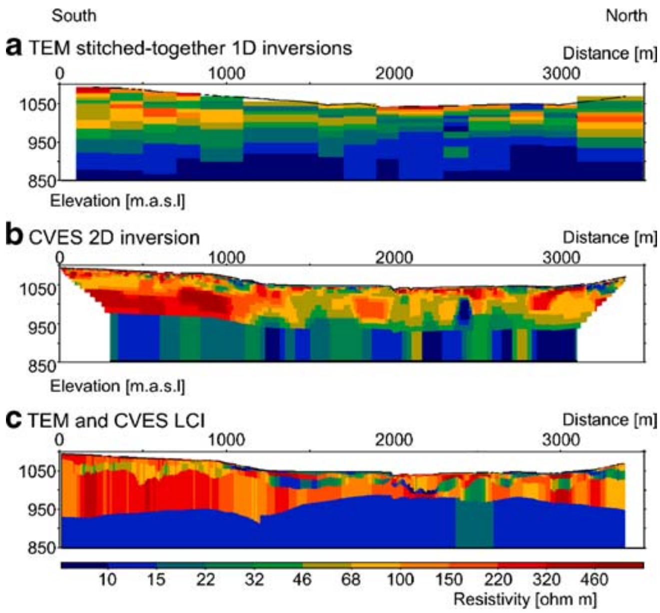

Fig. 9 Inverted model sections from line 5 at Sawmills: **a** is the one-dimensional multi-layer inversion based on TEM data, **b** is the two-dimensional robust inversion of CVES data, **c** is the one-dimensional mutually constrained inversion of TEM and CVES data

the horizontal resolution. However, a clear decrease in resistivity compared to lower profile coordinates suggests a change in the subsurface. In the LCI profile (Fig. 9c), this region shows fluctuations between extreme resistivities. These fluctuations may be due to inadequacy of the one-dimensional model assumption because of the fault zone. From 2,700 m upward, it seems that the typical scenario of weathered and fresh basalt underlain by the Karoo Supergroup sediments resumes, and it continues throughout the profile.

Depth slices

The inverted models from all the available TEM soundings were merged to form a quasi three-dimensional model, from which slices were differentiated with depth. Selected model slices, with the position of the railway marked for reference, are shown in Fig. 10. The top depth slice shows high resistivity in the central and eastern part. This high resistivity is interpreted to consist of mainly fresh basalt at an elevation from 1,040 to 1,060 and is shown in Fig. 10a. The northwestern corner shows intermediate to low resistivity that is interpreted as Upper Karoo Group Sandstone. Sandstone has also been mapped here in the regional geologic field map (Fig. 3). The contact between the high and intermediate to low resistivity areas is sharp and is considered to be the fault zone trending approximately N–S.

Along the W–SW edge of the mapped area, there is higher resistivity that probably corresponds to the Kalahari Group. This result agrees with the regional geologic map shown in Fig. 3. Distinct bands of lower resistivity are seen in the central high-resistivity regions, which are interpreted as fault zones.

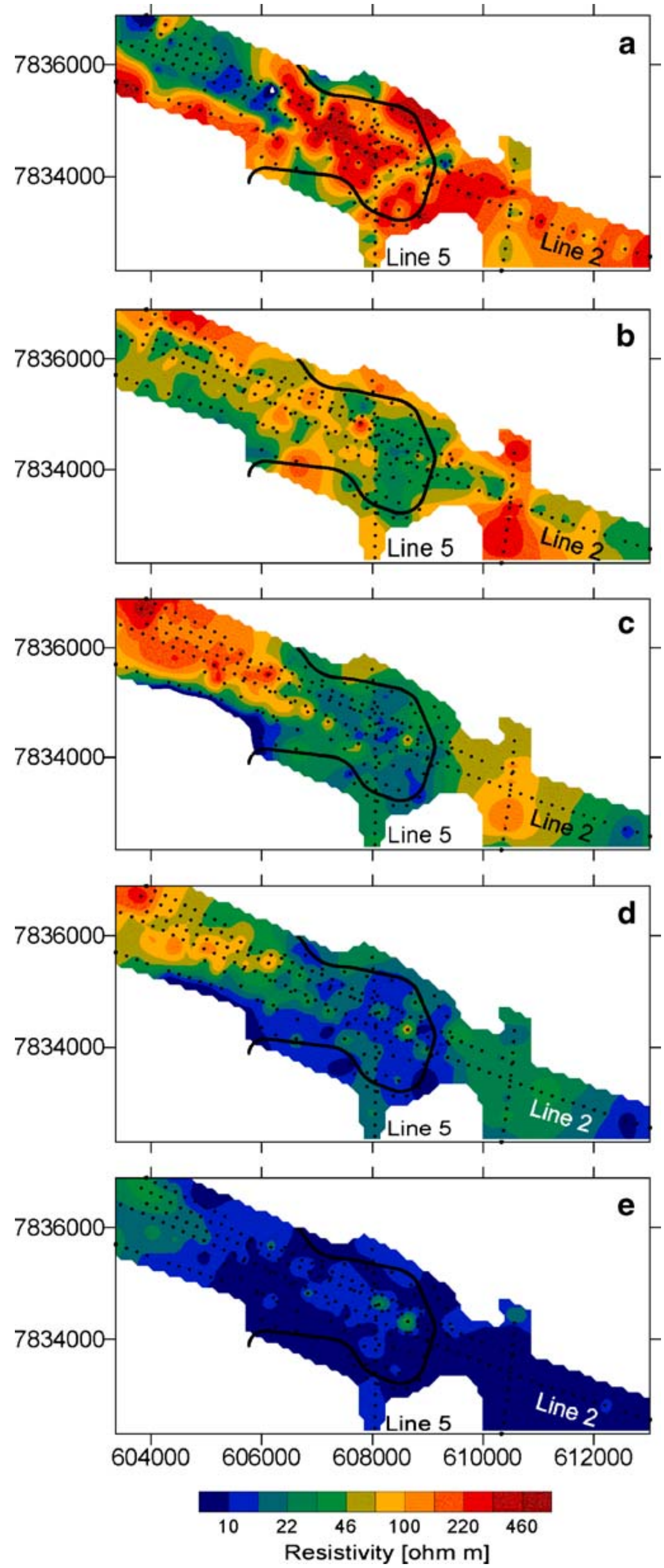

Fig. 10 Depth slices of merged multi-layer inverted TEM models. Depths in m.a.s.l.: **a** 1,060–1,040, **b** 1,020–1,000, **c** 980–960, **d** 960–940, **e** 920–900

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In the second depth slice in Fig. 10b, 1,020–1,000 m elevation, intermediate to low resistivity is seen in the central and most of the eastern parts of the area. Based on the drilling information and the interpretation for line 2 described above, this result is interpreted as the lower resistivity of the Upper Karoo Group sediments being closer to the surface in this area. The resistivity increases in the northwestern part of the area, indicating the presence of fresher basalt. In the W–SW corner, the lower resistivity is interpreted as the weathered basalt and/or sandstone below the Kalahari Group above. The following depth slice in Fig. 10c, 980–960 m elevation, very clearly shows a large intermediate to low- resistivity zone in the central part of the mapped area. This result is interpreted as a zone where the Karoo Supergroup sediments are upfaulted in relation to the surrounding basalts. It is at this level that the first yielding horizon is encountered at the borehole. The intermediate resistivity may be interpreted as the Upper Karoo Group. A similar interpretation can be done for the eastern end of the model. The western part of the area has consistently high resistivity that can be interpreted as fresh basalt, except along the southwestern edge of the area.

The low-resistivity central zone increases in size with increasing depth, and the resistivity decreases, as shown in the next depth slice in Fig. 10d, 960–940 m elevation. This result is interpreted as an increasing effect from the low-resistivity Lower Karoo Group sediments. The bottom depth slice in Fig. 10e, 920–900 m elevation, is dominated by low resistivity, and it is only in the northwestern corner where some intermediate resistivity is still seen. This low resistivity is interpreted as dominantly Karoo Supergroup sediments, with resistivity decreasing with increasing depth.

Conclusions and recommendations

Conclusions

Considering the interpretations described above, the following items are concluded concerning the hydrogeology at Sawmills, and the application of the TEM and CVES geophysical methods to investigations of the aquifers underlying the area:

- The Karoo Basalt consists of several flows with less compact and more weathered basalt horizons or interbedded sandstone layers in between. These weathered/sandstone horizons have lower resistivity, and this layering results in electric anisotropy that affects the geophysical results.
- The Upper Karoo Group consists of sandstone with some clay bands that can result in anisotropy. Due to the clay content and the alkaline groundwater, the Upper Karoo Group has a lower resistivity than the overlying basalts.
- The Lower Karoo Group is probably characterized by even lower resistivity caused by layers of shales, coal, and mudstones and the abundance of alkaline and conductive groundwater. The interbedded layers are expected to make the Lower Karoo Group anisotropic. This layer is probably too deep to be detected with the methods used in this study.
- The first productive aquifer is at the top of the Upper Karoo Group (yielding 0.16 m^3/h), and higher yielding horizons are present at the transition to the Lower Karoo Group (2.4 m^3/h) and within the Lower Karoo Group (four zones of almost 20 m^3/h in total). Thus, the model presentations displaying the low-resistive Karoo Supergroup sediments, as they were extrapolated from the borehole, are valuable tools for aquifer exploration. The Karoo Supergroup sediments are highly faulted and, as a result, the various aquifer units come closer to the surface in some localities. Because the cost of drilling and well completion is dependent on the depth required, it is important for determining these depths for the economic aspects of aquifer development.
- The use of the geophysical methods presented here provided valuable information for understanding the geological setting at and in the vicinity of the boreholes. A similar approach was adapted for the Nyamandhlovu area closer to Bulawayo.
- Plan maps, in the form of depth slices based on TEM, outline the major tectonic features. However, these maps are smeared out at deeper depths as a consequence of the one-dimensional assumption used in the model analysis. Furthermore, the resistivity of the upper relatively resistive layers is determined with less accuracy than with CVES.
- CVES provides better images and more detail on the tectonic structure in the fault zone because of the dense data cover, the two-dimensional inversion method used, and the shallow depth due to uplifted Karoo sediments. However, the thickness of the basalt is

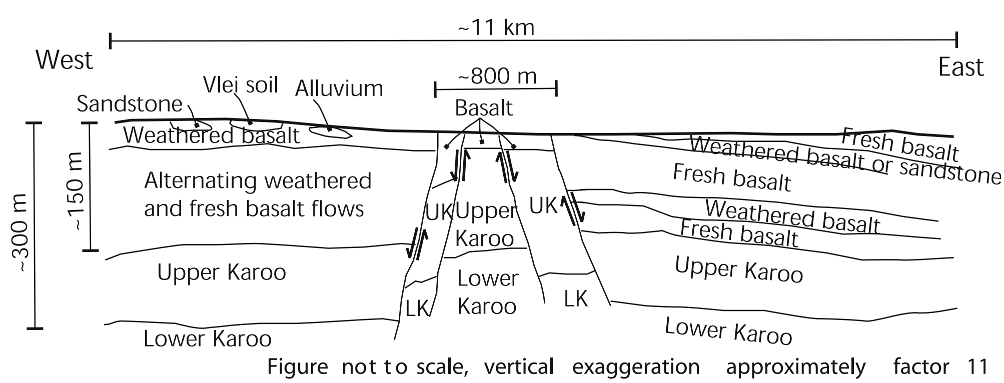

Fig. 11 Conceptual geologic model striking E–W along line 2. Not to scale

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overestimated and its resistivity underestimated due to the electrical anisotropy.
- The combined interpretation of TEM and CVES data using LCI accounts for the anisotropy and provides a better estimation of the true resistivity and depth of the layers. However, the horizontal definition is smeared due to the one-dimensional assumption and the lateral bands used.
- TEM has the advantage of not requiring galvanic contact with the ground in contrast to CVES. In CVES, the productivity and data quality can be affected in the parts of the area covered by high-resistivity Kalahari Group sands.
- Based on these items and the geologic interpretations of the geophysical models described above, a conceptual geologic model is shown in Fig. 11.

Recommendations

The following are recommended for future work at this location:

- TEM is a highly suitable method for mapping the overall structure and variations in depth to the Karoo Supergroup sediments that are the target aquifers at Sawmills. The TEM method can, thus, be expected to provide valuable information for further investigation of these key horizons. TEM can be performed quickly on the ground, and can also be performed from the air using a helicopter or fixed wing aircraft. Large areas can be surveyed efficiently with only a minor loss in resolution. Because relatively little man-made sources of disturbance are present in the area, aircraft use can be expected to give good results. An airborne survey can be followed up by more detailed ground-based TEM surveying in selected areas.
- CVES can be used to provide more detail on the tectonic structure and the layers overlying the aquifers, and should be carried out along lines selected on basis of the TEM results. This methodology allows for a better interpretation of the TEM data, and provides a more detailed image of the local geologic variation and a basis for well positioning. In other parts of the region where the Upper Karoo Group is closer to the surface or the Kalahari Group sands are target aquifers, the application of CVES is probably more important.
- In areas covered by Kalahari sands, the galvanic contact can be a problem for galvanic resistivity surveying. Even watering of the electrodes and the use of several 0.5–1 m long electrodes at each electrode point may be insufficient in places during the dry period. In such cases, surveying in the rainy season can be a way of securing reasonable surveying efficiency and data quality.

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