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The relationship between regional stress field, fracture orientation and depth of weathering and implications for groundwater prospecting in crystalline rocks

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Abstract In a uniform granite gneiss study area in central Zimbabwe, lineaments oriented parallel to the maximum regional compressive stress orientation exhibit the thickest regolith development, while lineaments oriented perpendicular to the maximum compressive stress show the shallowest development of weathered regolith. The principal fracture set orientations were mapped using aerial imagery. The regional stress field, estimated from global stress maps, was used to determine the stresses acting on each principal lineament orientation. Multi-electrode resistivity profiling was carried out across fractures with different orientations to determine their subsurface regolith conditions. The results indicate that the 360 and 060° lineaments, which are sub-parallel to the principal compressive stress orientation (σ_1) exhibit maximum development of the regolith, while 130° lineaments perpendicular to σ_1 do not exhibit significant regolith development. Since regolith thickness has been positively correlated with groundwater resources, it is suggested that fractures with orientations sub-parallel to the principal compressive stress direction constitute favourable groundwater targets. Knowledge of the regional stress field and fracture set orientations can be used as an effective low cost tool for locating potentially higher yielding boreholes in crystalline rock terrains.

Résumé Dans un gneiss granitique uniforme au centre du Zimbabwe composant la zone d'étude, les linéaments orientés parallèlement à la contrainte de compression régionale maximum exhibent les régolithes les plus épais, tandis que les linéaments orientés perpendiculairement à la contrainte de compression maximum montrent les régolithes altérés les moins profonds. Les orientations des principaux jeux de fractures ont été cartographiées par image satellite. Le champ de contraintes régional, estimé à partir de cartes de contraintes globales, a été utilisé pour déterminer les contraintes agissant sur l'orientation principale de chaque linéament. Des profils de résistivité multi-électrodes ont été réalisés au travers de fractures de différentes orientations pour déterminer les conditions de subsurface des régolithes. Les résultats indiquent que les linéaments à 360 et 060°, qui sont sub-parallèles à l'orientation de la contrainte de compression principale (σ_1), exhibent les régolithes aux développements les plus importants, tandis que les linéaments à 130° perpendiculaires à σ_1 n'exhibent pas de régolithes à développement particulier. Dés lors que l'épaisseur des régolithes a été positivement corrélée avec les ressources en eaux souterraines, il est probable que les fractures orientées sub-parallèlement à la direction de la contrainte principale de compression représentent des cibles favorables pour la recherche d'eau souterraine. La connaissance du champ de contraintes régional et de l'orientation des jeux de fractures peut être utilisée comme un outil peu coûteux permettant d'implanter, dans des terrains de roches cristallines, des forages à rendements potentiellement plus élevés.

Resumen En un área de estudio compuesta por neis granítico uniforme, en Zimbabwe central, los lineamientos orientados paralelos al esfuerzo compresivo regional máximo muestran el desarrollo de un regolito más espeso, mientras en los lineamientos orientados en dirección perpendicular al esfuerzo compresivo máximo, el desarrollo del regolito meteorizado es menos profundo. La orientación del conjunto de las fracturas principales se trazó usando imágenes aéreas. El campo de esfuerzos regionales, estimado a partir de los mapas de esfuerzos globales, fue usado para determinar las fuerzas que actuaron en cada orientación de lineamentos principales. Se llevó a cabo perfilaje de resistividad multi-electródica, a través de las fracturas con orientaciones diferentes, para determinar las condiciones de su regolito sub-superficial. Los resultados indican que los lineamientos de 360 y 060° que son sub-paralelos a la orientación del esfuerzo compresivo principal (σ_1), poseen un desarrollo máximo del regolito, mientras que los lineamientos de 130°, perpendiculares a σ_1, no

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muestran un desarrollo significativo del regolito. Puesto que el espesor del regolito ha sido relacionado positivamente con los recursos de agua subterránea, se sugiere que las fracturas con orientaciones sub-paralelas a la dirección de esfuerzos compresiva principal, constituyen objetivos favorables para el agua subterránea. El conocimiento del campo de esfuerzos regionales y las orientaciones de los conjuntos de fracturas, pueden usarse como una herramienta eficaz de costo bajo, para localizar perforaciones que potencialmente pueden ser altamente productivas en terrenos de rocas cristalinas.

Keywords Zimbabwe · Groundwater exploration · Fractured rocks · Stress field · Depth of weathering

Introduction

This study was carried out to ascertain the relationship between regolith thickness, and hence indirectly borehole yield, and lineament orientation in a crystalline rock terrain in central Zimbabwe (Fig. 1). The study site was selected in a largely uniform tonalite gneiss terrain in order to reduce effect of lithology as a variable.

Initially the study attempted to ascertain the statistical relationship between borehole yields and distance from lineaments and lineament orientation. A geo-referenced lineament map was constructed using Landsat TM and locally available aeromagnetic images. However, fieldwork showed that the borehole location data in the national borehole database are imprecise and that boreholes are not marked with any identification tag in the field. As a result, individual boreholes in the field cannot be identified as specific boreholes in the database. These factors make it impossible to directly assess the relationship between recorded borehole yield and distance from any lineament. For this reason, the study focussed on indirect parameters to try and determine the relationship between borehole yield potential and lineaments.

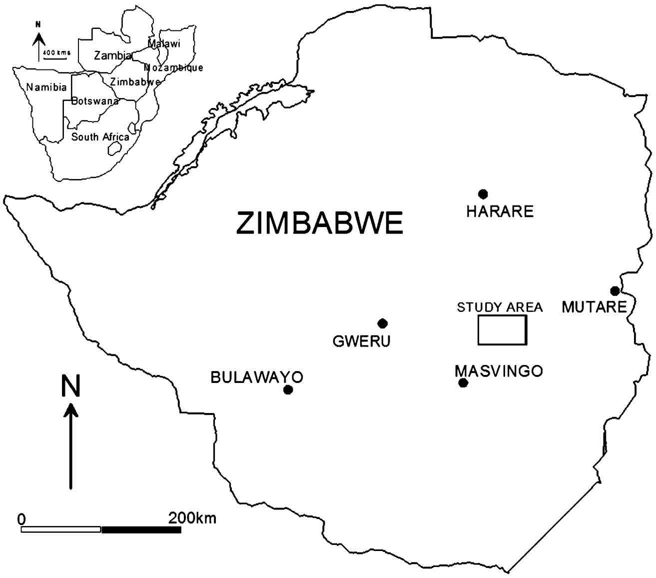

Fig. 1 Location map with southern Africa, Zimbabwe and study area. The outline of the study area in central Zimbabwe in an area of uniform granitoid gneiss geology is marked by the *box*

There are a number of indirect indicators that may be used to assess the relationship between borehole yield potential and lineaments. These include:

- Distance of borehole from any lineament or lineament intersection
- Stress state across the lineament (lineament orientation)
- Degree of regolith development (depth of weathering)
- Topography
- Lineament persistence
- Age of the erosion surface

The study gathered data on the lineament/fracture pattern, the regional stress field, the thickness of the weathered regolith and topography. These data, in particular the relationship between fracture orientation and the thickness of the weathered regolith, were then interpreted with regards to the groundwater yield potential.

As indicated in the preceding, the fracture pattern was mapped using geo-referenced Landsat TM satellite imagery and locally available aeromagnetic data. The regional stress field orientation was determined from the local stress map published by the World Stress Map project (Reinecker et al. 2005) on its web site (Fig. 2). The stress map shows the principal compressive stress orientation, determined principally from earthquake data. No data points fall within the study area, but the nearest data from Lake Kariba, southern Lake Malawi and eastern Botswana all show similar principal compressive stress orientations, suggesting that the orientation of the principal compressive stress (σ_1) in the study area is likely to be similar at approximately 045°. Using this estimate of the orientation of the principal compressive stress in the study area, the relative compressive and shear stresses can be calculated for different lineament orientations.

The depth and extent of the weathered regolith is known to be important for groundwater yields in crystalline rocks (e.g. Acworth 1987; Wright 1992; McFarlane et al. 1992; Barker et al. 1992). The weathered regolith is known to extend to greater depths in strongly fractured terrain. The upper part of the weathered regolith has a high porosity and forms the major storage component for crystalline aquifer systems, while the fractured bedrock below the weathered and altered zone forms the main high permeability zone. The depth and width of the weathered regolith across different fracture orientations has been determined using multi-electrode resistivity profiling.

The combination of the stress state across different lineament orientations and the associated depth of the weathered regolith has been the key factor in identifying lineament orientations with high groundwater potential. Topography can be a significant indicator of groundwater conditions in crystalline rock terrains (Davis and De Wiest 1966). The headwater areas of those lineaments that are under dilation or shear stress tend to be characterized by

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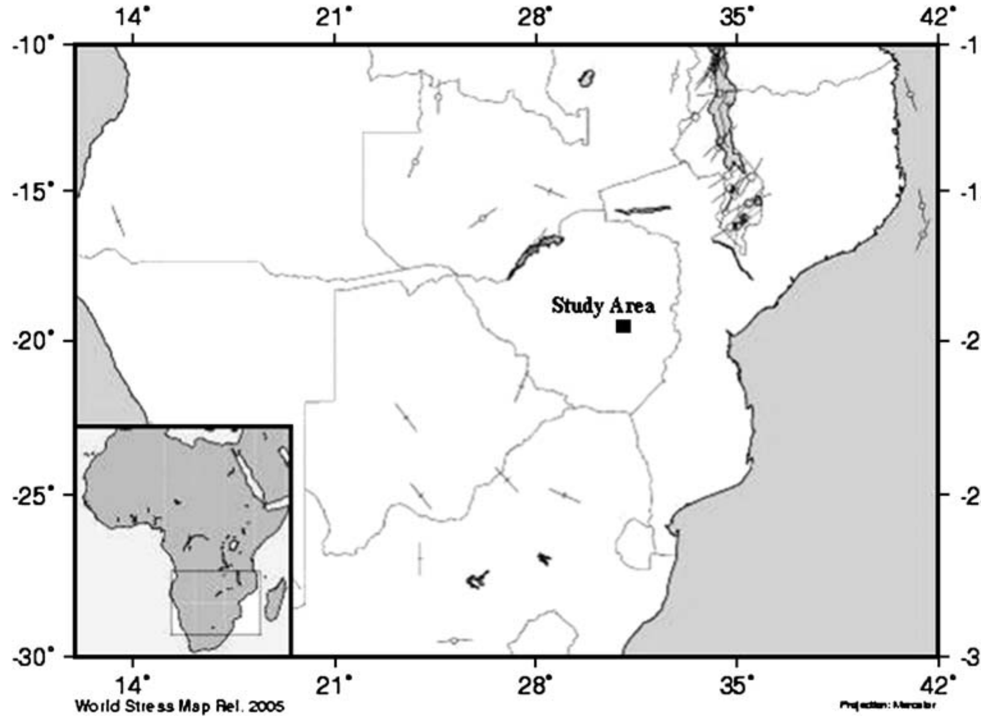

Fig. 2 Regional stress field based on the 2005 world stress map of southern Africa. The map shows a number of *short ornamented linear bars* that indicate the orientation of σ_1, the principal compressive stress, as obtained from a variety of sources. The study area is indicated by the *small square* in the centre of Zimbabwe. Although there are no stress measurements from the study site, the nearest measurements in Malawi, Botswana and Zambia (see Fig. 1) indicate a principal compressive stress orientation of NE–SW (modified from Reinecker et al. 2005)

broad open shallow, grassy dambo-type depressions with shallow water tables and seepage zones. Such broad open valley bottoms have been statistically linked with high groundwater yields. In contrast, lineaments which are under compression are generally characterized by narrow valleys with incised streams, and such incised topography has been statistically associated with lower borehole yields.

The methodology proposed here is considered to be capable of providing significant practical benefits in data-poor and resource-poor countries such as Zimbabwe. Once the regional stress field is known for any particular area, then hydrogeologists may reasonably infer that those fractures that lie parallel to the maximum compressive stress direction are likely to be under dilation and therefore potentially more favourable for groundwater development. Such an understanding has the potential to significantly reduce the time and costs involved in borehole site location and also improve the borehole success rate and median borehole yield.

Investigation methods

Since there was no possibility for a direct statistical analysis relating borehole yield to lineament orientation, the study focussed on three indirect investigation strategies. These are stress field analysis, geophysical studies of the regolith, and topographic analysis. The investigation methods were applied to each different lineament set in order to identify variations that may occur based on lineament orientation.

Stress field analysis

The lineament map (Fig. 3) reveals that there are three principal lineament orientations in the study area. Although there is quite some variation in orientation, the average orientation of the three lineament sets is approximately 360, 060 and 130°. The more persistent lineaments conform more closely to these estimated orientations, while the less persistent lineaments tend to exhibit greater variation in orientation.

As indicated above, the principal compressive stress direction (σ_1) in the study area is estimated at 045°. If one applies this σ_1 direction (45°) to the three principal lineament orientations observed, then stress resolution diagrams can be drawn for each of these orientations (Fig. 4). If an arbitrary value of 1 is used for the magnitude of σ_1, the principal compressive stress, then the relative magnitude for the shear stress and compressive stress for each lineament orientation can be calculated (Table 1). Under the present-day tectonic stresses, 060° lineaments have the lowest compressive stress and the highest shear stress values, 360° lineaments have intermediate values and 130° lineaments have the highest compressive stress and the lowest shear stress values. Theoretically those lineaments under dilation and shear stress may be expected to have higher borehole yields than lineaments under compression (Boeckh 1992). Therefore 060° lineaments may be expected to be the most favourable for groundwater and the 130° lineaments the least favourable.

Two of these fractures orientations, 060 and 130°, were identified in a gold mine approx. 150 km south-east of the

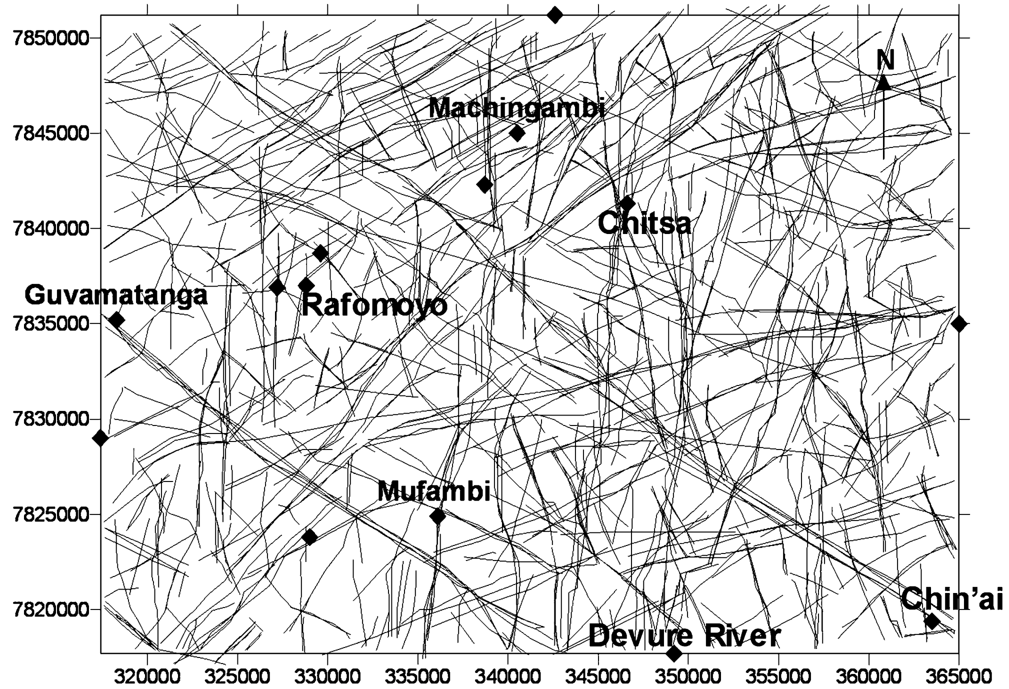

Fig. 3 The study area showing all orientations of Landsat and aeromagnetic lineaments. Apparent multiple coincident lineaments are the result of multiple lineament maps generated using different band-widths. Three principal lineament orientations are identified:- (350–010°, 045–075° and 130–140°). The locations of all the resistivity profiles are indicated by the *diamond symbols* and all localities mentioned in the text are identified. The locations of the three resistivity profiles presented in Fig. 5, Guvamatanga, Machingambi and Mufambi are shown. The grid (*UTM*) shows 5 km intervals

study area; the third fracture orientation (360°) was not observed at this mine. Underground it can be seen that the 060° fractures dip gently to moderately (10–40°) towards the east. At the two depths visited, 40 and 200 m below ground level, the 060° fractures are open and produce water, while the 130° fractures at both depths are closed and dry. This underground data appears to substantiate the assessment of stress field orientation.

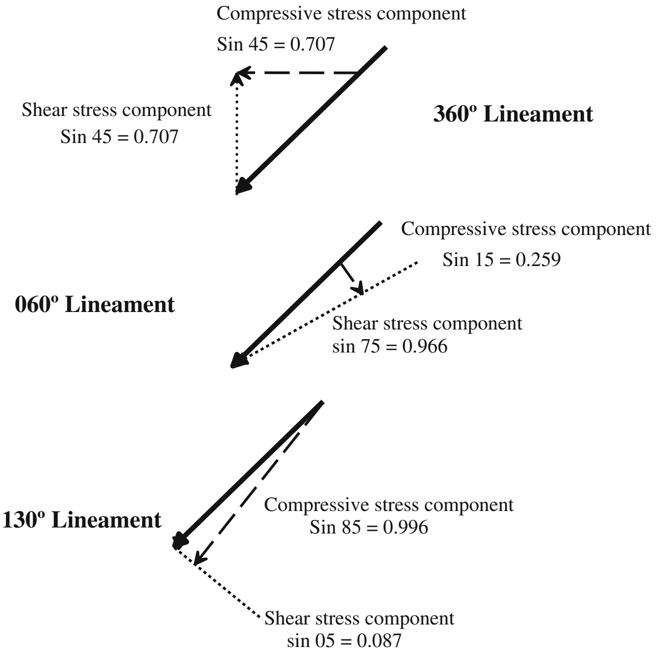

Fig. 4 Stress resolution diagrams with the regional compressive stress at 045° orientation shown as the *dark solid lines*. The relative magnitudes of the normal and shear stresses have been calculated for each of the three lineament directions. Shear stress (parallel to the lineament orientation) is indicated by the *dotted lines*, and compressive stress (perpendicular to the lineaments) by the *dashed lines*

Geophysical studies of the regolith

Multi-electrode resistivity profiling, using the Wenner electrode array with a minimum electrode spacing of 5 m, was carried out across lineaments of different orientations (Dahlin 1996). This type of resistivity profiling produces continuous two-dimensional vertical electrical pseudo-sections. The resistivity data were then inverted to produce estimations of the true resistivity of the ground along the cross section profiles (Loke et al. 2003). The resistivity profiles have been used to obtain a view of the sub-surface and in particular to observe the thickness and lateral extent of the weathered regolith across the three principal lineament orientations.

A total of twelve resistivity profiles were measured across lineaments at right angles to the lineament orientation. Four profiles were measured across 360° lineaments, three across 060° lineaments, four across 130° lineaments, while one profile was measured across a 095° lineament. The positions of these profiles are indicated on Fig. 3. Three selected representative profiles, one for each of the principal lineament orientations, are shown in Fig. 5. For hydrogeological purposes, the resistivity profiles may be broadly interpreted as saprolite (<50 Ωm), saprock (50–400 Ωm), which together constitute the weathered regolith, and fresh bedrock (>400 Ωm).

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Table 1 Relative stress resolution magnitude for the three lineament orientations

Lineament orientation	Relative compressive stress	Relative shear stress
360°	0.707	0.707
060°	0.259	0.966
130°	0.996	0.087

Resistivity profiles across the 130° lineaments show very shallow depths to fresh rock, which occurs near or at the surface. The maximum depth of weathering is only about 15 m. The resistivity profiles across the 360 and the 060° lineaments show a zone of much deeper and wider weathering, with the weathered regolith extending to depths in excess of 50 m.

These regolith configurations are expected from the resolved stress field on each lineament orientation. The two lineaments with higher shear stress and lower compressional stress components, 360° (Mufambi) and 060° (Machingambi), exhibit a thick and laterally extensive weathered regolith, while the lineament under compression (130°: Guvamatanga) exhibits minimal development of the regolith. Since all these resistivity profiles have been measured over tonalite gneiss with similar rock material resistivity values, comparison between the profiles is considered to be valid.

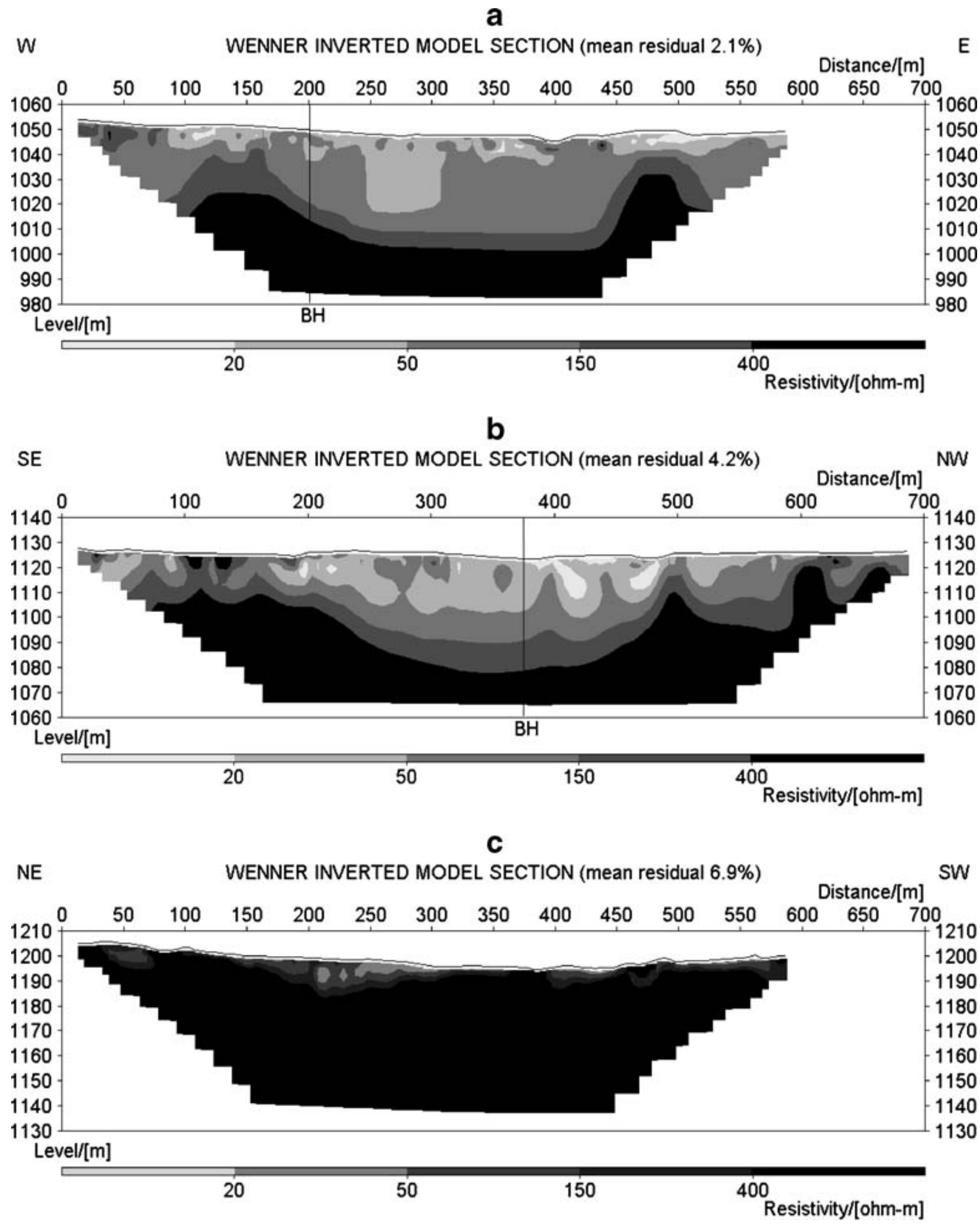

Fig. 5 Resistivity sections showing depth of weathering for the different directions. **a** Mufambi Profile: 360° lineament (shear stress); regolith extensively developed; borehole at 200 m. **b** Machingambi Profile: 060° lineament (shear stress); extensively developed weathered regolith; borehole at 375 m. **c** Guvamatanga Profile: 130° lineament (compressive stress); very shallow regolith development; no borehole

The other measured resistivity profiles exhibit a similar pattern, with thick regolith development observed in profiles measured over 360 and 060° lineaments—e.g.: Rafomoyo (040°) and Chitsa (360°)—while shallow regolith is observed in the profiles measured across the 130° lineaments,e.g. Devure River (160°).

For the lineaments under compression, the weathering front cannot advance deeply due to the inability of groundwater to penetrate into the tightly closed fractures. By contrast, fractures under dilation or shear stress allow groundwater to penetrate deeply, resulting in deep extensive weathering (Boeckh 1992). The resistivity profiles measured across the three principal lineament orientations support the assumption that the 130° lineaments are under compression, and the 060 and 360° lineaments are under dilation and shear stresses.

Acworth (1987) has linked regolith development to groundwater potential. The upper "saprolite" zone of the regolith has high porosity values and provides a reservoir zone to store groundwater. The lower "saprock" zone of the regolith has a low porosity but has high permeability, providing a conduit zone for groundwater flow. The importance of a thick, well-developed regolith for both groundwater storage and groundwater flow has been acknowledged by other authors who have concurred with Acworth's observations (e.g. Wright 1992; Barker et al. 1992 etc.).

The resistivity data for the 360 and 060° lineaments therefore strongly suggests that these lineaments are highly favourable groundwater targets, while the 130° lineaments exhibit very limited regolith development and may be poor groundwater targets. It should nevertheless be borne in mind that any lineament, regardless of its orientation, would tend to improve groundwater yields as compared to unfractured ground.

Topographic profiles

Field observations and the topographic cross sections (Fig. 6) show that the lineaments under the least compressive stress (060 and 360°) have the most open valley profiles, frequently without an incised defined stream channel in the headwater reaches. By contrast, the 130° lineaments, under compressive stress, have more incised valley profiles, often with a defined stream channel in the valley floor. Incision ratios have been developed for the three resistivity profiles presented above in the section on resistivity profiling.

The valley profiles may be hypothetically linked to the calculated stress fields across the different lineaments. The higher the relative compressive stress across the lineament, the more incised the valley cross-section profile. Since the 130° lineaments are under compression, these fractures are expected to be tightly closed and less able to absorb infiltrating groundwater. The rejected infiltration becomes surface run-off, and therefore these lineament valleys host streams. The resultant higher surface runoff component results in a greater degree of surface erosion and leads to valley incision. The two other lineament orientations (060 and 360°) are under dilation and are therefore likely to have open fractures which favour infiltration hence reducing surface runoff and promoting deeper weathering. The reduced runoff component reduces the degree of surface erosion and valley incision. This promotes gentle open valley profiles with shallow

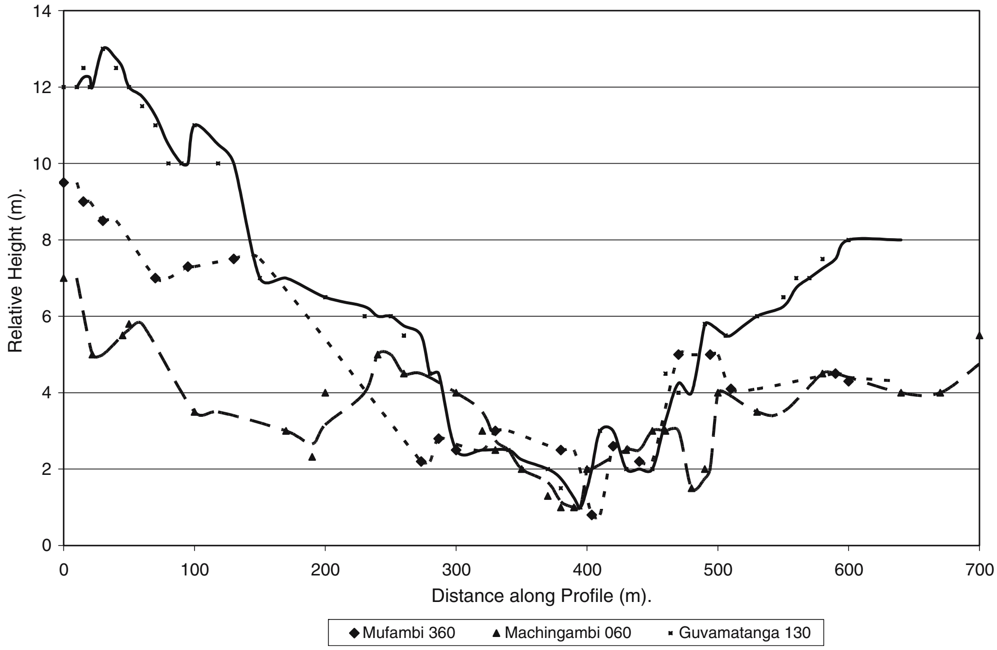

Fig. 6 Valley topographic profiles across three different lineament orientations. Incision ratios (valley width to depth ratios for the first 4 m height) are calculated for each profile. Compressive stress results in steeper incised valleys, while extensional stress gives rise to broad open gentle valleys. 360 profile: from 200–600 m (open at 600 m): width/height ratio 100:1—profile under intermediate compressive stress. This profile is open at the eastern end. 060 profile: from 50–700 m: width/height ratio 175:1—profile under lowest compressive stress. 130 profile: from 275–475 m: width/height ratio 50:1—profile under maximum compressive stress

groundwater occurring over a wide area. However, in contrast, it should also be noted that in the valleys under dilation, the deeply weathered material will be more easily eroded, therefore promoting incision.

Slug tests

Slug tests were carried out on three boreholes, each located in valleys that overlie three lineaments of different orientations. Using the existing hand-pumps on these boreholes, water has been pumped out and the recovery rate has been monitored with a dip-meter and stopwatch. Analyses have been performed using the Bouwer-Rice method in Aquifer Test 3.5. The results from the slug tests are shown in Table 2.

It is noted that slug tests have only been carried out on three boreholes; one for each of the principal lineament orientations. Clearly this is insufficient data to adequately assess the relationship between lineaments orientations and borehole yield as expressed by hydraulic conductivity measured from the slug tests. It is accepted that the limited slug test data will not prove conclusive.

The rationale behind the limited number of slug tests lies in the lack of specific borehole information. Individual boreholes cannot be identified in the field and therefore it is not easily possible to determine the formations penetrated, the borehole completion data, borehole depth, casing and screening installed etc. Given the complexity of the regolith development and the partition of the regolith into low-permeability shallow saprolite and higher-permeability deeper saprock, it is considered that slug testing in the absence of supportive borehole information can be highly misleading.

The slug test results show that the highest hydraulic conductivity occurs over the 360° lineament (Mufambi), while the 060° lineament (Machingambi) and the 130° lineament (Chin'ai) have similar low hydraulic conductivities. However, the borehole on the 060° lineament has a higher transmissivity than the 130° lineament, due to the greater aquifer thickness along this fracture orientation. Table 2 also indicates the specific capacity for boreholes on each of the three lineament orientations as calculated from published nomograms for the tonalite gneiss in Zimbabwe (Interconsult 1987).

It is noted that the calculated hydraulic conductivity value for the 060° lineament is lower than the calculated hydraulic conductivity value for the 360° lineament. Figure 5 shows the position of these two boreholes along their respective resistivity profiles. The 060° Machingambi borehole penetrates more than 20 m of weathered clay "saprolite" regolith with resistivity values lower than 50 Ωm, and this material is expected to have a low hydraulic conductivity. The Mufambi borehole, by contrast, penetrates mostly fractured "saprock" regolith with resistivity values between 50 and 150 Ωm, which tends to have a higher hydraulic conductivity. This may be used to explain the difference in the hydraulic conductivity values calculated from the slug tests, but it is accepted that there are many diverse factors that exert some control on borehole yields.

Discussion and conclusions

In the study area, three principal fracture orientations were identified; 360, 060 and 130°. The regional stress field has an assumed maximum compressive stress (σ_1) orientation of approximately 045°. Lineaments sub-parallel to this σ_1 orientation are presumed to be under dilation while lineaments perpendicular to this orientation are presumed to be under compression.

Multi-electrode resistivity profiling across fractures of different orientations indicate that lineaments under compression tend to have a minimum regolith development, while lineaments with a higher shear/dilation stress component tend to have a maximum regolith development. Several authors (e.g. Acworth 1987) have linked regolith development and regolith thickness in crystalline rocks to groundwater potential. However, limited slug testing carried out on boreholes located on different orientation lineaments was inconclusive.

Topographic profiles across the different orientation lineaments indicate that those lineaments under compression are characterized by incised valley cross section profiles, while those lineaments under shear stress are characterized by gentle open valley profiles. The technique of using satellite imagery to map the fracture pattern and freely available regional stress data from global datasets to determine the stress state across the principal fracture orientations appears to be a cheap and practical method for identifying those lineament orientations that are likely to be more deeply weathered and hence more productive with respect to groundwater resource development in crystalline rock terrains.

The stress field may change through geological time and it can therefore be anticipated that a lineament orientation that is presently under compression may have been under dilation or shear stress at some time in the past. This suggests that the methodology proposed here will be valid only in younger geological terrains that have undergone just one deformational event. However, a conceptual analysis of

Table 2 Slug test for 3 boreholes

BH locality and lineament orientation	T (m^2/day)	K (m/day)	Depth (m)	Specific capacity Qs (m^3/day/m)
Mufambi (360°)	62.3	1.78	35	70
Machingambi (060°)	27.0	0.600	45	42
Chin'ai (130°)	12.2	0.448	25	20

The following correspond to different daily pumping rates: *T* transmissivity; *Average K* hydraulic conductivity; *Qs* specific capacity; and *s* drawdown the proposal reveals that the effect of a change in the orientation of the regional stress field will result in changes to the stresses acting across fracture apertures of the various lineament orientations. Fractures that were formerly open under dilation will become closed under compression and vice versa. This in turn will control the infiltration–surface runoff partition and hence the depth and extent of weathering and the degree of erosion and incision of the valley profiles. These are the factors that control the thickness of the preserved regolith and hence the groundwater potential of the various fracture orientations. This suggests that the past tectonic history may be overprinted by more recent events, and that the groundwater potential may be estimated from the relationship between the present day stress field and the fracture orientation.

This methodology presented does not include sufficient borehole testing by either pump or slug testing and hence cannot definitively conclude that the method is successful. The method also relies on stress data that may have been measured from distant sites, as in this case, and hence may not account for local, possibly highly significant, stress field variations. The information presented here represents a single sample of three fractures with different orientations, and the methodology needs to be verified against more comprehensive data sets, including hydraulic testing.

In borehole development programmes in crystalline terrains, it is recommended that the regional field stress state should be ascertained from global data sets and the fracture pattern should be mapped from satellite imagery. Those fracture orientations that theoretically are under minimum compressive stress may be identified and this information may be readily factored into the groundwater exploration strategy.

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