SPOT SATELLITE DATA FOR EXPLORATION OF FRACTURED AQUIFERS IN A SEMI-ARID AREA IN SOUTHEASTERN BOTSWANA

by

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ABSTRACT: In areas with little primary porosity and low bedrock hydraulic conductivity, hydrogeological properties are mainly determined by secondary factors, such as fracture zones and associated weathering. Fracture zones in areas with limited regolith cover are often detectable on satellite images as linear features originating mainly from pronounced vegetation anomalies, topographic effects or both. SPOT multispectral and panchromatic data of a 2000 km^2 semi-arid area in southeastern Botswana have, in this study, been merged and interpreted in an image processing system resulting in a detailed lineament map and a delineation of dry season vegetation. The lineament data have been analyzed in a geographical information system and correlation studies of borehole and geophysical data with satellite lineaments have been carried out. The study shows that a digital approach, using satellite data in combination with existing field data, can provide a time- and cost-effective tool for the identification and narrowing of target areas for groundwater exploration in semi-arid areas.

RÉSUMÉ: Dans les régions où la roche possède une faible porosité primaire et une conductivité hydraulique réduite, les propriétés hydrogéologiques sont essentiellement déterminées par des facteurs secondaires, tels que les zones de fractures et l'altération associée. Là où la couverture de régolite est limitée, les zones de fractures sont souvent détectables sur images satellite sous forme d'alignements révélés surtout par des anomalies marquées de végétation et/ou par des effets topographiques. Les données panchromatiques et multispectrales de SPOT d'une région semi-aride de 2000 km^2 dans le sud-ouest du Botswana ont été rassemblées et interprétées sous forme d'une image synthétique donnant une carte détaillée des linéaments et une carte schématique de la végétation en saison sèche. Les linéaments ont été introduits dans un système d'information géographique et des corrélations ont été recherchées entre les données des forages et de la géophysique et les linéaments des images satellites. Bien que préliminaires, les résultats de cette étude montrent qu'une approche numérique, utilisant les données satellitaires combinées aux données de terrain existantes, peut fournir un outil, économe en temps et en coût, efficace pour identifier et pour définir des zones cibles pour la recherche d'eau souterraine en région semi-aride.

INTRODUCTION

Satellite data have been used since the early seventies in groundwater exploration in arid and semi-arid areas, but due to the fairly coarse resolution of the Landsat MSS sensor, the satellite data were initially used only for regional studies, while conventional aerial photography was used for more detailed interpretations. To a certain extent this is still a common approach and has prevented satellite data from being used other than for regional mapping, despite the arrival of Landsat TM and SPOT data with higher resolution.

SPOT multispectral (XS) and panchromatic (P) data, with 20 and 10 m resolution, are competitive alternatives to conventional aerial photography, having a lower resolution, but several advantages. Satellite data are registered in digital format and can be ordered as precision-corrected products with high geometric accuracy. Up-to-date cloudfree images are available of most semi-arid areas of the world and, as opposed to air-photos, registrations are often available from different seasons. The main advantage is that the data can be easily processed, analyzed, and interpreted in image processing systems, to produce digital output of high quality for use in, for example, geographical information systems.

Interpreting paper prints of air-photos or satellite images using acetate overlays has been a common approach and the interpretations have sometimes subsequently been digitized. During the last few years, several user-friendly and economically feasible image processing systems have emerged, making it possible in most projects to avoid such redundant steps. The accuracy of the interpretations increases significantly through avoiding intermediate digitizing, but more important is the possibility of locally enhancing features in the image.

Groundwater resources are of crucial importance in semi-arid areas, since the rainfall and, subsequently, the surface water are very unpredictable. Although the extractable amounts of groundwater are directly related to precipitation, the seasonal storage of groundwater is much higher than for surface water and groundwater is often necessary as a back-up during the dry season or dry spells. Many arid and semi-arid areas are underlain by hard rocks in which the primary porosity and hydraulic conductivity are low and the groundwater resides mainly in fractures or weathered zones of the bedrock, i.e., what is generally referred to as secondary porosity and hydraulic conductivity.

Although the term "hard rock" strictly applies only to igneous and metamorphic, non-volcanic, non-carbonate rocks (UNESCO 1984), the term can, from a groundwater exploration point of view, include all rocks without sufficient *primary* porosity and conductivity for feasible groundwater extraction. In such areas, exploration is directed towards finding increased transmissivity and storativity caused by secondary effects such as fracturing and weathering. In semi-arid areas, weathering concentrates along lines of structural weakness, such as faults, fracture zones and dykes, which often show as linear features on satellite imagery, generally referred to as *lineaments* (Carruthers et al. 1991 and Greenbaum 1992).

Lineaments interpreted from remote sensing data correspond to anything from minor drainage features or individual fractures on, for example, 1:25,000 scale air-photos to large valleys representing major fracture zones on Landsat MSS data at 1:250,000 scale. Shuman (1991) showed that lineament frequency plotted against imagery scale reveals a negative power function and average lineament length plotted against scale shows a positive polynomial relationship. This is probably not so much due to the actual scale of the image as it is due to the resolution. Low altitude air-photos have a resolution of less than a metre (Rengers et al. 1992) while Landsat MSS has 80 m resolution, which evidently gives possibilities for a more detailed interpretation in the former case. SPOT XS and P registrations have been available for groundwater exploration since 1986 and, despite having a lower spectral resolution than the more widely used Landsat TM data, the higher spatial resolution is advantageous for interpretation of linear features.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF THE STUDY AREA

Eastern Botswana is part of the southern African Precambrian shield and is characterized by an Archaean granitoid/metamorphic complex partly covered by a Proterozoic to Mesozoic volcano-sedimentary succession of strongly lithified platform deposits (Dietvorst et al. 1991). The 2000 km^2 study area is located in southeastern Botswana immediately north of the capital, Gaborone, and comprises a diverse geology as well as topography. The 76 x 27 km^2 area is dominated by an E-W trending, 50 km long range of hills of moderate to high relief between the two villages of Molepolole and Mochudi. On both sides of the range the topography is flat to gently sloping.

The bedrock geology is Archaean to lower Proterozoic in age and dominated by three major units; the Kanye Volcanic Group, the Gaborone Granite and the Waterberg Supergroup. The Kanye Volcanic group consists of fine grained felsite of rhyolitic composition and forms the major part of the range. The south side of the range is dominated by the Gaborone Granite, a coarse grained porphyritic rock which, according to some authors, is intrusive in the Kanye Volcanics, although the relationship is not fully understood.

The northern side of the range is dominated by the Waterberg Supergroup, consisting of several stratigraphic subunits; an arenaceous lower group and an argillaceous upper group. The lower group attains a thickness of around 150 m and includes the Gakobakwe Sandstone, which consists of a purple to brown quartzitic sandstone and repetitive bands of conglomerate. This formation is the only part of the Waterberg formation that outcrops to any extent in the area and forms prominent ridges along the whole

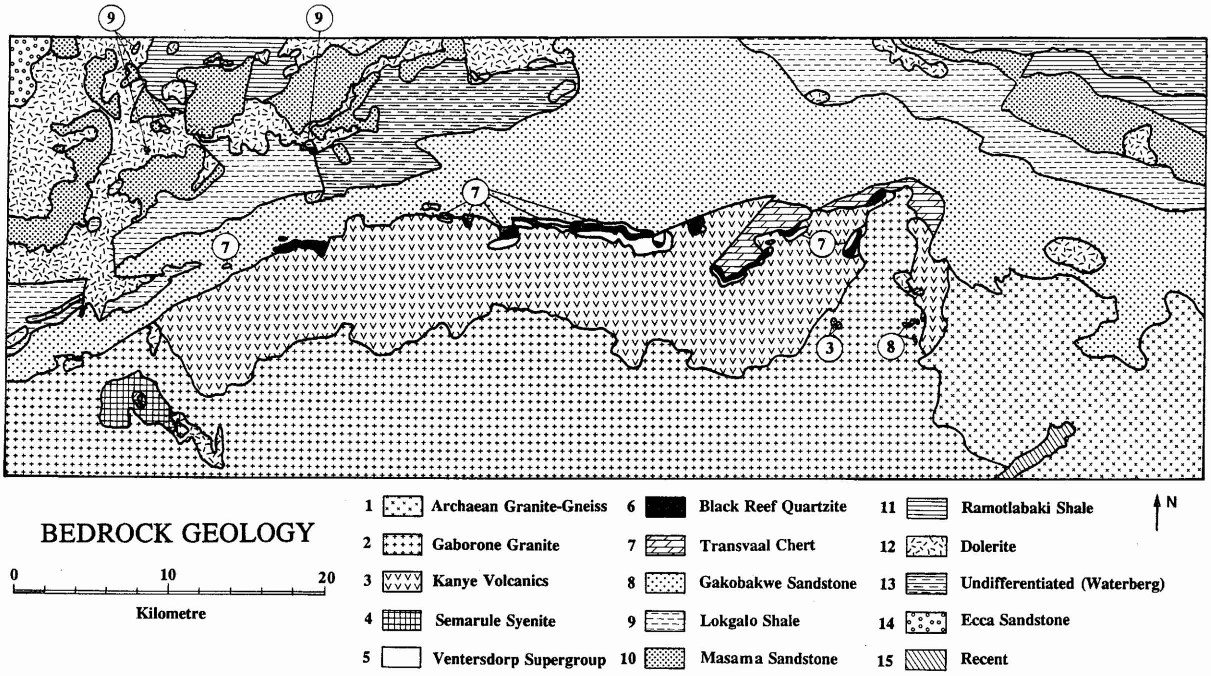

Figure 1. Bedrock geology of the study area.

northern boundary of the Kanye Volcanics. The upper group consists mainly of siltstones, claystones and shales, which outcrop only along the major drainage features.

The Transvaal Supergroup, consisting of conglomerate, quartzite and cherts is sandwiched between the Gakobakwe Sandstone and the Kanye Volcanics in the central part of the study area. The cherts were derived from dolomite which, from borehole information, is known to exist at depth. The oldest rocks in the study area are Archaean granite-gneisses, which outcrop south of Mochudi and underlie most of the southeastern part. Intrusive rocks of post-Waterberg age are widespread and comprise several dykes and sills of dolerite, which are especially prominent in the northwestern part.

From a hydrogeological point of view, none of the rocks have sufficient primary porosity for any significant groundwater storage. The rocks are, however, extensively tectonized and a large number of fracture zones intersect the area. The water demand is high and many groundwater investigations have been carried out during the last two decades. The main target for groundwater extraction is the Gakobakwe Sandstone in the Waterberg Supergroup and several wells have been drilled in this formation, especially in the area immediately northeast of Molepolole. Good yields have been obtained from boreholes sited in highly fractured zones, sometimes near the numerous and otherwise poorly transmissive dolerite intrusions.

The Archaean rocks have generally low transmissivity and storativity, although a few successful boreholes exist in the granite-gneiss area in the southeast. The few wells drilled in felsite and granite are mainly for small village supplies and capacities have not been thoroughly evaluated. Recharge is low, estimated at only 5-40 mm/year (Sloots and Wijnen 1990; VIAK 1984), having implications for long-term discharge of wells.

Previous groundwater investigations have mainly concentrated on identifying fracture zones in the Waterberg formation or fractures adjacent to the numerous dykes in the area, which could act as conduits for groundwater. Methods used to select drill targets include various geophysical techniques, air-photo interpretation and a limited use of satellite data. To date, no hydrogeological investigations have used a full digital approach, integrating satellite data and field data as an exploration tool.

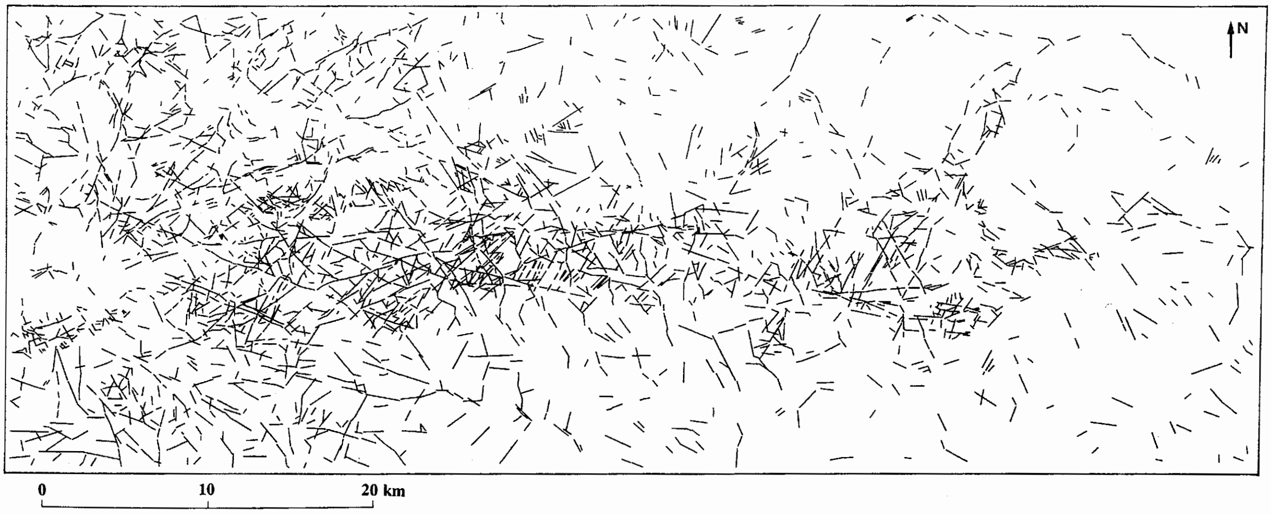

Figure 2. Lineament map of the study area.

LINEAMENT INTERPRETATION

SPOT multispectral (XS) and panchromatic (P) data, from both the wet and dry seasons, have been interpreted in a workstation image processing system, ER Mapper. The imagery was produced for a recent groundwater project in the area and has been precision-corrected to the level of orthophotomaps and tailor-made to match the three topographical map sheets covering the area. Although a number of enhancement techniques are easily performed in the system, the image combination found to be the most suitable for interpretation of linear features was SPOT XS from dry season (registration date 30 May 1986) merged with SPOT P (registration date 23 March 1986). The XS bands were high pass filtered and contrast stretched and merged with the high pass filtered and contrast stretched panchromatic data. The XS bands were represented in RGB and the panchromatic band as an intensity overlay.

Lineaments were interpreted on-screen using an annotation overlay in ER Mapper. The images were mosaiced together to enable interpretation across map boundaries. A zoom window with an interpretation scale of about 1:30,000 was then moved across the image, overlapping 50%, i.e. covering the area four times. This scale is an ideal compromise between high interpretation accuracy and resolution of the image. Local contrast stretching was applied for each zoom window to optimize the identification of linear features.

The aim of the lineament interpretation was to digitize accurately all linear features that could represent a lineament of tectonic origin, well aware that some manmade features might be included. Interpolation between, or extrapolation from, end-points was avoided, since this would introduce bias in the lineament map. The actual interpretation of lineaments on screen is, and needs to be, a subjective process, since automatic interpretation introduces many errors, which are time-consuming to correct. The tectonic analysis of the lineament map should be carried out after the lineament map is completed, to avoid bias during the actual interpretation process.

Field reconnaissance was carried out during both the wet and dry seasons, to gain a thorough knowledge of the area when interpreting on-screen. Linear features visible on paper prints of the imagery were also field checked to try to verify or discard inferred lineaments. No evidence of "false", i.e., manmade, lineaments was found in the study area and the majority of the lineaments corresponded to negative-relief features, from narrow ravines to broad valleys and/or linear vegetation anomalies. Both often coincided with the drainage pattern and the latter often consisted of dense or broadleaved vegetation. In several places the lineaments on the dry season images were found to correspond to verdant vegetation, without obvious topographic evidence.

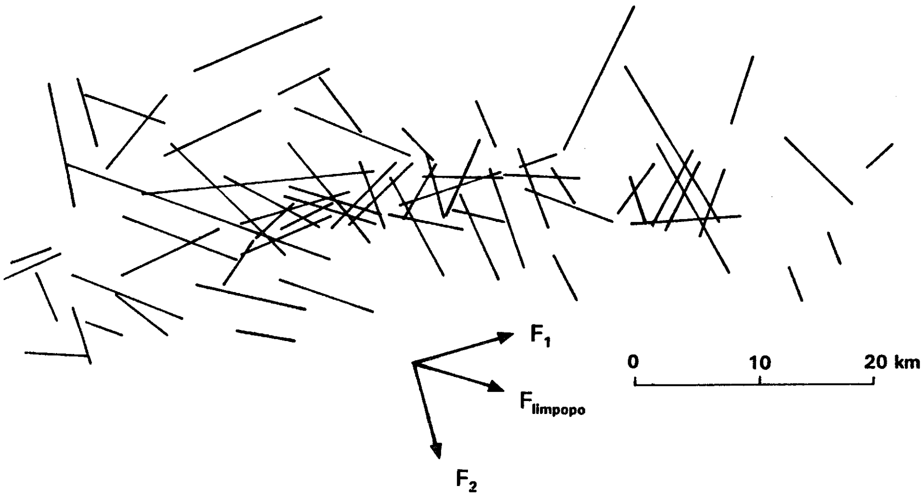

Figure 3. General lineament trends of the study area, showing the F_1, F_2 and $F_{limpopo}$ events as described by Dietvorst et al. (1991).

The lineament interpretation resulted in a lineament map with nearly 3000 lineaments, of which some consist of two to several segments. The minimum lineament length is around 300 m, but the majority are more than 600 m. Continuous curved lineaments have been digitized as one lineament with vertices at breakpoints, to give the possibility of making a correct analysis of lineament lengths in the different bedrock units. Drainage features in the area are more difficult to interpret. Straight portions of dry streambeds have, in general, been interpreted as indications of existing fracture zones. Other problems encountered during a detailed interpretation are, for example, wide valleys or densely vegetated areas, where it is difficult to position lineaments with satisfactory certainty.

In areas covered with regolith, certain lineament azimuths are more pronounced than others, introducing a possible bias in the lineament map. The distinct lineaments often follow the drainage pattern, while perpendicular to sub-perpendicular linear features are less evident. This is probably explained by the fact that superficial deposits tend to fill in negative relief features perpendicular to the local gradient and etch out features parallel to it. This does not necessarily have any implication for the hydrogeological potential of the different lineaments. In recently and extensively glaciated areas, research has shown that certain lineament directions can be obscured by the direction of flow of the ice sheet (Wladis 1992; Shuman 1991). It is likely that this applies also for areas of extensive weathering and flow of erosion material.

A few of the interpreted lineaments in the study area have been found to correspond to dolerite dykes which, as opposed to most fracture zones, sometimes show as positive-relief features, characterized by rubbly outcrop and less distinct linearity. In areas with deeper regolith cover, such as a major part of the study area north of the range, or areas with dark vertisols, such as the southeastern part, south of Mochudi, lineaments are much less distinct and the interpretation accuracy more uncertain. The ideal solution would be to interpret lineaments in different categories according to their appearance on the imagery. This would, however, be very time consuming.

TECTONIC HISTORY

According to Dietvorst et al. (1991), deformation of the basement complex in southeastern Botswana began during late Archaean along roughly east-west-oriented axes. A basin developed due to subsidence of the Kaapvaal Craton and deposition of the Ventersdorp and Transvaal volcano-sedimentary sequences took place in late Archaean and early Proterozoic time. Folding remained active until after deposition of the Transvaal Supergroup, resulting in a syncline stretching through the northern half of the study area in which younger (Proterozoic to Mesozoic) sediments were deposited. These are represented by the Waterberg Supergroup in the study area and the Karoo Supergroup immediately north of the study area.

Dietvorst et al. (1991) describe three major tectonic events in southeastern Botswana. (1) The Limpopo event, oriented WNW-ESE, originating from the formation of the Limpopo mobile belt separating the Kaapvaal Craton from the Zimbabwe Craton, is referred to as the $F_{limpopo}$ event. (2) The late Archaean deformation, with WSW-ENE direction, is referred to as the F_1 event. (3) Refolding of these trends occurred along a NNW-SSE direction in pre-Waterberg time, i.e., before 1790±90 Ma, and is referred to as the F_2 event.

The Molepolole-Mochudi study area shows a distinct WSW-ENE structural trend, parallel to the Zoetfontein fault about 70 km north of Molepolole. This structural trend is especially distinct along the boundary between the Kanye Volcanics and the Transvaal and Waterberg Supergroups. The boundary between the Kanye Volcanics and the Gaborone Granite follows the same trend but is much less distinct. It is evident, though, that the study area has a structural trend equivalent to the Zoetfontein structure, i.e., related to the F_1 event.

As shown in Figure 3, the interpretation of the lineament map shows that the tectonic events described by Dietvorst et al. (1991) are all clearly represented in the study area. It is also apparent that deformation in post-Waterberg time has reactivated the tectonic zones established by these events. The lineament statistics shown in Figure 4 reveal that the F_1 event is more evident in the Kanye Volcanics, while the F_2 event is much more evident in the Gakobakwe Sandstone of the Waterberg Supergroup. The F_{limpopo} event is equally represented in these formations and is also the dominating lineament trend in almost all of Botswana.

The only major lineament azimuth not accounted for by Dietvorst et al. (1991), is related to the NNE-SSW striking zones that are fairly distinct in the whole study area. These zones are almost perpendicular to the F_{limpopo} zones and probably originate from the same tectonic event as the Lobatse-Serowe trend, which stretches for over 400 km through eastern Botswana and South Africa. According to SMEC et al. (1991) this structure is probably due to a plastic deformation phase (folding) rather than to rigid (fault) deformation. The structure is parallel to the Great Dyke of Zimbabwe, which was formed at about 2.46 Ga (Petters 1991), suggesting that the NNE-SSW trending lineaments are fracture zones formed by inheriting the existing structural trend of the basement, which, like the other major structural trends of the area, has been reactivated in post-Waterberg time.

HYDROGEOLOGICAL RELEVANCE OF SPOT INTERPRETATIONS

Successful boreholes in rocks with little primary porosity and hydraulic conductivity depend upon the interception of fracture systems in the rock mass. However, also in rocks with both primary and secondary porosity, siting of boreholes in open fracture systems will increase the yields significantly. Although satellite image or air-photo interpretations do not allow us to reliably interpret the physical characteristics of fracture zones, such as dip and width, remote sensing is a very valuable means of narrowing the search for promising target areas for groundwater exploitation.

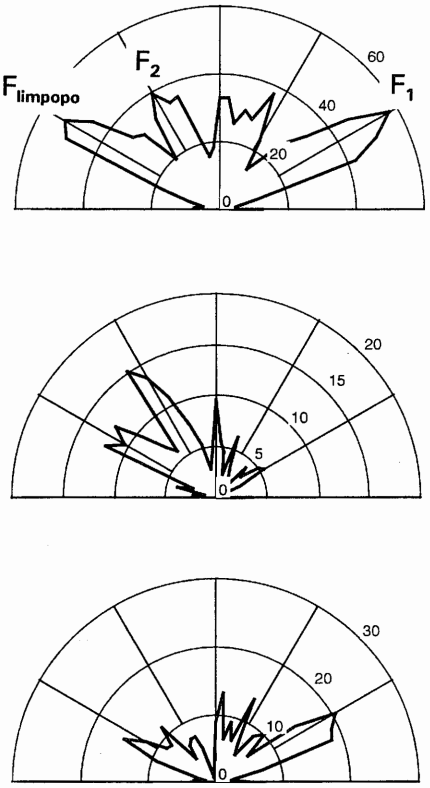

Figure 4. Polar graphs of total lineament distribution in the Molepolole area (top), lineament distribution in Gakobakwe Sandstone (centre) and Kanye Volcanics (bottom), with total lineament lengths (km) in five degree increments according to UTM.

Lineaments interpreted from satellite data generally represent fracture zones or dykes. Basic dykes, such as the dolerite dykes of the study area, are normally poor aquifers, although the boundary between the dyke and the country rock often contains fractures with high storage capacity. Dykes may also act as barriers to groundwater flow, in which case, favourable well sites may exist upstream of the dyke. Fracture zones related to brittle deformation are normally separated into tension zones and shear zones. Tension zones generally have a high storage capacity, while shear zones can range from tight to highly permeable, depending upon their stage of development (UNESCO 1984).

Table 1. Main lineament azimuths (UTM) according to VIAK (1984) and this study.

VIAK 1984	Type, according to VIAK model	This study (Molepolole area)
N60-80°W	tension, open	N50-65°W ($F_{limpopo}$)
N35-50°W	shear	N20-35°W (F_2)
N15°W-N10°E	tension	0°-N25°E ($F_{Lob/Ser}$)
N40-60°E	shear, partly open	N50-70°E (F_1)

Lineament interpretation has, in some projects, formed the basis for a delineation of the original stress regime, which subsequently has been used to develop a "hydro-tectonic" model, from which promising fracture zones for groundwater development have been identified (VIAK 1984). However, in this area, it is most likely that reactivation of fracture zones has occurred under new stress conditions on several occasions, which has changed their original compressive or tensile nature. A recent project in a hard rock area in southeastern Zimbabwe (Greenbaum 1992; Carruthers et al. 1991) suggests that, as a result of gravitational unloading, temperature changes and lateral expansion during uplift and erosion, the near-surface zone down to possibly hundreds of metres is dominated by tensile stresses. The lack of any favoured lineament directions in that particular area, when correlating borehole data with lineaments from both satellite images and air photos, supports the hypothesis.

The lineament azimuths interpreted by VIAK (1984) using Landsat MSS data for the Molepolole area coincide reasonably well with the results from this study. The suggested open tension direction, N 60-80°W coincides with the most prominent lineament azimuth of this study, which is believed to be related to the $F_{limpopo}$ event.

The VIAK model was not extensively tested and the borehole information in the Molepolole area is, as of today, not sufficient to revalidate the model. Until further tests have been carried out, the general approach suggested in this study is to use geophysical methods and, preferably, test drilling to try to identify the nature of the target fracture zones selected from the detailed lineament interpretation.

Figure 5. Lineament map and vegetation anomalies from a part of the study area. Size of area approximately 3 x 2.5 km².

In this study a vegetation index was applied to SPOT XS bands 2 and 3 and a classification of the resulting image was made to enhance dry season vegetation. This could be used to identify lineaments with a higher groundwater potential by distinguishing unvegetated from vegetated lineaments. An example from the study area is shown in Figure 5. The ultimate aim is to try to distinguish clearly between *green* dry season vegetation and dry vegetation, using Landsat TM data with a better spectral resolution. Field reconnaissance has shown that certain lineaments support very healthy vegetation during the end of the dry season, indicating water-bearing fracture zones.

Outcrop joint mapping is sometimes used to try to confirm the main fracture zones identified on satellite imagery. In this study, the joints in the Gakobakwe Sandstone show a very poor correlation with the lineaments; the main azimuths of the outcrop joints being oblique or even perpendicular to the main lineament azimuths from the same formation. Although these preliminary results are based on a small joint and lineament population, it is known from investigations in other areas (e.g., Greenbaum 1987), that outcrop joints in hard rock areas can be non-representative of the main fracture zones and only a limited correlation is sometimes encountered. This restricts the possibility of drawing conclusions from outcrop mapping.

CORRELATION STUDIES

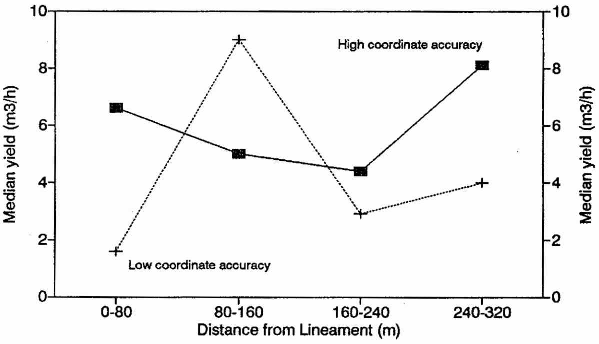

Figure 6. Correlation between borehole yield and proximity to satellite image lineaments, using boreholes with high positional accuracy (better than ± 50 m) and boreholes with low positional accuracy (± 50 m to ± 500 m)

Lineament interpretations of the study area have been correlated with existing borehole and geophysical data in a geographical information system. The correlation studies have taken advantage of the high positional accuracy of around 150 GPS-positioned or surveyed boreholes in the study area. The GPS (global positioning system) measurements, which included post-processing, have yielded coordinate accuracies of better than ± 1 m, while the surveyed boreholes have an accuracy of better than ± 50 m. Figure 7 shows a direct relationship between borehole specific capacity and proximity to satellite image lineaments, while the yield-proximity relationship shown in Figure 6 is more ambiguous.

Figure 6 also shows the correlation between lineaments and 120 boreholes in the same area, classed with low positional accuracy, i.e. boreholes from previous investigations where GPS or surveying have not been used. The estimated accuracies of these borehole coordinates are between ± 50 m and ± 500 m. Despite having roughly the same median yield, 4.0 and 3.7 m^3/h respectively, the result is clearly different. Figure 7 shows a comparison between lineaments and specific capacity of the same borehole population, before and after repositioning with GPS.

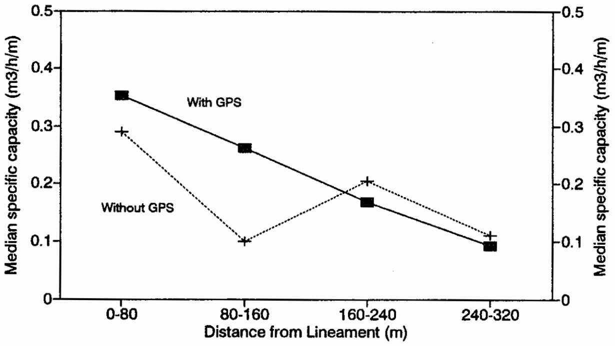

Figure 7. Correlation between borehole specific capacity (yield per m drawdown) and proximity to lineaments, before and after repositioning with GPS.

Although based on a small borehole population, this study clearly illustrates the importance of accurate coordinates when comparing various types of spatial data in a geographical information system (GIS). Proximity to lineaments does not necessarily mean, however, that the borehole specific capacity is high. Low capacity of boreholes sited on satellite lineaments could occasionally be connected to poorly transmissive dykes or clay gouge in fracture zones.

A large number of geophysical field traverses (EM and magnetics), with a total length of nearly 500 km, have been subject to a rough interpretation of anomalies and correlated with distance to lineaments. This comparison was made to see whether the geophysical investigations picked up the inferred fracture zones interpreted from the satellite data. The traverses, which have been positioned with GPS, do not, however, show a significant correlation between the number of negative anomalies and proximity to satellite lineaments (Fig. 8). This could partly be explained by the fact that some traverses are located in areas where the regolith cover is fairly thick and, consequently, fracture zones are harder to detect on satellite images. The geophysical response of inferred fracture zones interpreted from satellite image lineaments is dependant on several factors, such as width, depth, weathering and water storage, which consequently will have a great impact on a correlation study.

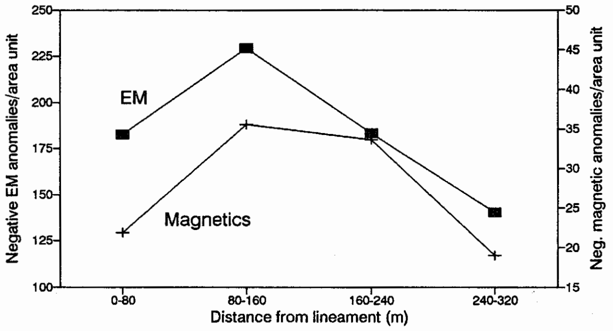

Figure 8. Correlation between number of negative magnetic and electromagnetic (Slingram) anomalies and proximity to satellite image lineaments. Compensation made for decreasing buffer zone areas.

Although these analyses have been performed on a small amount of data, they are examples of methodologies that could be used when combining data of hydrogeological significance in a GIS. A GIS is an ideal tool for exploration and the integration of various types of data in a digital environment will provide an excellent decision support. The analyses in this study have been performed in an advanced GIS, which is dynamically linked to the image processing system.

DISCUSSION AND CONCLUSIONS

SPOT multispectral (XS) and panchromatic (P) data offer very competitive alternatives to conventional aerial photography, having good enough spatial resolution to enable detailed interpretations as well as reasonable spectral resolution. Satellite data also have the advantage of being in digital format, which means that interpretations and analyses can be carried out in a digital environment, without intermediate digitizing. The satellite interpretations form an excellent basis for a geographical information system, which is ideal as a tool for groundwater exploration.

Lineaments interpreted on SPOT panchromatic images can usually be identified with reasonable accuracy (often better than 50 metres) in the terrain if the contrast is high enough (Gråsjö et al. 1991), and promising drill targets could possibly be selected from satellite lineaments alone. However, satellite data provide little information about the nature of the lineament, such as dip, width, and extent of weathering, and it is therefore highly advisable to use geophysical methods to refine the drill site location.

It is necessary to develop a tectonic model based on lineament interpretation and the regional tectonic history, in order to be able to separate important structural trends from ”interpretation noise“. However, the use of hydro-tectonic models, based on lineament data, to identify certain fracture azimuths as more promising for groundwater exploration has to be considered as very difficult without extensive and precise exploration drilling and test pumping.

This study has also shown that coordinate reliability is, not surprisingly, very important when analysing borehole and geophysical data in relation to interpreted lineaments. GPS technology will thus be of great importance in areas without good coverage by conventional maps of high quality, as is the case for most semi-arid areas, due to the often low population density.

The selection of promising target areas for detailed groundwater exploration could effectively be carried out in a GIS, using a multi-indicator approach. The most promising sites or target areas can be selected on the basis of as many indicators as possible which could favour or limit groundwater availability. The indicators, which may include lineaments, dry season vegetation, bedrock geology, size of drainage area, existing boreholes, geophysical evidence, etc., can be weighted according to their believed importance. A geographical information system is the ideal tool for handling and analysing the large amount of data that may be available from an exploration area.

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