# Aeromagnetic and Landsat TM structural interpretation for identifying regional groundwater exploration targets, south-central Zimbabwe Craton

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ABSTRACT

Aeromagnetic (AM) and Landsat Thematic Mapper (TM) data from the south-central Zimbabwe Craton have been processed for the purpose of regional structural mapping and thereby to develop strategic models for groundwater exploration in hard-rock areas. The lineament density is greater on TM than on AM images, partly due to the resolution of the different datasets, and also because not all TM lineaments have a magnetic signature. The derived maps reveal several previously undetected lineaments corresponding to dykes, faults, shear zones and/or tectonically-related joints, striking predominantly NNE, NNW and WNW. We suggest the possible hydrogeological significance of some of these patterns as follows: the aeromagnetic data can be used to map faults and fractures of considerable depth which are likely to be open groundwater conduits at depth (typically under tension), while TM lineaments, although not necessarily open (mostly under compression), represent recharge areas.

The interpreted persistent lineation and well developed fracture patterns are correlated with existing boreholes and indicate a spatial relationship between regional structures and high borehole yields (>3 $m^3/h$). This relationship is combined with other lithological and hydrogeological information to identify potential regional groundwater sites for detailed ground investigations. These are defined as dyke margins, faults, fractures/joints or intersections of any combination of these structures. Priority should be given to coincident AM/TM lineaments (e.g., NNW and NNE fractures) and continuous structures with large catchment areas (e.g., NNE and WNW faults). The late Archaean (2.6 Ga) granites are considered the most favourable unit because of their associated long and deep brittle fractures between numerous bornhardts (inselbergs) and kopjes. Several small-scale TM lineaments also form important local sources of groundwater for hand-dug wells. Based on measured rock susceptibilities from the area, we present a model of the typical magnetic responses from the possible groundwater exploration targets. The developed magnetic model could be applicable to similar terrains in other Archaean Cratons.



## 1. Introduction

It is now generally known that crystalline basement terrains lack primary permeability and porosity, and are therefore usually considered to have poor groundwater potential (e.g., UNESCO, 1984; CSC, 1989; Wright and Burgess, 1992; Saraf and Choudhury, 1998; Saraf et al., 2004; Yadav and Singh, 2007). However, exploitable groundwater in these hard-rocks may occur due to the development of secondary permeability and porosity; mainly in faults, fractures, dyke contacts and deeply weathered zones (e.g., Clark, 1985; Jones, 1985; Acworth, 1987; McFarlane, 1990; Wright and Burgess, 1992; Owen and Maziti, 2003; Porsani et al., 2005; Sharma and Baranwal, 2005; Yadav and Singh, 2007). Various geological conditions or processes involving magnetite creation and/or destruction make most of these features easily distinguishable by means of aeromagnetic (AM) surveys (cf. Henkel and Guzman, 1977; Grant, 1985; Schwarz et al., 1987; Astier and Paterson, 1989). Also, the mineralogical and/or petrological differences and metamorphic conditions of the geological units not only affect susceptibility but also give different visible and infrared spectral reflectances which can be identified on Landsat Thematic Mapper (TM) images. However, it should be noted that not all satellite imagery lineaments will have a magnetic signature. Research in the last two decades has shown that the use of AM and TM data for regional structural mapping before ground (geophysical) surveys are undertaken results in significant borehole success rates and increased yields (e.g., Astier and Paterson, 1989; Zeil et al., 1991; Boeckh, 1992; Koosimile, 1992; Ranganai and Zeil, 1995; Drury et al., 2001; Srivastava and Bhattacharya, 2006). More recently, the main emphasis is the synergetic use of remote sensing data and related

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datasets in conjunction with geographic information systems (GIS) techniques (e.g., Saraf and Choudhury, 1998; Owen et al., 2002; Saraf et al., 2004; Frei et al., 2006; Srivastava and Bhattacharya, 2006).

The present study, which extends that of Ranganai (1996), has involved the use of available regional AM and high resolution TM data (both as separate sets and jointly in a GIS) in developing strategic models for groundwater exploration in the granite–greenstone terrain of south-central Zimbabwe. Although borehole siting and drilling projects are continuously and currently underway in the study area and elsewhere in the country, the approach is purely empirical, being aimed at providing water supplies where and when required. This has inevitably resulted in poor borehole success rates (e.g., Houston and Lewis, 1988). In order to support both domestic consumption and income-generating rural agro-projects, boreholes of sustainable yields are needed (e.g., Boeckh, 1992; Rao, 2003). A systematic and scientifically based regional analysis of groundwater exploration targets using modern techniques is therefore required. The objectives of this paper are to 1) employ enhanced AM and TM data in lineament interpretation; 2) explain the lineament patterns in terms of geology; 3) define groundwater targets of regional importance; and 4) model the typical magnetic responses of these targets. The interpreted lineaments and fracture patterns are correlated with existing boreholes to study the relationship between the lineaments and borehole yields. These relationships are then used, in combination with other lithological and hydrogeological information, to identify potential groundwater sites for detailed ground investigations. The approach taken in a part of the crystalline basement of Zimbabwe may be useful in other parts of central and southern Africa where geological conditions are similar.

## 2. Regional geology and hydrogeology

The study area is the south-central part of the Archaean Zimbabwe Craton and lies between latitudes 19.9°S and 21.1°S and longitudes 28.9°E and 30.5°E, with several rural service centres and mining towns located throughout the area (Fig. 1). A relatively detailed description of the regional geology and tectonic setting can be found elsewhere (e.g., Greenbaum, 1992a; Wilson et al., 1995; Campbell et al., 1992; Jelsma et al., 1996; Jelsma and Dirks, 2002) and only aspects relevant to aeromagnetic interpretation and groundwater exploration are presented here. Topography can be a significant indicator of groundwater conditions in crystalline rock terrains (e.g., McFarlane, 1990; Drury et al., 2001; Owen et al., 2002; Owen and Maziti, 2003; Saraf et al., 2004), and therefore this factor is also included in the geology summary below.

The area is mainly underlain by Archaean basement gneisses and tonalites (3.5–3.0 Ga) that tend to form rather flat featureless country, with a number of greenstone belts (2.9–2.7 Ga) forming the main supracrustal rocks and a less regular terrain. The latter are characterised by a sequence of ultramafic, mafic, felsic and volcanic–sedimentary assemblages, mainly with greenschist facies metamorphism. The area is locally intruded by late Archaean granites (~2.6 Ga), ultramafic complexes, the ~2.5 Ga Great Dyke and its satellites, and Proterozoic dykes and sills (Fig. 1). The intrusive massive

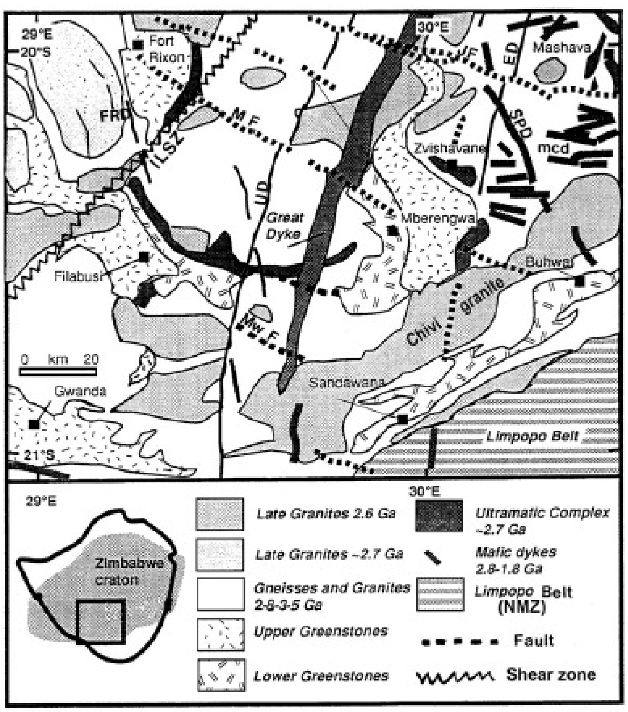


Fig. 1. Simplified regional geology of study area (After Ranganai, 1995). Main features discussed in text (Section 3.3) are labelled: FRD = Fort Rixon dykes, ILSZ = Irrisvale–Lancaster shear zone; MF = Mchingwe fault, JF = Jenya fault, MCD = Mashava Chivi dykes, ED = East dyke, UD = Umvimeela dyke, SPD = Sebanga Poort dyke. Greenstone belts named after labelled towns (e.g., Mberengwa greenstone belt). Index map shows study area (box) within the Zimbabwe Craton.

and pophyritic granites outcrop as high, bare, rocky hills and ridges, with the development of exfoliated bornhardts (inselbergs) as well as rectangularly-jointed castle kopjes containing some of the highest points in the area (e.g., Bickle and Nisbet, 1993). Large masses of (~2.7 Ga) tonalite–trondjhemite–granitoids (TTG) also occur; they are intermediate between gneissic granite and the true intrusive granites, and show characteristics of both. Granulite facies rocks of the North Marginal Zone (NMZ) of the Archaean Limpopo Orogenic Belt transect the southeastern corner of the study area. The NMZ mainly comprises paragneisses containing several mafic and ultramafic intrusions (Rollinson and Blenkinsop, 1995). The area has been strongly influenced by brittle deformation and three major structural directions have been identified and discussed by Wilson (1990) and Campbell et al. (1992). The oldest direction is ENE (060°), parallel to the fabric of the NMZ and may record the northward thrusting of the NMZ onto the Zimbabwe Craton. The other two dominant directions are NNE (Great Dyke and satellites trend) and NW–WNW (Proterozoic mafic dykes and major faults) (Fig. 1). For example, the WNW-trending Mchingwe fault (MF, Fig. 1) is a major brittle–ductile to brittle fault zone which can be traced for almost 125 km, transecting the northern half of the study area (Campbell and Pitfield, 1994; Fig. 1).

Due to their economic importance as hosts of various mineral deposits, most of the greenstone belts have been carefully mapped in terms of structure, stratigraphy and lithology (e.g., Bickle and Nisbet, 1993; Campbell and Pitfield, 1994). On the other hand, the gneisses, tonalites and granites, altogether covering over sixty percent of the study area, are relatively poorly mapped. Previous hydrogeological studies have also suggested that these rocks have poor groundwater development potential due to their low permeability (e.g., DWD, 1985). By virtue of their areal extent and high population density however, the granitoids form the most important hydrogeological unit in the area. Exploitable groundwater in such impermeable, hard-rock areas is almost exclusively confined to faults, fractures, dyke contacts and weathered zones (e.g., UNESCO, 1984; Clark, 1985; Jones, 1985; Acworth, 1987; CSC, 1989; McFarlane, 1990; Wright and Burgess, 1992; Owen and Maziti, 2003; Porsani et al., 2005; Sharma and Baranwal, 2005; Yadav and Singh, 2007).

The present studies can provide such structural information and further identify deeply weathered zones which facilitate groundwater movement and ensure sustainable borehole yields. For example, water presence enhances magnetite destruction and therefore water-saturated fractures are expected to have low magnetic signatures (e.g., Henkel and Guzman, 1977; Astier and Paterson, 1989; Koosimile, 1992; Ranganai and Zeil, 1995; Owen et al., 2002). Similarly, edges of areas of (deep) weathering or thick regolith often occur over extensively fractured basement and appear as areas or zones of low

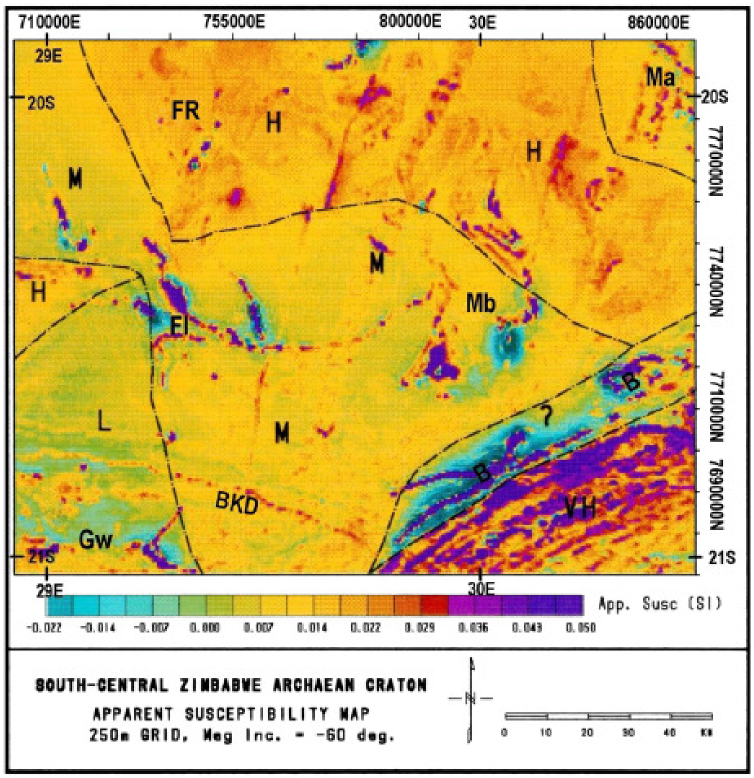


Fig. 2. Apparent susceptibility map of the study area showing different 'magnetic zones' as weathering zones. Greenstone belts: B = Bulwa, Fi = Filabusi, FR = Fort Rixon, Gw = Gwanda and Mb = Mberengwa; other units: BKD = Botswana Karoo dykes; Ma = Mashava ultramafic complex. Magnetic zones (L = low signatures; M = medium, over predominantly late granites; H = high, encompassing mainly old tonalitic gneisses normally expected to have low values due to weathering, and VH = very high signatures, over granulitic gneisses of the North Marginal Zone, Limpopo orogenic belt). Major dykes and ultramafic complexes (e.g., BKD, Ma) stand out as high susceptibility units.

susceptibility (e.g., Koosimile, 1992; Ranganai, 1995; Ranganai et al., 2003). On appropriate TM band composites, vegetation patterns and vigour are diagnostic of soil moisture and water-saturated fractures, while distinct tones may reflect weathered zones (e.g., Greenbaum, 1985, 1992b; Boeckh, 1992; Drury, 1993). In summary, it is clear that conditions favourable for borehole and well sites are associated with extensive fracturing and development of thick permeable regolith. The thickness of the regolith appears to be a critical factor which controls recharge processes (Jones, 1985; Acworth, 1987; Gieske, 1992; Saraf et al., 2004). Since the thickness and permeability of the regolith is partly determined by bedrock lithology and structure, the primary purpose of aeromagnetics and Landsat TM in groundwater exploration is to aid in the lithologic and structural mapping of bedrock.

## 3. Data processing and interpretation

The use of AM and TM in geological mapping and mineral exploration is well established and reported in the literature while reports on its application in groundwater is not that easily available, especially in Africa (e.g., Frei et al., 2006). Fortunately, the processing and presentation techniques are generally similar (e.g., Reeves and Zeil, 1990; Milligan and Gunn, 1997). There are therefore numerous digital processing techniques which could be employed to enhance the AM and TM datasets for maximum extraction and display of the required lithologic and structural information (e.g., Kowalik and Glen, 1987; Reeves and Zeil, 1990; Reeves et al., 1997). A summary of some of the processing techniques applied is given below and more details can be found in various texts (e.g., Drury, 1993; Blakely, 1995).

### 3.1. Aeromagnetic data processing

The aeromagnetic data used were obtained from the Zimbabwe Geological Survey (ZGS) and are based on 1 km spaced flight lines with 305 m flight altitude. The data were first gridded in the UTM co-ordinate system at 250 m cell size using a bilinear algorithm. They were then reduced to the pole to correct for the effect of the magnetic inclination. For purely induced magnetisation, or minimal remanent magnetisation, reduction to the pole (RTP) shifts the anomalies to lie directly over the sources, thus producing anomaly maps that can be more readily correlated to the surface geology (Blakely, 1995). The Geosoft algorithms used to calculate the RTP caters for both high and low magnetic latitudes (−60 in the study area). The RTP grid was then analysed by the application of frequency domain digital filter operators and enhancement techniques, in particular apparent susceptibility calculation, vertical and horizontal derivatives, and shaded relief imaging (e.g., Blakely, 1995). In apparent susceptibility, the sources of the continuous potential field are modelled as an approximation to the distribution of susceptibility in the ground (e.g., Letros et al., 1983), thereby giving an indication of geology (cf. Figs. 1 and 2). It reduces anomaly overlap because a regional field has been removed and the

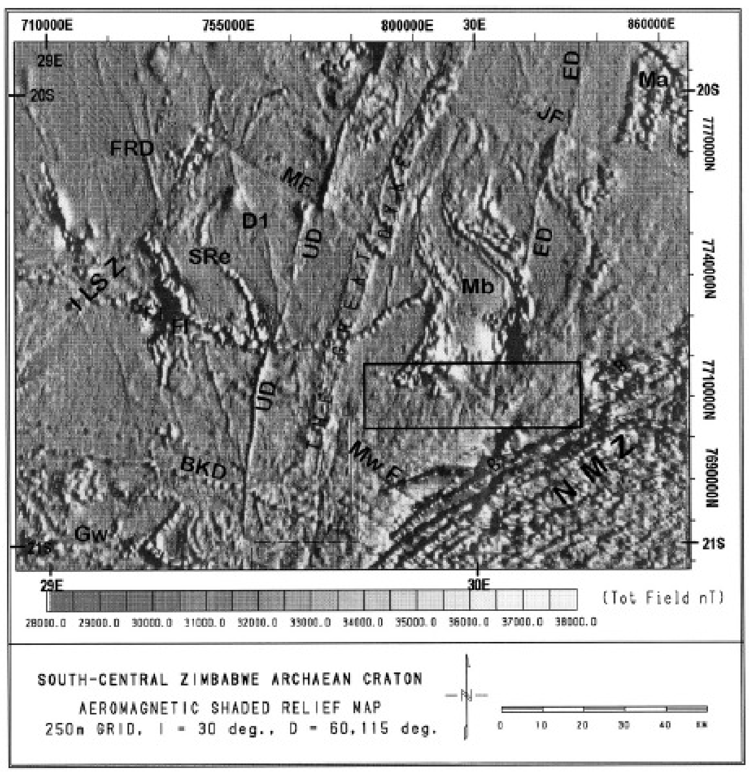


Fig. 3. Aeromagnetic shaded relief image: Inclination = 35, Declination = 45 and 115 (two illumination angles are used to enhance structures at many orientations). Structural features labelled are discussed in text (Sections 3.3 and 4): D1 = dyke; SRe = Shamba (ultramafic) range extension, MwF = Mwenezi fault; other labels as in Figs. 1 and 2). Note the dominance of NNW (FRD dyke) and NNE (Great Dyke) dyke trends and NW to WNW fault directions. Rectangle shows the area covered by Fig. 6a.

data are downward continued; thus allowing easy location of contacts between rocks of different susceptibility (i.e. lithological mapping). However the contribution of remanent magnetisation is ignored in this calculation. Derivatives enhance short wavelength anomalies while suppressing long wavelength components caused by deep-seated features, allowing more accurate lithological contact and edge-detection. This is particularly useful in determining the existence and location of steeply dipping boundaries of igneous intrusive bodies in the crystalline basement such as in the study area (e.g., Thurston and Brown, 1994). Further, the results of the process of first vertical derivation give a better resolution of closely spaced magnetic sources such as dykes, with a zero intensity level expected over the boundaries of steeply dipping bodies (e.g., Hood, 1965; Blakely, 1995).

In shaded relief imaging, the aeromagnetic data are treated as topography illuminated from different directions by an artificial light source, thus accentuating some of the finer details perpendicular to the illumination direction (Fig. 3; e.g., Kowalik and Glen, 1987; Broome, 1990). This is particularly useful for enhancing linear, low amplitude short wavelength anomalies. Combined colour–shadow maps are also effective as they contain information on both anomaly amplitude (colour) and anomaly gradient (relief), the latter also related to the depth of burial of the causative structures (e.g., Reeves et al., 1997).

### *3.2. Landsat TM data processing*

The Landsat data used are from TM Scene 170/74 of 25 July 1990 (e.g., Fig. 4) and were obtained from the British Geological Survey (BGS) as bands 1, 4, 5 and 7. The images were geo-referenced onto the UTM co-ordinate system for direct comparison with geological and aeromagnetic maps. The selected bands (1, 4, 5 and 7) have the following characteristics, all of which are of direct or potential relevance to groundwater: B1 belongs to the visible blue, B4 has strong reflectance from green vegetation, B5 responses to soil tones and moisture, and B7 contains information on the geology (lithology/structure) and has moderate reflectance from soils (e.g., Greenbaum, 1985, 1992b; Drury, 1993). Two 1:250 000 scale prints of Band 5 in grey scale and a 471 (RGB) false colour composite were selected as the best representation of both structural and lithological information, respectively (Fig. 4). The latter combination also contains information related to both vegetation and soil types.

The 471 band combination with well separated wavelengths was also selected to avoid interband correlation which often produces muted colour images (cf. Hunt et al., 1986). The scale was considered appropriate for a synoptic view of the area while the grey scale representation is intended to highlight structural features. This is because for structural and tectonic interpretation, the eye operates most effectively in black and white (Drury, 1993); something equivalent to the shaded relief presentation used in aeromagnetic data. On the other hand, spectral response is as important as high frequency spatial information for lithological discrimination and contact mapping, and a colour image is appropriate in this case. In order to enhance subtle spectral-reflectivity differences, the images were contrast stretched and edge enhanced before prints were made at various scales. Contrast stretching involves expanding pixel values so as to maximize the range of grey values, thus effectively minimising correlation between bands. Edge enhancement was achieved by high pass filtering in order to emphasize high spatial frequencies useful for lineament mapping.

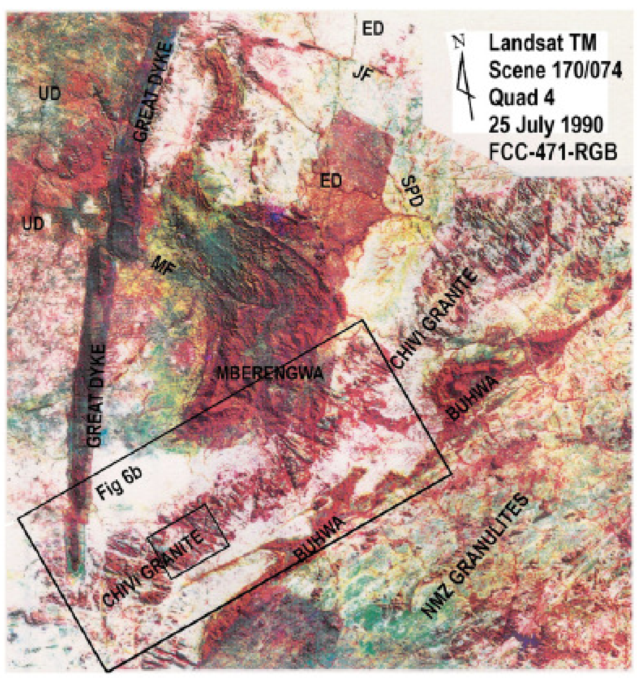


Fig. 4. Landsat TM false colour composite using bands 471 (RGB) suitably edge enhanced and contrast stretched (after Greenbaum, 1992b). Image only covers eastern half of study area encompassing the Great Dyke, the Mberengwa greenstone belt and the post-volcanic (2.6 Ga) Chivi granite (see Fig. 1). Other geological units labelled for reference purposes as in Fig. 1. Note the strong ~NW and ~NNE-striking lineaments and jointing in the granite pluton, interpreted as good recharge zones/areas. Rectangles show the areas covered by Figs. 5 and 6b.

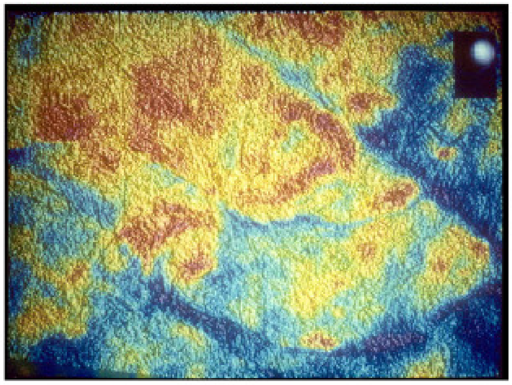

Fig. 5. Screen-shot (~50 km by 35 km) of co-registered Landsat TM (band 5 — grey scale) and aeromagnetic image (colour) of part of the Chivi granite (see Fig. 4 for location). Red and blue tones represent high and low magnetic signatures, respectively. The intensity, hue and saturation (IHS) transform that integrates the TM and AM data uses the higher resolution (30 m) TM data (Band 5) as the intensity component with the lower resolution (250 m) AM data as input to the IHS. Effectively, the TM data provide a black and white (shaded relief) image on top of which colour-contoured magnetic data are draped.

### 3.3. Interpretation

The interpretation of the data and/or images was guided by printed colour maps at various scales and 'on screen' displays with higher resolution than figures presented (e.g., Figs. 3 and 4). The two datasets were first interpreted separately and later jointly through an intensity, hue and saturation (IHS) or hue, saturation and value (HSV) transform that integrates TM and AM data in one image (e.g., Fig. 5; Milligan and Gunn, 1997). The most useful aeromagnetic products for structural aspects, particularly positions of anomalous features, e.g., faults, dykes and lithological boundaries, are derivative and shaded relief maps (e.g., Fig. 3) which enhance short wavelength anomalies related to relatively shallow features important for groundwater evaluation (<100 m, Ranganai, 1995, 1999; typical borehole depths range is 50–80 m (e.g., Houston and Lewis, 1988; Owen et al., 2002)). Discontinuities and displacements of linear features are also clear on contour maps (not shown). 3D Euler deconvolution has been applied to estimate and/or confirm the type, location and depths of the interpreted structures (e.g., Ranganai, 1999). On the other hand, apparent susceptibility maps (Fig. 2) have been used to identify areas with a potential for deep weathering or thick permeable regolith, as well as other alteration zones.

The lineament density is greater on TM images than on the aeromagnetic images, partly due to the resolution of the different datasets (30 m and 250 m, respectively) and also due to the fact that the methods respond to different physical properties of the geological units and features. For example, tholeeitic dykes tend to contain a high silica content and are therefore non-magnetic (e.g., Schwarz et al., 1987), but at the same time resistant to erosion and readily identified on TM images. Lineament maps were constructed by on screen digitising of each fracture direction for several images and only the better developed lineaments are shown (i.e., persistent lineaments of regional extent appearing in many images); particularly recognising that not all TM lineaments have a magnetic signature. The combined interpretation of enhanced aeromagnetic and geo-referenced TM images (e.g., Fig. 5) allowed subtle anomaly patterns to be identified and traced with much greater certainty than in one dataset alone (e.g., Kowalik and Glen, 1987; Zeil et al., 1991). These data reveal the presence of several previously undetected regional lineaments cutting across the study area (~100 km; e.g., Figs. 3 to 6). Correlates of these new features have been confirmed in the field about 20 km to the east, corresponding to dykes, faults, shear

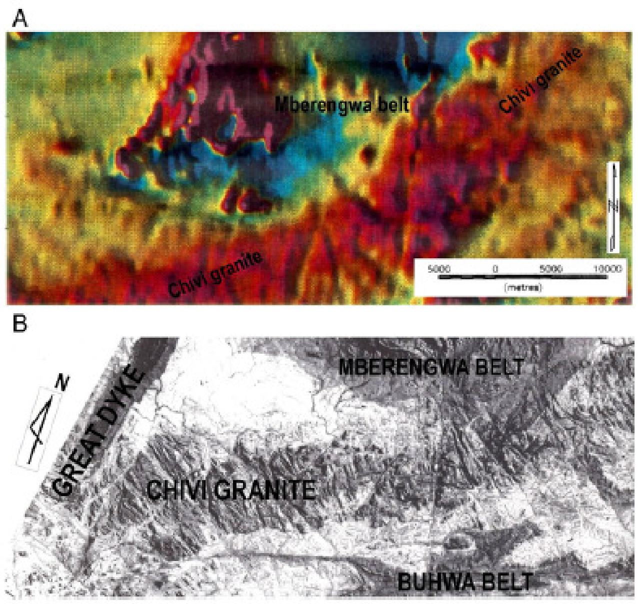


Fig. 6. Aeromagnetic (A) and Landsat (B) lineaments in the Chivi (post-volcanic) pluton, illustrating coincident AM and TM structures (see Figs. 3 and 4 for location). Note the length and width of the fractures, as well as the density of lineaments, characteristics considered favourable for groundwater targets.

**Table 1**
Major aeromagnetic and Landsat TM structural trends: geological interpretation/association and groundwater potential (see Figs. 1, 3 and 7)

| Trend/direction | Type of feature (aeromagnetic – AM; Landsat imagery – TM) | Associated craton tectonic event and timing/age (Wilson, 1990; Campbell et al., 1992; Ranganai, 1995) | Groundwater potential |
|---|---|---|---|
| EW to ESE | AM – dykes (Botswana Karoo dyke swarm) | Gondwana break-up: 170–200 Ma (extensional event) – *Dilation?* | Low/medium |
| ENE/WSW | AM – dykes (Limpopo dyke swarm) | Karoo Igneous event: 170–200 Ma (extensional event) – *Shear stress* | Low/medium |
| | AM/TM – ultramafic/iron formation horizons | Limpopo orogenic belt: 2.65 Ga (collisional event) – *Shear stress* | Low |
| NNW/SSE | AM/TM – dykes (FRD, SPD; Figs. 1 and 3) | Mashonaland Igneous Event: 1.8–2.0 Ga (extensional event) – *Compression?* | Medium/high (weathering) |
| NW to WNW | AM/TM – faults (MF, JF, MwF; Figs. 1 and 3) | Dextral shear couple acting on craton: ~2.0 Ga (under –*Compression*) | Medium/high (brittle) |
| NNE/SSW | AM/TM – dykes, faults and fractures (ED, UD) | Great Dyke Fracture System: 2.5 Ga (Under *Shear stress*) | High |

zones and/or tectonically-related joints (Greenbaum et al., 1993; Ranganai, 1995). Furthermore, numerous NNE- and NNW-trending fractures that are a few km to tens of km long can be identified on Landsat TM imagery, particularly in the late Archaean Chilimanzi suite plutons (e.g., Chivi granite, Figs. 4 and 6). Some of these fractures appear as short wavelength aeromagnetic anomalies (e.g., Figs. 3 and 6a) which represent shallow sources (<100 m; Ranganai, 1995, 1999). This is important for groundwater prospects as deeper fractures tend to be closed due to compressive forces from overlying rocks. Overall, five major structural trends can be identified (NNE, ENE, NNW, NW and WNW) and associated with various geological units and craton tectonic events (Table 1).

Analysis of the regional stress field based on the world stress map (Reinecker et al., 2005) gives an indication of whether a lineament direction is under compression or shear stress, which also suggests whether a fracture is likely to be closed or open (Table 1). Based on in-situ stress measurements (overcoring) in the region, the map shows that the principal compressive stress in the study area is at approximately 045°, with orientations accurate to within 25°. Thus the present day relative shear and compressive stresses for each lineament direction can be assessed using simple stress resolution diagrams (Table 1; e.g., Owen and Maziti, 2003). Possible geological explanations for these structural patterns are briefly suggested, and their hydrogeological significance is discussed later. Two of the three known trends are readily observed on

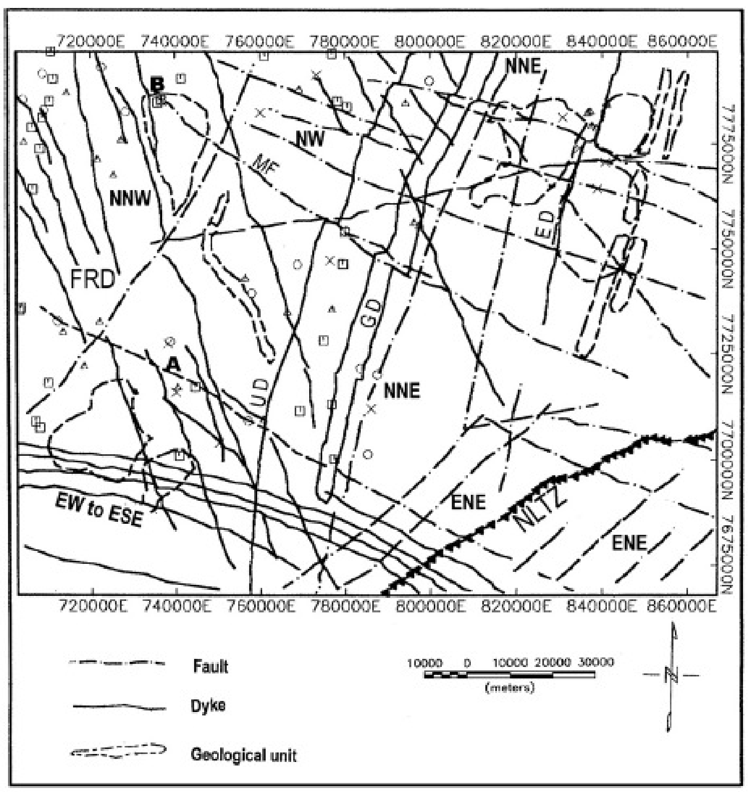


Fig. 7. Dyke and structural interpretation map of the study area, showing borehole locations. Symbols for borehole yields are: cross (X)=<1 $m^3$/h, circle (O)=1–2 $m^3$/h, triangle (Δ)=2–4 $m^3$/h, and box (□)=>4 $m^3$/h. Structural features: NLTZ – Northern Limpopo Thrust Zone, GD = Great Dyke, other labels as in Fig. 1; ENE, EW to ESE, NNE, NNW and NW labels refer to general trends of the features and structures. The apparent sparse borehole data is mainly due to inadequate location information. A and B represent sites where two or more boreholes with different yields are close together, illustrating the point that proximity to fracture does not guarantee productivity.

both TM and AM images; they are the most persistent, but most widely spaced. The NNW and WNW magnetic trends correlate predominantly with Proterozoic dykes and Mesozoic dykes and sinistral faults, respectively (e.g., D1, FRD, Fig. 3). Major faults in the area parallel the WNW-trending Mchingwe fault (MF, Fig. 1), some filled by mafic dykes and/or quartz (Campbell and Pitfield, 1994), and most appear as linear zones of low magnetic signatures (e.g., MF, Fig. 3). The faults have increased magnetic values where they cut dykes and other units (e.g., UD and Great Dyke, Figs. 2 and 3), probably due to introduction of magnetic minerals by hydrothermal fluids. The NNW direction appears as drainage lineaments and/or as dense vegetation lines on TM images (cf. Figs. 3 and 4). NNE-striking lineaments appear to be due to both dykes and fractures, with the latter forming a conjugate set with known WNW sinistral faults (e.g., Mchingwe fault, Fig. 1). ENE magnetic trends are mainly due to iron formation and mafic/ultramafic horizons or intrusions in paragneisses of the NMZ of the Limpopo orogenic belt. This trend could also represent the Mesozoic Limpopo dyke swarm (e.g., Wilson et al., 1987). It is less persistent than others, but has the closest fracture spacing. The EW to WNW trend in the southwestern parts of the area does not seem to occur anywhere else on the craton and could represent splays of the giant Okavango dyke swarm in northern Botswana (Ranganai et al., 1995a,b).

### 3.4. Relationships of borehole yields to lineaments

The final interpretation map (Fig. 7) is based on the various geoscience information. Existing borehole data were used to study the relationship between the interpreted structures and borehole yields. Although many more boreholes have been drilled, the few boreholes having their locations and yields recorded are shown in Fig. 7. Boreholes were divided into four groups based on yields: poor (<1 $m^3$/h), fair (1–2 $m^3$/h), good (>2–4 $m^3$/h), and excellent (>4 $m^3$/h).

Successful boreholes are shown to be spatially related to dykes and faults but proximity to these features does not guarantee productivity (Fig. 7). Relatively close pairs of productive and dry holes (e.g., sites A and B, Fig. 7) illustrate this point. Many of the low yield sites were chosen for logistical, rather than geological, reasons. That is, sites were greatly influenced by village, school, or clinic location, with boreholes typically required to be <2 km from settlements (e.g., Houston and Lewis, 1988). It is highly probable that borehole success rates and borehole yields would have been better had the structural mapping been undertaken before field surveying and drilling. Results indicating such positive correlation between borehole yields and distance from lineaments have been reported from the West African craton (Astier and Paterson, 1989), northeastern Botswana (Zeil et al., 1991; Koosimile, 1992), and southeast of the Zimbabwe Craton (Ranganai et al., 1995a,b; Ranganai and Zeil, 1995; Owen et al., 2002). However, based on previous British Geological Survey investigations (Greenbaum et al., 1993), we emphasize the need for caution when using photolineaments as evidence of the underlying structure. Field geophysical investigations showed resistivity, electromagnetic and magnetic anomalies coincident with, or offset parallel to the photolineaments (e.g., Fig. 8). Drilling on some of the photolineaments found no evidence of fracturing. However, the studies concluded that satellite images provide an important initial guide to target selection at the sub-regional level. It should also be noted that accuracy of the location data on the national borehole database is not that good (e.g., Greenbaum, 1992a); field observations indicate that most boreholes that do not plot along lineaments are in fact drilled into lineament zones (Owen and Maziti, 2003).

## 4. Structures and borehole targets of regional importance

In general, both fractures and dykes are of hydrogeological significance because they are zones of permeability and barriers to flow, respectively. Areas with a combination of major faults and a thick saprolite represent a particularly favourable target for groundwater exploration, as they provide storage and transmissivity which ensures sustainable borehole yields (cf. Wright and Burgess, 1992; Rao, 2003; Srivastava and Bhattacharya, 2006). Potential regional groundwater sites in the study area are therefore identified at dyke margins, faults, joints and intersections of any combination of these structures (cf. Greenbaum, 1992a; Yadav and Singh, 2007). These areas of broken rock have higher transmissivity values than the surrounding rocks,

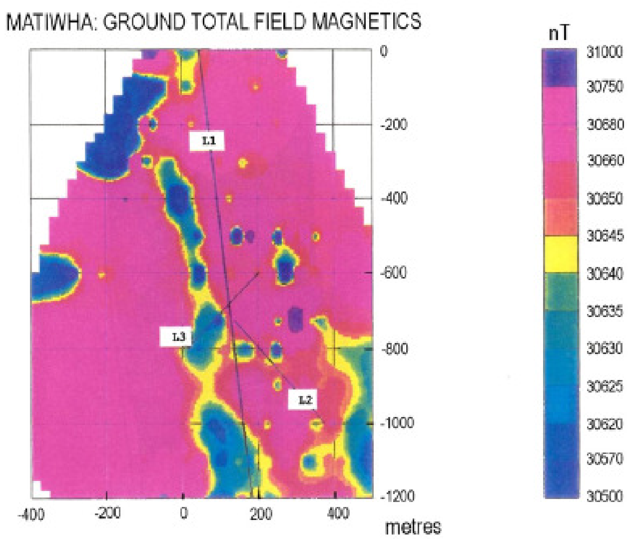


Fig. 8. Filled contour map of ground magnetic results from the eastern portion of the Chivi granite (see Figs. 4 and 6), outside the present study area (Greenbaum et al., 1993). Note a prominent magnetic low parallel to, but offset from, lineament L1 interpreted as a probable pegmatite-rich zone (a water barrier).

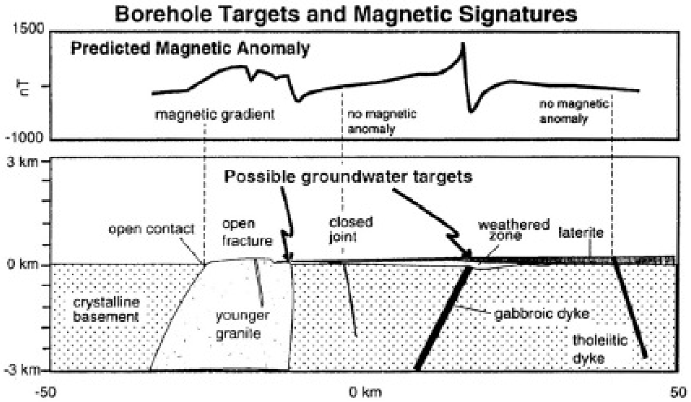


**Fig. 9.** Schematic outline of borehole targets (dykes, contacts, continuous fractures, weathered zones, etc.) and their typical magnetic signatures. Modelling based on measured susceptibilities from the study area (Table 2; Ranganai, 1995).

and boreholes located in these geological features can produce high yields (Astier and Paterson, 1989; Drury et al., 2001; Owen et al., 2002; Porsani et al., 2005).

The late Archaean (2.6 Ga) granites are considered the most favourable unit because of their associated long and deep brittle fractures between numerous bornhardts (e.g., Fig. 6). Several small-scale TM lineaments in these rocks also form important sources of groundwater locally for hand-dug wells. In addition to the regional scale effects of topography on groundwater flow from higher elevation to lowlands, it is anticipated that on a local scale, there will be a pattern of complex flows controlled by local scale topographic features, a factor important for local scale well siting (Owen et al., 2002). Under similar tectonic conditions, fractures in coarse grained felsic rocks tend to occur at wider intervals, but are more extensive and usually have thicker and more permeable regolith than fine grained varieties (Jones, 1985). On the other hand, weathering in the older gneisses gives rise to a low relief terrain of thicker permeable regolith, overlying the bedrock (McFarlane, 1990). These gneisses are mapped mainly as zone H on the apparent susceptibility map (Fig. 2) with relatively high signatures, contrary to expectations. These rocks were also affected by several episodes of post younger granite fracturing and dyke emplacement (Wilson, 1990). It is suggested here that tensional stresses associated with the subsequent dyke emplacement might have opened up fractures within the gneisses. Theoretically, lineaments under dilation and shear may be expected to have higher groundwater well yields than lineaments under compression (Boeckh, 1992; Owen and Maziti, 2003).

Several NNW-trending olivine-bearing dykes, not visible in the field due to weathering and overburden cover, are recognised as linear magnetic highs (e.g., FRD, Fig. 3). Preliminary magnetic modelling on some of the dykes (e.g., D1; Fig. 3) suggests that most dykes are sub-vertical. These could represent buried water channels, and they appear as drainage features or linear dense vegetation on Landsat TM images. Vegetated lineaments suggest the availability of groundwater in open fractures. A few tholeiitic non-magnetic dykes are also mapped in the field (e.g., MCD, Fig. 1) and on TM images as ridges slightly above ground. These dykes could form zones of water accumulation through being barriers to groundwater movement. The NNE and NW conjugate set of sinistral faults also appear to be of regional importance; they are long and are likely to be open (brittle fractures). In an area northeast from the current study, Owen and Maziti (2003) suggest that the NNE lineaments are under shear stress, topography plots show an open valley profile, and resistivity profiles indicate intermediate to deep weathering (20 to 40 m).

**Table 2**
Measured susceptibilities and computed apparent susceptibility values for the main rock types of the study area

| Rock unit/type | *N* samples | $\chi$ range ($\times 10^{-3}$ SI) | Apparent susceptibility values ($\times 10^{-3}$ SI) |
|---|---|---|---|
| Gneisses | 8 | 0.00–0.40 | – |
| Granites | 27 | 0.00–0.32 | 0.00–0.54 |
| Basaltic greenstones | 14 | 0.00–0.06 | 0.00–0.04 |
| Ultramafics/Schists | 10 | 0.01–3.30 | 0.10–5.30 |
| Dolerites (dykes) | 15 | 0.01–0.28 | 0.00–0.20 |
| Amphibolites | 11 | 0.00–0.60 | – |

Based on this study, and Greenbaum et al. (1993), we present in Fig. 9 the possible targets for groundwater exploration in crystalline basements and their typical magnetic responses. The magnetic modelling was partly based on the calculated apparent susceptibilities and some measured susceptibilities (Table 2). Unfortunately, it is not possible to show field data that look like the typical responses since there is no single profile that cuts across all the features presented and/or modelled. Other targets in the area include BIF horizons within greenstone belts (they either form groundwater barriers or have brittle fractures), fractures cutting across the belts, and linear to curvilinear ultramafic intrusions.

## 5. Summary and conclusions

The groundwater potential of the various features and structures have been evaluated and prioritised for detailed ground follow-up. The relative importance of the datasets used is also commented upon; this will allow others to develop exploration strategies. In general, priority for ground geophysics should be given to continuous structures with high recharge potential from streams (e.g., NNE and NW conjugate set of sinistral faults in Chilimanzi plutons; Figs. 6 and 7). Their trends take them from areas of higher elevation in the north (the watershed) to relatively lowland areas in the south, and regional groundwater flows generally follow the main topographic gradient (Gieske, 1992; Saraf and Choudhury, 1998; Drury et al., 2001; Owen et al., 2002; Saraf et al., 2004). Furthermore, the coincidence of AM/TM lineaments is important: AM data have been used to map buried magnetic dykes under weathered zones and also deep fractures likely to be open groundwater conduits. TM lineaments, although not necessarily open (e.g., Carruthers et al., 1991; Greenbaum, 1992a,b; Owen et al., 2002), have outlined fracture density/intensity which reflects recharge capacity. The different roles of the methods are explained by the fact that AM data respond to susceptibility contrasts of rocks at the surface as well as at depth, while on the other hand TM relies on surface radiation reflectances related to topography and vegetation. The main advantage of TM here is that the dry season images used provide the greatest contrast between bare soil/rock and green plants, information related to the persistence of ground moisture. It is clear that rasterised aeromagnetic data and Landsat TM images emphasize different aspects of the mapped structures and, therefore, provide complementary information on the hydrogeology of the area.

Overall, we identify three main possible regional groundwater targets in order of priority as follows (Figs. 5 to 9; Table 1):

(a) AM+TM lineaments — these are barriers and/or open fractures, both long and continuous. These favour infiltration and therefore promote deeper weathering.
(b) AM lineaments with no TM — these may be barriers (magnetic highs), open fractures (magnetic lows), or contacts (magnetic gradients) (see Fig. 9). Long, continuous structures and/or features should be selected.
(c) TM lineaments with no AM — these are barriers, fractures or drainage channels; these data select medium to long lineaments, preferably occupying topographic lows; they provide a check for moisture indicators and lineament density/intensity features are important for shorter ones.

The combined interpretation of enhanced aeromagnetic and geo-referenced TM images has revealed the presence of several regional lineaments corresponding to some known and several previously unknown dykes, faults, shear zones and/or tectonically-related joints (e.g., Figs. 1, 3 and 4). Existing data about borehole yields show some correlation between high yields and regional structures and lineaments identified from AM and TM data. Many of the low-yielding sites were chosen for logistical, rather than geological, reasons. Results of this work and previous studies show that an effective approach to selecting potential groundwater sites in crystalline basement areas is to employ aeromagnetic data and Landsat imagery in conjunction with other available hydrogeological data. Ground follow-up geophysics (mainly magnetics, electromagnetics and resistivity) can therefore be directed at the most promising fractures/features to pin-point drilling sites. Expected advantages include a more rapid selection of appropriate areas, a reduction of survey costs, an improved borehole success rate, and increased yields.

Potential regional groundwater sites in the study area are identified at dyke margins, faults, joints and intersections of any combination of these structures. The late Archaean (2.6 Ga) granites are considered the most favourable unit because of their associated long and deep brittle fractures with clear, coincident AM and TM signatures. These rocks also have intense small-scale fracturing important for recharge and/or hand-dug wells. NNW-trending Proterozoic magnetic dykes intruded into weathered tonalitic gneisses are also important, the latter have an advantage of thick weathering which is important for sustainable yields. Similarly, strike–slip or dextral faults in the area are due to tensional stress and are thus probably open. They have magnetic lows due to magnetite oxidation, suggesting groundwater movement. Finally, non-magnetic (tholeiitic) dykes visible in the field may be barriers to groundwater movement and, therefore, constitute zones of water accumulation. A magnetic model has been developed that could assist others working in similar terrains.

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