Report: 85/8

REVIEW OF REMOTE SENSING APPLICATIONS

TO GROUNDWATER EXPLORATION IN

BASEMENT AND REGOLITH

WC/OG/85/1

by

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March 1985

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1. INTRODUCTION

Remote sensing may be broadly defined as the collection of information about an object by a recording device that is not in physical contact with it. More specifically, it relates to the technique of recording information about the environment and surface of the earth from aircraft or satellites. The term is usually restricted to methods that record reflected or radiated electromagnetic energy (including light, heat and micro waves) rather than measurements of force (e.g. electrical, magnetic, gravity properties) that involve significant penetration into the earth. The techniques employ such imaging, profiling and point-sampling devices as the camera, visible and infra red detectors, microwave radiometers and radar systems.

The original and most widely used remote sensing technique for geological applications is aerial photography which records EM energy mainly in the visible part of the spectrum. Since 1972, satellite imagery, mainly from the LANDSAT series of satellites, has become available which has extended the sensor range and revolutionised processing and interpretation techniques.

Applications of remote sensing in the field of water resources assessment are many, and cover such diverse topics as surface water, meteorology, soil moisture, snow and ice, coastal zone and water quality, as well as groundwater. Hydrogeological analysis of aerial photography or satellite imagery for groundwater exploration is one of the most complex uses of remotely sensed data. This results from the fact that the object of study, groundwater, is not directly portrayed on the imagery but must be inferred indirectly from surface hydrogeological conditions. In practice, this involves the interpretation of geological and geomorphological features and structures, drainage characteristics, soil types and soil moisture anomalies, vegetation types and distribution patterns, occurrences of springs and seeps, etc.

Although there is a tradition of the use of aerial photography in groundwater surveys for siting boreholes, comparatively few published accounts consider the subject in detail. Nefedov and Popova (1969) refer to this situation and provide a state-of-the-art review up to that time, heavily weighted in terms of Russian authors. This work, as well as other case studies, concentrates on two main aspects: the geomorphological interpretation of unconsolidated surficial deposits, and fracture trace analysis of hard rock areas. In recent years, a vast number of reports involving the use of LANDSAT imagery have appeared in the literature. Whilst a few of these represent innovative approaches to groundwater exploration, most are either straightforward case studies, or deal with other aspects of water resources unrelated to groundwater. To give one example, the proceedings of the Fifth W T Pecora symposium on remote sensing published in 1981 and entitled "Satellite Hydrology" contains only ten papers on groundwater-related subjects out of a total of 113 contributions (and, in fact, only two of these have any direct relevance to basement aquifer studies).

In preparing this review, and bearing in mind the particular objectives of the project, the fundamental question that was addressed in selecting material for inclusion was: "in what ways can remote sensing studies contribute to the search for groundwater in crystalline basement or in regolith?". It became apparent at an early stage that papers directly concerning this topic were few, and, in the event, this review has involved the bringing together of research in two often quite separate fields: those of the basement tectonics and hydrogeology.

Literature search statistics illustrate some of the problems referred to above. Stevenson (1982) in a review of groundwater in fractured rock reported that out of a total of 29,889 mentions of groundwater in a computer search, less than 200 were concerned with fractured hard rock. (Further examination of his reference list showed that only 3 of these involved remote sensing).

In the present study, a Georef search was instigated using the following keywords as input:

REMOTE SENSING + (TECTONICS or BASEMENT or STRUCTURE or HYDROGEOLOGY) + (AFRICA or INDIA or SE ASIA)

This search provided 236 hits. The majority, however, were found to have only a vague relevance to the theme: only 42 directly concerned the occurrence of groundwater in basement or regolith. A further difficulty resulted from the fact that relatively few of the relevant papers are published in international scientific journals, the majority being in comparatively obscure conference proceedings, consultants reports or in unpublished country reports; a similar observation was made by Stevenson (op cit). In view of this, a shortcoming of this review is likely to be the omission of potentially useful data contained in unpublished, restricted or proprietary reports prepared by geological surveys, aid organisations and hydrological consultants.

Despite such difficulties in obtaining reports, it is apparent from the searches undertaken that comparatively few comprehensive or innovative studies on this subject have been carried out. This conclusion is surprising and perhaps, even in itself, instructive. In view of the importance of zones of fracturing in crystalline basement and basins of deep weathering as targets for groundwater exploration over large regions of Africa and India, it was expected that several detailed reports on remote sensing inputs would be available. The fact that few such reports apparently exist confirms this as an important opportunity for applied research.

In contrast to the lack of reports concerning groundwater, there are abundant references in remote sensing literature relating to the enhancement, extraction, analysis and interpretation of lineaments, as well as other papers covering potentially important topics such as the detection of buried structures. Many of these subjects have relevance to groundwater exploration and are discussed in this report.

In summary than, three main subject areas will be considered in this review. These are:

1. Characteristics, processing and analysis of remotely sensed data.
2. Geological and geomorphological interpretation.
3. Structural analysis in areas of basement and regolith.

2. IMAGERY CHARACTERISTICS AND PROCESSING TECHNIQUES

2.1 Aerial photography and satellite imagery

Aerial photographs and satellite images are the two main forms of remote sensing media used in geology. Each is capable of providing valuable information about the earth's surface, and it is important to appreciate their differing characteristics and capabilities in order to understand their largely complementary roles in geology.

Aerial photographs record wavelengths in the visible and near infrared parts of the EM spectrum: various filter and film combinations allow the recording of sensitivities between UV and reflected IR (0.3 - 0.9μm). They are mostly low-altitude, large-scale images (scales usually greater than 1:60,000) with correspondingly high spatial resolution and information content. Overlapping photographs provide a parallax shift that allows adjacent images to be viewed stereoscopically, substantially improving interpretability. However, the combination of the optical system and low-altitude result in a radial displacement of relief features producing significant geometric distortion. Aerial photographs are widely available, comparatively cheap and can be processed and interpreted using largely unsophisticated equipment. Also, they are frame sensors, an advantage for some applications, and the nature of their optical distortions are fairly well understood and can be corrected for.

Space imagery of the earth includes photographs from several manned missions e.g. Gemini, Skylab, Shuttle and satellite scanner images, notably the Multispectral Scanner (MSS) and Thematic Mapper (TM) imagery from the LANDSAT series of satellites. Other space imagery includes radar and thermal infrared. MSS imagery is the most widely available and will be the main type discussed here.

The MSS sensor is a scanning imaging spectrometer system which records reflected solar radiation from successive 79m x 79m areas on the ground as it scans. For each such area it records in 4 wavelength bands, viz:

Band 4 (0.5-0.6μm) - green
Band 5 (0.6-0.7μm) - red
Band 6 (0.7-0.8μm) - reflected IR
Band 7 (0.8-1.1μm) - reflected IR

Blue is not recorded by the MSS (although it is on TM) in view of the attenuation of low wavelengths through atmospheric scattering. Data in each band are recorded as digital numbers representing pixel (picture element) brightness values. Once processed (see below) imagery may be viewed as panchromatic single band images or as a 3-colour composite. By convention, Band 4 is displayed in blue, Band 5 in green and Band 6 or 7 in red. This combination is called a "false colour composite" (FCC). A LANDSAT MSS scene covers a nominal area of 185km square.

Some of the advantages offered by LANDSAT imagery for geological applications include:

1. The synoptic view with uniform illumination which allows the easier recognition of regional features such as landforms, large faults, geological units and major boundaries.

2. Low to intermediate sun-angle which enhances subtle geological features, especially structures.

3. Repetitive imagery to show seasonal variation.

4. Digital format of imagery allowing computer enhancement of imagery and integration with other types of data. Low spatial resolution which makes boundaries that are gradational on the ground appear sharp on the image.

5. High spectral resolution allowing the discrimination of subtle tonal variations.

6. Lack of geometric distortion on corrected images and ability to warp to required projection.

Comparing aerial photography and MSS imagery it is apparent that whereas the former depends for information content largely on high spatial resolution, allowing the recognition of complex textural patterns and fine structural details, satellite imagery is more dependent on spectral sensitivity and large-scale patterns. Appropriate use of these different media is therefore largely a matter of scale.

2.2 Computer processing of satellite imagery

The ground reflectances recorded by the MSS sensor on the satellite are converted at the ground receiving station into a computer compatible tape (CCT) suitable for processing on an image analysis system to provide either an image on a graphics monitor, or a hard copy photographic film output. Raw data tapes consist of codified intensity values of pixels for each spectral band. Unprocessed data suffers from a number of distortions and noise effects which must be corrected before further enhancement and analysis is carried out. The techniques involved in image correction and enhancement are summarised below.

Image correction: Within the MSS an oscillating mirror scans across a swath width of 185km causing reflected radiation to fall on a bank of sensors arranged in 6 lines of 4 sensors corresponding to the 4 bandwidths. A drift in spectral response between the 6 detectors can produce miscalibration seen as sixth line scanner noise. Similarly, dropped lines result from data loss during acquisition or transmission. Both are corrected by recalculating line pixel values with reference to average values in the other sensors. Another example of radiometric distortion is atmospheric attenuation, due to the higher scattering of lower wavelength radiation. A haze correction may be applied to reduce these effects.

Geometric distortions are caused by variations in satellite altitude, attitude and speed, earth rotation and non-linearity in mirrror scan velocity. These can be corrected using LANDSAT tracking data and ground control points.

Bands 4, 5 and 6 are encoded in 7-bit format or 128 DN (digital number) intensity levels, whereas Band 7 is encoded in 6-bit format. During restoration all bands are usually re-scaled to 8-bit format. A DN value of 0 represents black and 255 white or full saturation.

Image enhancement: Enhancement techniques are applied to image tapes which have been previously corrected. Two basic techniques are used to enhance a digital image - stretching and filtering - although other types of data manipulation are also possible. The first changes the DN value of a pixel as a function of the brightness range of the entire scene, thereby changing the contrast of an image. The second technique changes the value of a pixel as a function of the values of neighbouring pixels; enhancement of detail relative to larger features is based on this approach. (e.g. Condit and Chavez, 1979).

Original MSS data usually occupies only part of the dynamic range of the system. The simplest and usually the most effective processing technique to enhance digital images is "contrast stretching". This involves assigning new intensity DN values to pixels to extend their distribution over the entire dynamic range (256 tone levels) whilst preserving their relative relationships. The conversion is achieved by a pixel-by-pixel transformation using a 'look-up table' calculated from the histogram of the original DN range. Various types of contrast stretch may be used to produce different effects including linear, 2-way linear, gaussian and histogram equalisation. As the names suggest, these convert the original DN distribution to a new distribution. A contrast stretch may be applied according to the DN histogram of the entire image or of a sub-image so that grey-level values can optimise the contrast between particular features of interest. Some saturation of DN values at the zero and maximum levels can be permitted to achieve a greater contrast increase in areas of interest. Contrast stretches may be designed through inspection of the band histogram and carried out in batch mode or interactively on an image display system.

A second important technique is "spatial filtering" which may be considered to be a contrast enhancement which takes specific account of the relationship between neighbouring pixels. Filtering may be used to smooth or defocus the data (low-pass filter) or sharpen the detail (high-pass filter). Thus it may be designed to enhance particular types of feature. The filter box is an array of pixels that is moved sequentially across the image. A low-pass filter (e.g. 3 lines x 3 samples) will return to the central pixel the average value of the 9 original pixels. This will result in a smoothed image and will serve to enhance features that are larger than the filter box. Conversly, a high-pass filter will calculate the average and subtract this from the original value of the central pixel. In this way features smaller than the size of the cell window will be enhanced. High-pass filtering is a particularly useful technique for enhancing linear features including lineaments. Several important variants exist that can, for example, serve to enhance 'edges' of different orientation. In addition, various add-backs of the original DN value are possible. If 100% is added back, for example, a version is produced in which the high frequencies are doubled and the low frequencies left the same: this is the usual form of 'edge enhancement'.

Another method of image enhancement is ratioing in which the ratio of two bands is calculated and the quotient contrast stretched. This may be used to emphasis spectral differences while suppressing topographic illumination effects and albedo variation: if a bright material and a light one are of identical colour their colour ratios will be identical irrespective of their albedo differences. Three sets of ratios may be combined to produce a false colour composite.

Finally, a little used technique with 4 band MSS data but one which has more application for 7 band TM data, is principal components analysis. Here, new variables are produced which are the uncorrelated transformation of the original highly correlated bands. By this means, a high percentage of the original total variation can generally be displayed in a single 3 principal component colour composite.

Many other sophisticated data manipulation techniques are possible and are discussed by Taranik (1978) and Condit and Chavez (1979) among others.

2.3 Thermal infrared imagery

The thermal IR region of the EM spectrum extends from the upper limit of the reflected IR at about 3µm to the lower limit of the microwave portion (1mm). The important region for thermal IR sensors is in the range 3-14µm covering the two atmospheric transmission windows at 3-5µm and 8-14µm. These wavelengths cannot be recorded by photographic film and require the use of special detectors and optical-mechanical scanners mounted on either aircraft or satellite platforms. The Daedalus airborne thematic mapper instrument (AADS 1268) flown in the NERC experimental campaign records a single thermal IR channel in the range 8.5-13µm. A new Daedalus thermal IR multispectral scanner (AADS 1285) includes 6 bands between 8.2 and 12.2µm. The Heat Capacity Mapping Mission (HCCM) satellite carried a 2-channel radiometer which included a single band covering the range 10.5-12.5µm. The LANDSAT 5 Thematic Mapper has a single thermal IR band in the range 10.4-12.5µm.

Thermal IR imagery can be used to deduce information on sub-surface soil moisture and perched water tables. The technique has potential application in the study of near-surface groundwater conditions such as those represented by dambos. However, in view of its less important application to basement studies only a brief outline is presented here. A fuller discussion may be found in Salomonson (1983).

Perched water tables influence surface and sub-surface soil temperatures because of a heat sink created by the high heat capacity of water (Heilman and Moore, 1981a). In general, a positive correlation is found between areas with shallow groundwater and low thermal IR emission (e.g. Huntley, 1978). Thermal IR may be recorded during day or night. It would seem,however, that the best results are obtained from imagery taken just before sunrise under low wind conditions and near to the autumnal equinox. The technique is applicable to aquifers occurring at depths affected to a significant degree by the diurnal variation in soil temperature, perhaps down as far as 4.5m (Moore and Myers, 1972; Heilman and Moore, 1981a). Interpretation of the data is complicated by environmental effects such as thermal inertia, evapotranspiration, topography, atmospheric absorption and others including the opposing effects on temperature of soil moisture under certain conditions (Heilman and Moore, 1981a; 1981b).

A related technique involves the estimation of thermal inertia determined from the diurnal temperature amplitude acquired during times of maximum and minimum temperatures. Variations in soil moisture content are reflected by changes in thermal inertia. Results of recent studies and further details of the method are given in Heilman and Moore (1981a), Ezra et al (1982) and Borriello et al (1982).

2.4 Radar imagery

Although not extensively used hitherto in groundwater surveys, radar systems have potential importance in this area, and are briefly described here.

Radar operates in the radio and microwave regions of the EM spectrum in the range 0.8-100cm (the commonly used bands in geology being Ka (0.86cm), X (3 and 3.2cm), and L (25cm). Unlike other "passive" forms of remote sensing, such as photographic and IR sensors, which detect available natural radiation, radar is an "active" system which provides a source of energy to "illuminate" the terrain and detects the returning energy beam which is recorded as imagery. Radar systems can be operated from aircraft or space platforms (e.g. SEASAT, SIR-A).

The way that microwave energy is returned from the target is to a large extent determined by the geometric/geomorphic features of the surface and its dielectric properties, as well as the energy wavelength and depression angle used by the system. These properties tend to be largely complementary to those of passive reflectance systems.

The potential value of radar in hydrogeological surveys is in two main areas. First, because the radar return signal is related to the dielectric properties of the surface there is the possibility of using this as an indication of soil moisture content (e.g. Schmugge, 1983). In a related application it has been demonstrated that under extremely dry conditions buried stream channels, lineaments and other sub-surface features can be detected through several metres of sand in the Sahara using SIR-A imagery (McCauley et al, 1982). Second, radar may be effectively used to highlight structural features such as lineaments that may be poorly represented on other types of imagery. This would appear to result from the suppression of surface detail due to low spatial resolution, and the shadowing effects caused by oblique illumination (e.g. MacDonald et al, 1967; Sabins, 1978). A number of studies have demonstrated that radar may be significantly better under particular circumstances (e.g. tropical forested terrain; subtle geomorphic features) than either aerial photographs or LANDSAT imagery (e.g. Snaveley and Wagner, 1966; Elachi, 1980; 1982). Radar also has the advantage of an "all weather" sensing capability.

Despite such advantages, the usefulness of radar is reduced by limited coverage, dependence on look-angle, aspect distortions etc., as well as a lack of basic research into groundwater applications. An up-to-date review of radar techniques and applications is given in Harris et al (1984).

3. REMOTE SENSING METHODOLOGY

The purpose of this section is to briefly summarise he main procedures likely to be followed in a remote sensing study related to groundwater. The list covers both general aspects of data acquisition and processing as well as stages of data extraction, analysis and interpretation. The exact methodology adopted will, of course, depend on the specific requirements of the groundwater search - the types of target and the scale of the project area - but many of the stages listed will need to be included to a greater or lesser extent.

Remote sensing will form only part of any groundwater programme and will need to be integrated with other phases of the work. Groundwater exploration may be divided into two general categories: regional surveys (generally covering 10km^2 or more) and local surveys. The benefits that accrue in the use of remote sensing are generally greater when this technique is applied at the beginning of a study. For example, evaluations carried out in Upper Volta and Niger have shown that the use of remote sensing to detect lineaments over basement areas can improve drilling success rates by as much as 40% and reduce overall costs of exploration by 35% (Amesz and Lausink, 1984). Regional reconnaissance usually involves the interpretation of satellite images at scales of between 1:1,000,000 and 1:250,000. Office-based studies employing one scientist can expect to cover in the region of 7,000 to 34,000 km^2 per day. Regional studies of this type will be used in conjunction with other data (e.g. geological reconnaissance, hydrologic reconnaissance, regional magnetic and gravity surveys) to categorise the main hydrogeologic characteristics of the broader region and to define smaller areas of high priority as targets for local follow-up studies, i.e. production of a groundwater exploration guide map (e.g. Zall and Russell, 1981). An additional phase of remote sensing, here using enlarged satellite imagery and aerial photographs, may again be employed to provide additional detailed information on potential aquifers. Rate of cover at this stage may be of the order of 100 to 500 km^2 per day. It should be noted that estimates of cover rate for remote sensing studies are broad generalisations, and moreover, do not include time for more sophisticated analysis of such features as drainage pattern or lineament density.

Papers which discuss in general terms a methodology for the use of remote sensed data in groundwater exploration include Zall and Russell, 1981; Schowengerdt et al, 1981; Sahai et al, 1982; Rao, 1982 and Stefouli and Osmaston, 1984. The following scheme is based partly on that provided by Salomonson, 1983.

A Regional Studies

Stage	Remarks
1. Acquisition of appropriate imagery as CCT.	Consideration to be given to low cloud cover; low sun angle (i.e. winter scenes) which enhance topographic features (e.g. lineaments); rainy-season images often reveal stratigraphy due to ground moisture and less atmospheric haze (Grootenboer, 1973) but dry-season imagery may provide groundwater data (see also Salomonson, 1983, p. 1506). Repetitive imagery may aid detection of shallow groundwater bodies (Cooley and Turner, 1982; Zafiryadis, 1982)
2. (a) Image restoration and enhancement	Restoration (or correction) may include:- drop-line correction; de-striping; atmospheric haze correction and geometric corrections (e.g. earth's rotation and map projection adjustments). Enhancement will involve contrast stretches for full scenes and sub-areas, and spatial filtering (for enhancement of 'edges', lineaments etc.)
(b) Photographic hardcopy/ interactive processing	An enhanced false colour composite (FCC) at the appropriate scale and map projection will be a general requirement. For lineament studies, a panchromatic Band 7 (near IR) may be used in addition, or as an alternative. Low cost (e.g. 35mm slides) photographs of interactive image analysis products (e.g. spatial filters) will be required in addition.
3. (a) Imagery interpretation	Analyse tones, textures, shapes, patterns, locations and associations. Specific studies of lineaments, drainage patterns, geomorphological features.

(b) Data analysis	Study and analysis of drainage and lineament patterns. Digitisation of lineament data and preparation of lineament density maps. Lithological and structural interpretation of imagery.
4. Ancillary data/Ground-truth	Assemble available supportive data including geological maps, land-use, hydrogeological data (e.g. borehole data), geophysics, rainfall, etc. Some limited aerial photograph work may help to resolve and identify imagery features. Reconnaissance ground-truth data acquisition (fieldwork) if practicable.
5. Correlation of imagery and ancillary data	Integration of various thematic types of information. Preparation of final interpretation maps and reports.
6. Recommendations for follow up studies.	

B. <u>Local Studies</u>

1. (a) Acquisition of appropriate scale B and W and/or colour aerial photography	Scales of between 1:20,000 and 1:60,000 are commonly used
(b) Process applicable sub-scenes from satellite imagery	Employ contrast stretches, geometric correction, spatial filtering, ratioing as appropriate. Photographic hardcopy at scales up to 1:100,000 (MSS) or (?)1:50,000 (TM).
2. Interpretation of aerial photograhy and satellite imagery.	Detailed analysis of land forms,textures and structures. Hydrogeological interpretation
3. Ground-truth/ancillary data	Indentification of major hydrogeological features on ground (e.g. rock types, structures).

4. PREPARATION OF HYDROGEOLOGIC GUIDE MAP FROM REMOTELY SENSED DATA

4.1 Summary and examples of interpretation criteria

In this section the criteria used to interpret remotely sensed data are described and some examples given of the application of these methods to particular groundwater problems. The principal objective of this phase of a remote sensing study is to provide a general interpretative map of the study area. Here, the imagery will be used to try to extract information on such features as distribution of geological units and surficial deposits, the nature of lithologies, structural features, geomorphological landforms, present and older drainage systems, distribution of surface water, weathering surfaces, vegetation patterns and agriculture. These data contribute to the understanding of the general hydrogeologic character of the region and can be used to prepare what Zall and Russell (1981) referred to as a 'groundwater exploration guide map'.

Shapes, patterns, tones and textures provide indirect evidence relating to near-surface or buried hydrogeological features. This stage should be regarded as a basic step in the interpretation process which may be followed by more detailed analyses, for example, in areas of basement rock by lineament studies. Among the features that may be used are the following (after Salomonson, 1983):

A. Near-surface (alluvial) groundwater indicators

(a) Shape or form

- -stream valleys, particularly broad valleys, with low stream gradients
- -underfit valley represented by topographically low, elongate areas
- -natural levees
- -meander loops defining the location and relative thickness of point bars
- -meander scars in lowlands, ox-bow lakes, arcuate dissection of upland areas
- -deltas
- -drainage line offsets, changes in drainage patterns, or changes in size or frequency of meanders (e.g. neotectonic fault influence)
- -braided channels and scars
- -alluvial fans

(b) Pattern

- -drainage patterns and deposits infer lithology and structural control and reflect permeability
- -distinctive types of natural vegetation may show upstream extensions of drainage patterns, areas of high soil moisture and landform outlines; abrupt changes in land cover type or land-use may reflect landforms that may be hydrologically significant but do not have characteristic shape

-elongate, sinuous or aligned lakes may represent remnants of a former stream valley
-topographically low, elongated, aligned areas represent abandoned stream valleys

(c) Tone

-Soil type: fine grain soils commonly darker than coarser grained
-Soil moisture: wet soils are darker than dry soils
-Vegetation: generally well adapted to type and thickness of soil, drainage pattern and seasonal variation of root zone

(d) Texture

-uniform or mixed types and species of native plants
-contrast between sparse vegetation on topographic highs and dense vegetation in low (wetter) areas

B. <u>Consolidated rock aquifers</u>

(e) Outcropping rock type

-landform, relief
-outcrop patterns; banded patterns for sedimentary and some metamorphic rocks; fold structures; volcanic flows; erosional appearance
-drainage patterns, density and texture
-fracture types and symmetry (as inferred from lineaments and drainage patterns
-abundance, shape and distribution of surface standing water
-tones and textures; the total effects of lithology, structure and texture often reflected in vegetation patterns

(f) lineaments

-continuous or discontinuous stream channels, valleys, ridges, gaps
-elongate or aligned lakes, sinkholes and volcanoes
-aligned deflections in adjacent stream channels, valleys or ridges
-elongate or aligned native vegetation patterns
-alignment of dark or light soil tones

The relative importance of the criteria listed will depend upon the geographical and geological conditions, and upon the aquifer type sought. Basement aquifers are primarily a function of structural control and this is looked at in detail in a later section. There are several examples in the literature of the value of surficial studies which may also have relevance to areas of regolith.

In the western desert of Egypt, studies by El Shazly et al (1977; 1982) found that although major structures (large lineaments, probably faults) provided the fundamental regional control in the location of groundwater, local variations were strongly dependent on the presence and type of younger surficial deposits, the distribution of which could be mapped using LANDSAT imagery. A similar use of satellite imagery was made by Salman (1983), who was able to identify two sedimentary units, each representing a different form of important aquifer. In Libya, Giovacchini et al (1982) used imagery to map the distribution of Quaternary alluvial deposits and geomorphological units which provided a basis for interpreting groundwater flow in the region.

The possibility of groundwater storage in dunes was investigated by Kruck (1981) in the Republic of Niger. Streams in the Liptako area flow only during a quite short rainy season. In several instances these river courses are dammed by fixed dunes which result in the formation of temporary lakes that become sediment pans (mares). Groundwater presumably occurs in the former continuation of present river beds beneath dunes, which can be mapped from photographs or imagery, which would be repeatedly recharged and continuously protected against evaporation. Figure 1 from Kruck's study provides an example of the type of information that can be included on hydrogeological interpretation map from LANDSAT imagery.

An example of the interpretation of features observable on satellite imagery is given in a paper by Sahai et al (1982). These authors studied the lithlogical and structural criteria controlling groundwater in an arid/semi-arid area of Gujarat, western India, covered by Deccan basalts, sedimentatary rocks and alluvial deposits. Table 1 from their report is a list of the hydrogeological features recognised and inferences for groundwater potential in each zone.

LANDSAT imagery can be expected to be of use at the reconnaissance stage in the regional identification and mapping of dambos. Soil moisture content and vegetation pattern are likely to be well-displayed on wet-season imagery, whilst dry-season imagery will contain information on phreatophyte distribution relating to maintained area of relative near-surface groundwater (Moore and Deutsch, 1975; Berlin et al 1982).

As previously mentioned, in Africa some of the most productive aquifers are fractured or faulted zones in bedrock where the shattered rock possesses good porosity and permeability. Satellite images and/or aerial photographs can be used initially to map out areas of hard rock such as basement. The principal distinguishing characteristics will include topographic elevation, textural fabric, light drainage density and tonal character. In general, the goal of the geological remote sensing studies over hard-rock areas is to map out lineaments as indicators of fracture pattern as this provides one of the best criteria for determining likely groundwater occurrences. (Drainage pattern analysis and lineament analysis are discussed more fully below). Areas of regolith, occupying weathering basins overlying basement, are identified by contrasts in the above mentioned features. Referring to hydrogeological studies in Sahelian zone of Mali, Upper Volta and Niger, the following extract from the review by Cooley and Turner (1982) provides a good example of the applicability of LANDSAT imagery.

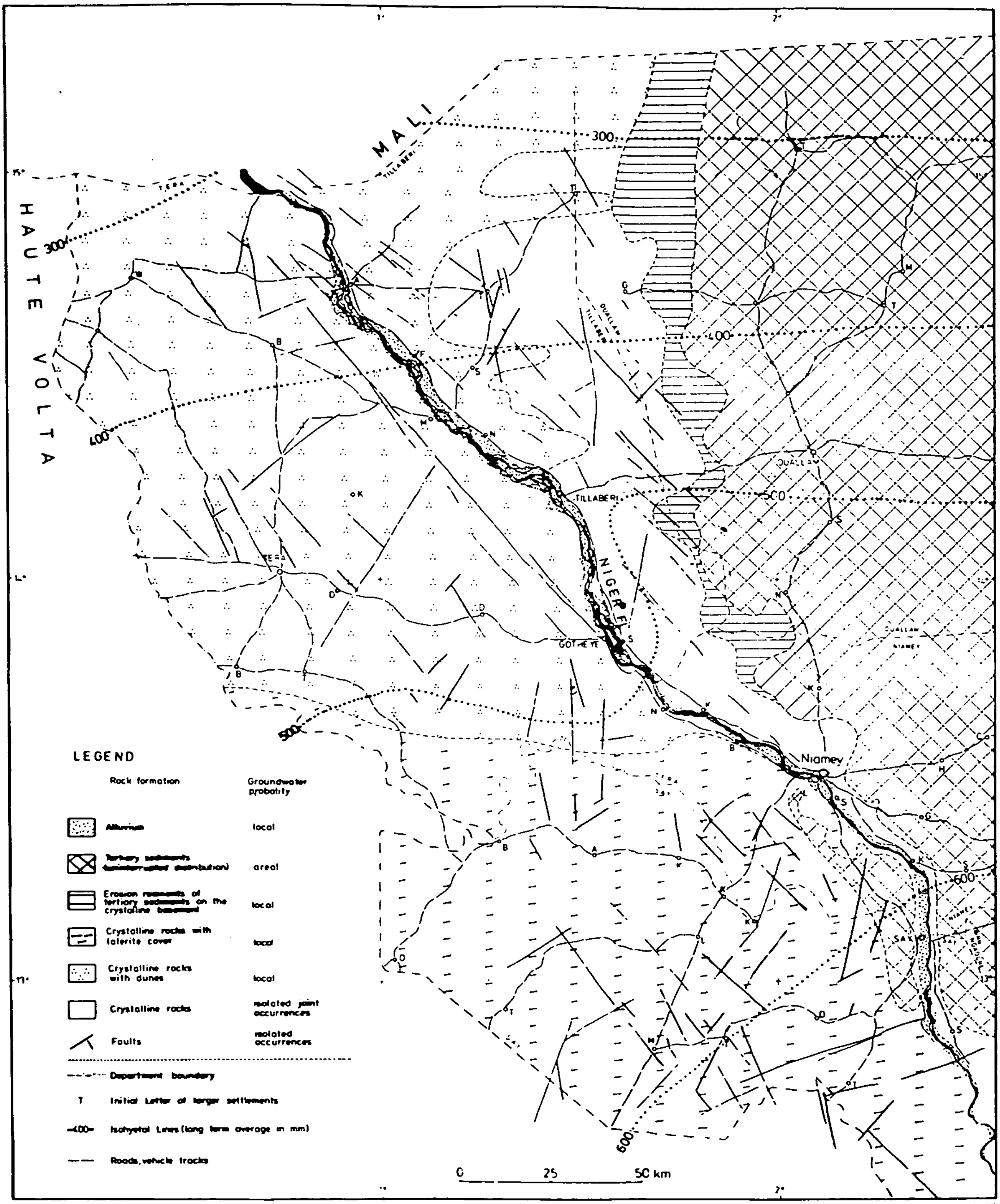


Figure 1 Republic of Niger: Liptako – Hydrogeologic Interpretation of Landsat Images.

Table I. Potential areas for groundwater exploration

Location	Hydrogeological features	Inference
1. Dhari basin (Dhari, Bagasra and Chalala) (21°25'N, 71°10'E)*	Faults, straight river courses, anomalous vegetation	Thick alluvium, presence of fracture system
2. Bhadar, Uben basins, west of Dhoraji (21°50'N, 70°20'E)	Palaeochannel (old flood plain, buried/abandoned channel), vegetation anomalies	Alluvium fine-grained material as shallow aquifer
3. Bhadar basin (Saradiya, Sardargarh) (21°35'N, 70°00'E)	Anomalous vegetation, lithological contact, wider river beds, disappearing streams, alluvial fans	Fracture system, buried channels, alluvium
4. Ojat-Uben basin (Mandodara) (21°25'N, 70°10'E)	Alluvial fan, lithological contact, anomalous vegetation, wider river bed	Thick alluvium, fracture system, fine-grained material
5. Shetrunji basin, west of Gariadhar (21°30'N, 71°30'E)	Controlled stream, domal structure, dykes, wider river beds	Fracture system, subsurface structure and dykes for impounding subsurface water
6. Rangola river basin (21°45'N, 72°00'E)	Lithological contact, inferred fault, anomalous vegetation, wider river channel	Fracture system, thick alluvium fine-grained material
7. Ghela and Keri Nadi basins (21°00'N, 71°55'E)	Aligned stream (presence of fracture), thick vegetation, wider and braided river channel	Fracture system, fine-grained material
8. Bhadar basin (Eastern Saurashtra) Near Dhandhuka (22°25'N, 72°00'E)	Anomalous vegetation, wider and braided river channels	Thick alluvium, fine-grained material
9. North of Than (22°40'N, 71°10'E)	Thick vegetation, lineaments	Fracture system, alluvium
10. North of Kandorna (22°00'N, 70°25'E)	Thick vegetation, lineaments	Fracture system, buried channel
11. East of Rawal (21°55'N, 69°35'E)	Lithological contact, thick vegetation	Fracture system, buried channel
12. Southeast of Khambhaliya (22°05'N, 69°35'E)	Fractures, annular drainage	Fracture system, suitable sub-surface structure (domal)
13. Vasavad-Babra (21°55'N, 71°10'E)	Dyke swarm, fractures	Impounded subsurface water
14. North of Rajula (21°10'N, 71°30'E)	Dyke swarm, fractures and lineaments	Impounded groundwater

* Mean coordinates of the location.

"(2) Can weathered or fractured zones in the Precambrian crystalline basement rocks, likely to be productive of groundwater, be identified?

Generally, the Precambrian basement rocks are concealed by laterite duricrust or by a thin surficial mantle of alluvium. Near Ouagadougou, hand-dug wells, penetrating through the laterite, yield small amounts of water ... from deeply weathered regolith developed in the upper part of the basement rocks. The area of low relief is identifiable on the imagery because of the generally light, rather even colour tone and general lack of conspicuous drainage features.

Linears identifiable on the imagery in areas of consolidated rocks may be related to faults, fractures and joints along which water movement and accumulation are facilitated. Weathering in such zones, and especially at points of intersection would improve the potential for accumulation of important sources of water." (p. 14).

4.2 Drainage pattern analysis

According to Charon (1974) drainage lines are one of the most important indicators of hydrogeological features. Drainage pattern, texture and density (i.e. total linear length of drainage channels per unit area) are determined in a fundamental way by the underlying lithology, and an analysis of these features can provide accurate information on both rock type and permeability.

The type of drainage pattern developed is a reflction of the amount of precipitation that can penetrate the ground as compared to that which is discharged through surface run-off. This infiltration/run-off relationship is controlled largely by the permeability of the ground, which is in turn a function of rock type and fracturing. Comparing two terrain types, that which contains the highest drainage density is usually the less permeable. According to Salman (1983) the correlation is more precise or even quantifiable. He considers that "terrain transmissibility is inversely proportional to the square of the drainage density" (p. 185), although he provides no direct evidence in support of this statement.

Figure 2 taken from Zall and Russell (1981) illustrates some of the major types of drainage patterns, which include dendritic, rectangular, trellis and parallel. Very coarse drainage textures will initially serve to distinguish the more permeable surficial deposits such as alluvium. In areas underlain by hard rock, stream networks consisting of straight or angular segments may be interpreted as fractured or jointed terrain, whereas finer, less regular or dendritic patterns would be characteristic of less permeable, unfractured rock types (e.g. Owen and Shown, 1976).

Drainage pattern variations, used either separately or in combination with lineament studies of the same imagery, may be used in the first instance to map out boundaries between rock types. In Upper Volta, Zall and Russell

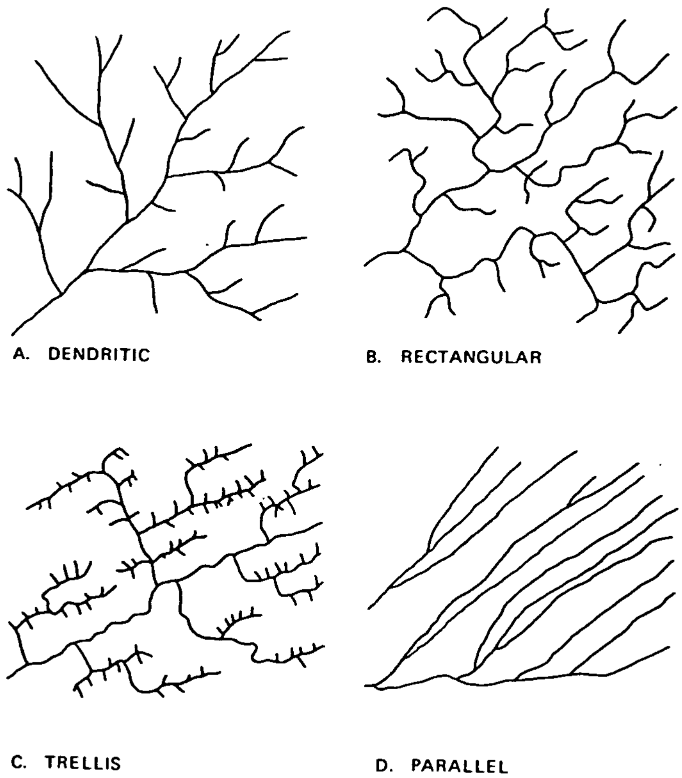
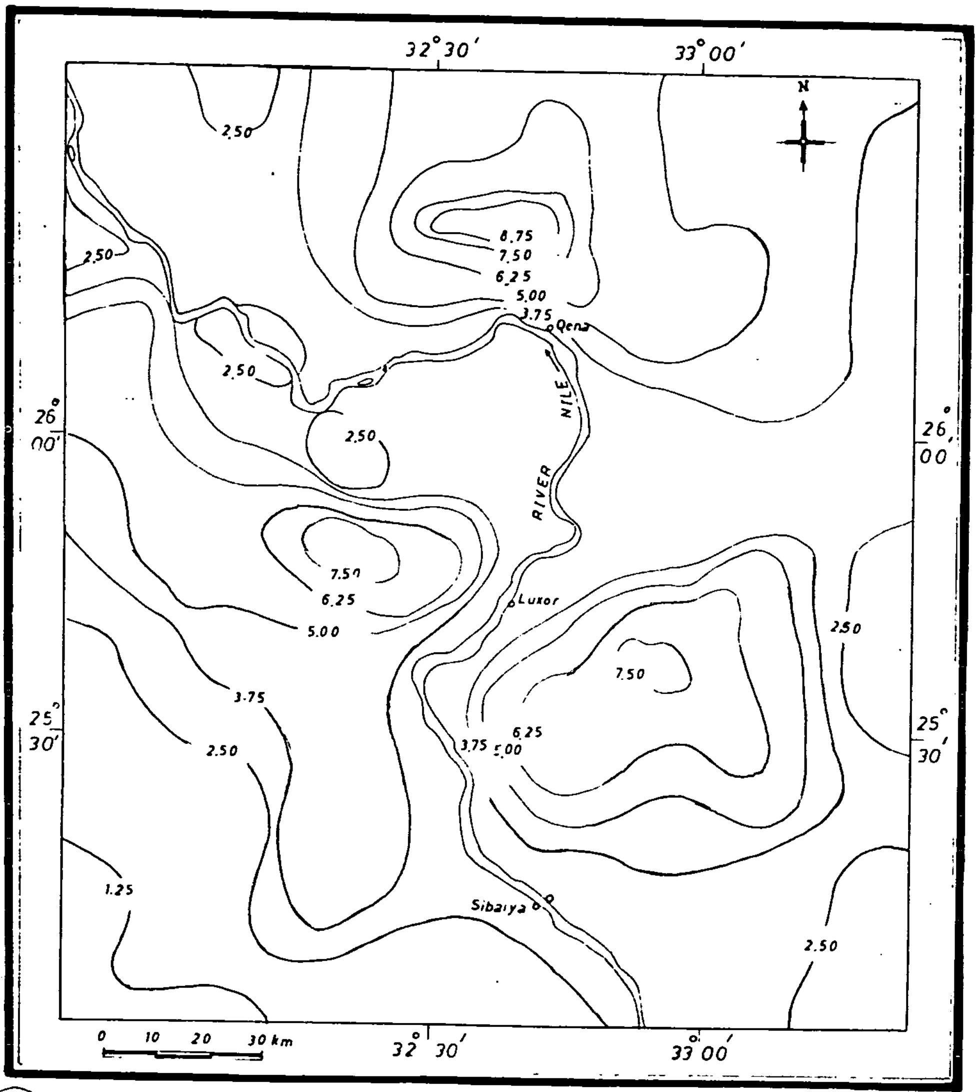


Figure 2 Some of the Basic Drainage Patterns Which Provide Structural and Lithological Information.



5.00 Contour lines (Number of drainage lines intersections / km²)

Figure 3. Drainage density map, Qena Province, Egypt (based on Landsat images, 1972).

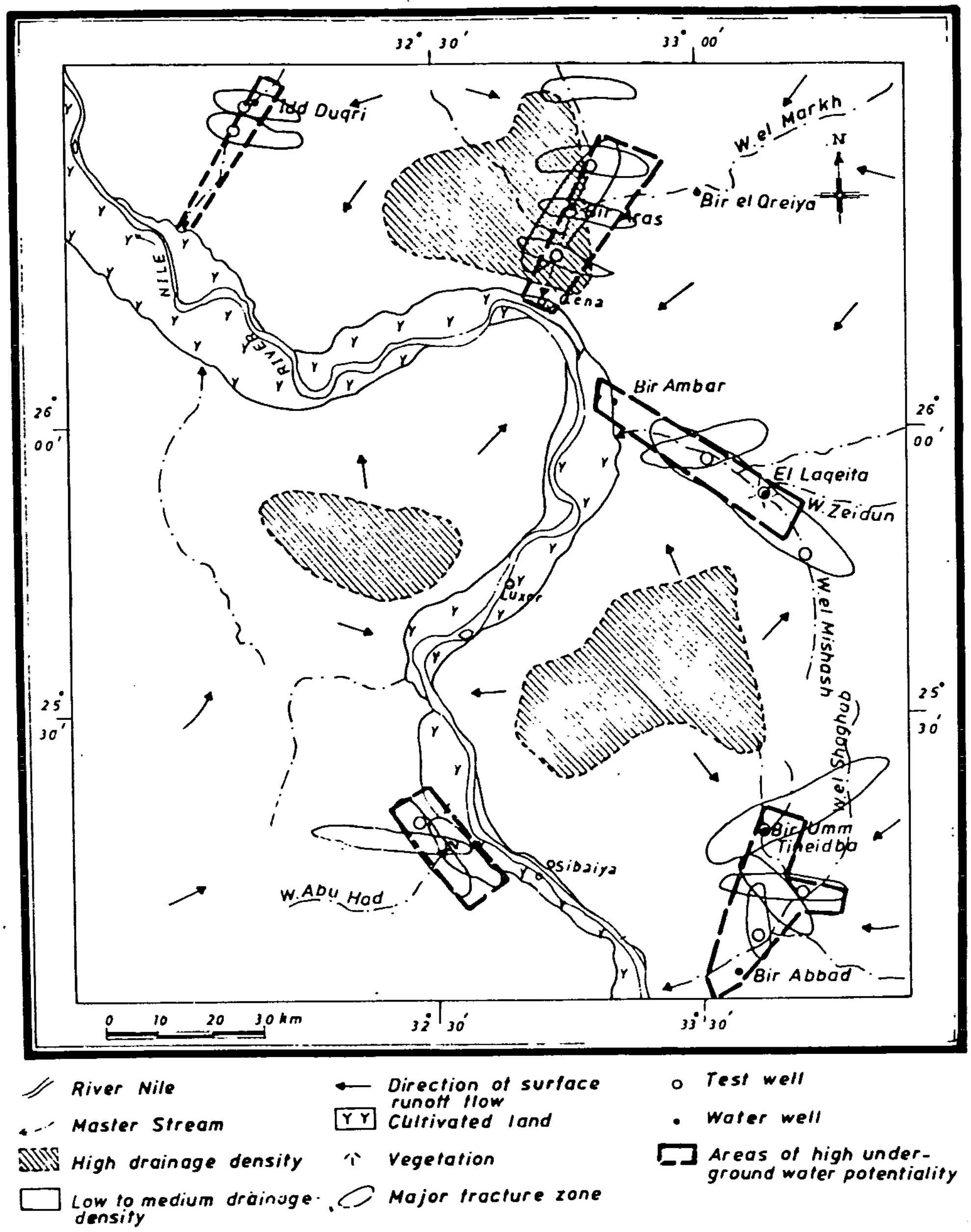


Figure 4 Map of groundwater-exploration areas, Qena Province, Egypt (based on Landsat images, 1972).

(1981) showed that the change in character of the regional drainage pattern could be used to accurately delimit the boundaries between sandstone (widely spaced, rectangular) and gneiss (denser, angular, dendritic). Similarly Sahai et al (1982) used drainage texture to map out areas of Deccan Traps basalt, having 'medium drainage texture', from unconsolidated and Jurassic sandstones possessing 'a coarse to very coarse' drainage texture suggestive of a highly permeable lithology.

A more systematic approach involves the construction of a drainage density plot - prepared either manually of by computer processing of previously-digitised drainage data. Salman (1983) provides an example of this approach for an area in Egypt. Fig. 3 is Salman's density map and Fig. 4 shows how areas of high drainage were used by him as input to a groundwater exploration map. Comparisons with his geological map of the region shows that lithological units, which include coarse-grained porous beds, are of low drainage density.

Drainage pattern analysis would seem to be a potentially useful technique at both the regional and local level in groundwater exploration in areas of Basement Complex and regolith. Both drainage pattern and density studies can provide information on relative permeability of rock types, and aid in defining lithological boundaries. This approach would supplement lineament studies and could make use of similar data processing techniques to those described elsewhere in this review.

5. LINEAMENT STUDIES

5.1 Definitions and general concepts

The term 'lineament' was introduced by Hobbs (1904) to describe linear geomorphic features that he considered the surface expression of sub-surface geological phenomena. Hobbs (1912) defined lineaments as "the significant lines of landscape which reveal the hidden architecture of the rock basement" and "character lines of the earth's physiognomy" (p 227). Among the landscape features that Hobbs included were: crests of ridges or boundaries of elevated areas; drainage lines; crest lines; boundary lines of formations, of petrographic rock types, or of lines of outcrop; ravines or valleys; lines of fractures or zones of fault breccia. Importantly, he did not restrict the term only to lines of displacement.

Present day usage defines lineament as "a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a sub-surface phenomenon" (O'Leary, Freidman and Pohn, 1976, p 1467). The surface features comprising a lineament may be physiographic (expressing relief) - such as landforms, or the boundaries between different types of terrain - or tonal (expressing contrast) - such as boundaries between areas of contrasting brightness, or a stripe against a contrasting background. Differences in vegetation, moisture content or soil/rock composition account for most tonal lineaments.

Although offset (i.e. fault displacement) is not an essential requirement in the definition, a lineament is regarded as the manifestation of a geological discontinuity. Modern usage thus tends to exclude some of Hobbs categories, such as bedding or other clearly non-structural features. In practical terms, however, many remote sensing studies will include in the initial dataset linear features of other than structural - or even geological - origin (i.e. man-made features). In a sense these too must be regarded as lineaments until such time as ground data or other information can be used to screen out spurious data. The close scrutiny and interpretation of lineament data is consequently an essential element of any study.

No maximum or minimum length is included in the definition of a lineament, which will depend primarily on the scale of the photography or imagery used in the study. Intrinsically, however, the aspect ratio (length/width) of any features identified as a lineament will be very large.

Lineaments may be recognised on remotely sensed images including aerial photographs, satellite scanner images and radar images, as well as on topographic, gravity, magnetic and seismic contour maps etc, where they will be formed of such elements as aligned highs and lows, steep contour gradients or aligned offsets of trends. Lineaments are particularly well expressed on LANDSAT images because of the oblique illumination, suppression of spatial details and regional coverage (Sabins, 1978) although a bias may result from illumination and scan directions. However, the use of aerial photographs for lineament analysis of small areas - or as a follow-up to regional studies involving the use of satellite imagery - remains a valuable, though often neglected, technique.

It is perhaps pertinent at this point to consider more precisely what the lineaments identified on aerial photographs or satellite images actually represent on the ground and why these features are important from the point of view of groundwater exploration. In general, aerial photograph lineaments are small-scale features, commonly without significant topographic expression, which can often reliably be interpreted as discrete fractures (joints, zones of joint concentration or faults: Lattman and Matzke, 1961). Satellite lineaments, on the other hands, tend to be much larger, composite features, having important topographic expression, which are often found to represent major fracture zones. On the ground such zones may comprise a complex of smaller en echelon or intersecting faults, joints or breccia zones. It is because such fractures and fracture zones are generally less resistant to erosion than unfractured rock that valleys and stream segments tend to run along them. Zones of fracturing or shattering, also result in increased porosity and permeability so that the broken rock may itself become an aquifer. Alternatively, such zones of high transmissibility may either permit ingress of surface water to some deeper aquifer or control discharge of groundwater to an overlying high capacity aquifer or along a line of springs. As discussed later, differences in well yields often tend to reflect differences in degree of fracturing or weathering rather than inherent differences of mineralogy or fabric within the rock (Davis and De Wiest, 1976).

From a hydrogeological viewpoint the main advantage of satellite imagery is to reduce the need for fieldwork which, in large regional studies, is the most costly and time-consuming phase of a groundwater survey. Additionally, many large regional fractures which can be easily recognised on satellite imagery would be difficult or impossible to detect on the ground or on low-altitude aerial photographs. Thus the synoptic view and the apparent sharpness of boundaries that appear gradational on the ground offer the two main advantages over aircraft photographs. Targets of interest - and these often include the large-scale features to which LANDSAT interpretation is best suited - can commonly be delineated in less than half the time required with aerial photographs (Moore and Deutsch, 1975). Moreover, the accuracy is adequate for many hydrogeological purposes.

Finally the following extract from a paper by Moore and Holliday (1976) serves to illustrate the unique role of satellite imagery in the detection of large structures:

> "The Beech Grove lineament is not obvious on maps or on either low or high altitude aerial photographs. Furthermore, it was not recognised as having regional extent during detailed geological mapping on the ground. The lineament can be seen and traced on Skylab photographs, but its continuity and possible significance are not as obvious as on ERTS [=LANDSAT] imagery; the synoptic view of ERTS imagery was necessary for the detection of this lineament." (p. 164).

5.2 Rock stress and fracturing

Fundamental to the interpretation of lineaments is an understanding of the nature of rock stress and fracturing. A rock is said to be in a state of stress when a force is applied to it. Unlike force, which is a vector quantity, stress (defined as force/unit area) is a three-dimensional entity, called a tensor, which requires either 6 or 9 quantities to describe it. The state of stress in a body is described by considering the stresses acting on each surface of a small cube at a point within the body. On each face the force F can be resolved into a normal stress (σ) and a shearing stress (τ), the latter of which may itself be resolved into two components orientated parallel to the axes of the chosen co-ordinate system (Figure 5A). Any number of forces acting on the cube from various directions may be added to produce a single resultant set of 18 stress components (Figure 5B). Because shearing stress components acting on the six faces of the point cube tend to cancel one another, three mutually perpendicular planes are found to exist in which shearing stresses vanish and the total stress condition can be described in terms of the normal stresses to these planes. These are denoted the maximum (σ_1), intermediate (σ_2) and minimum (σ_3) principal stresses.

The physical effect of stress on rocks (i.e. strain) depends upon such features as pressure, pore fluid, deformation rate, mineralogy etc. Brittle deformation causing fracturing occurs at high stress values, exceeding the ultimate strength of the material concerned. A common observation from both experimental work on brittle failure and field studies, is that such failure occurs by shearing along conjugate planes orientated at an angle of 45° or

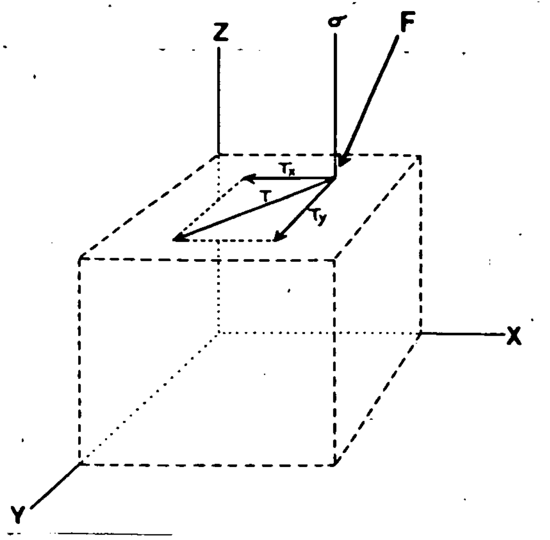


FIGURE 5A Resolution of a force *F* into normal (sigma) and shear (tau) components. The shear is resolved into components parallel to the coordinate axes.

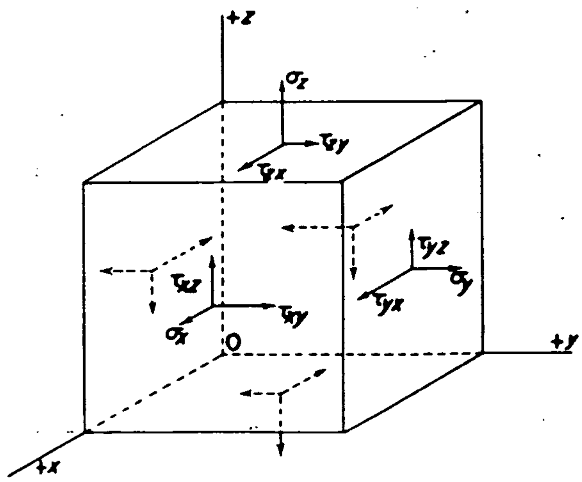


FIGURE 5B Stresses on a cubical element in equilibrium. (*From Varnes, 1962.*)

less (usually around 30°) to the maximum principal stress axis and containing the intermediate principal stress direction. In addition, irregular tension partings, lying within the plane of the maximum and intermediate principal stresses, may occur formed as an early response to compressional stress: these openings tend to give way to shear fractures as the stresses increase (Figure 6).

Anderson (1951) argued that the normal to the earth's surface tends to be one of principal stress directions. With this assumption, he recognised three likely cases of stress distribution causing faulting: (i) maximum principal stress vertical - normal faults (ii) maximum and intermediate principal stresses horizontal - thrust/reverse faults and (iii) maximum and minimum principal stresses horizontal - wrench/strike-slip faults (Figure 7).

Since conjugate shear fractures tend to develop in a constant relationship to the principal stress directions, the determination of these shears may be used to reconstruct the palaeostress configuration. In the field, geological evidence of rock displacement and/or slickensides will determine the nature of the fault movement and whether or not families of fractures relate to a single or multiple tectonic event. However, remote sensing lineament studies without corroborative field evidence may support a variety of interpretations. Thus, for example, a set of intersecting fracture directions may equally well represent conjugate shears or the traces of two superimposed episodes of normal faulting formed under different stress conditions (Figure 8). The likelihood of multiple stress events in a single area, especially in older cratonic regions, is strong and it may be impossible to distinguish these situations using remote sensing data alone.

Because it is considerably easier to explain intersecting fractures derived from remote sensing studies as conjugate shears produced by a strike-slip stress configuration, there has been a tendency to interpret such datasets in this way without any fundamental justification for so doing. This is exemplified by the Tectosat model promulgated by Nigel Press Associates, which they have applied to parts of both Europe and Africa. The model follows the early work of Moody and Hill (1956), who suggested that once the initial conjugate strike-slip shear is developed, local stress conditions are re-orientated so that second-order and subsequent sets of shears are developed, each with diminishing intensity. The Tectosat model also includes the development of subsidiary shears - called Reidel shears - and tensional openings. The approach is to overlay a Tectosat protractor (Figure 9) over the lineament rose diagram positioned according to the maximum lineament peaks and then read off the directions of σ_1 and σ_3. It is evident that virtually any lineament pattern can be interpreted in this way regardless of whether the direcions actually relate to a single stress event.

Whereas the determination of palaeostress is not generally of importance in hydrogeology, it may have relevance in the context of open or closed fractures. In this regard, a study undertaken in Botswana by VIAK, a Scandinavian firm of consultants, is interesting and requires comment. The model they use seeks to identify certain lineaments as tensional openings (rather than shears) on the basis that these will act as the main water-bearing fissures. From their description, it would seem that they too make the initial assumption that fracture sets intersecting at about 60° will be conjugate shears. The model (Figure 10) assumes that in addition to

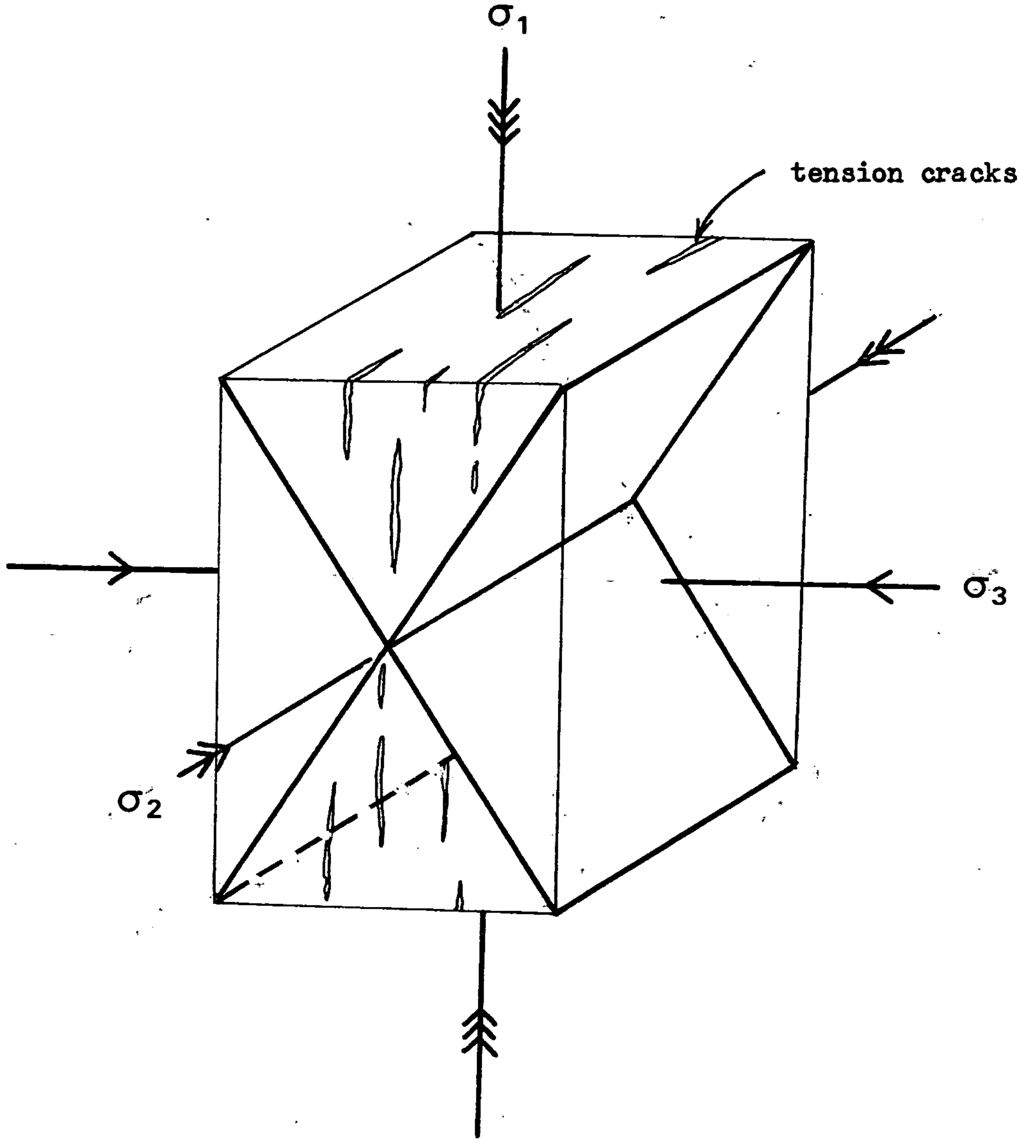


Figure 6: Relationships between the principle stress directions and the formation of shear planes and early tension cracks.

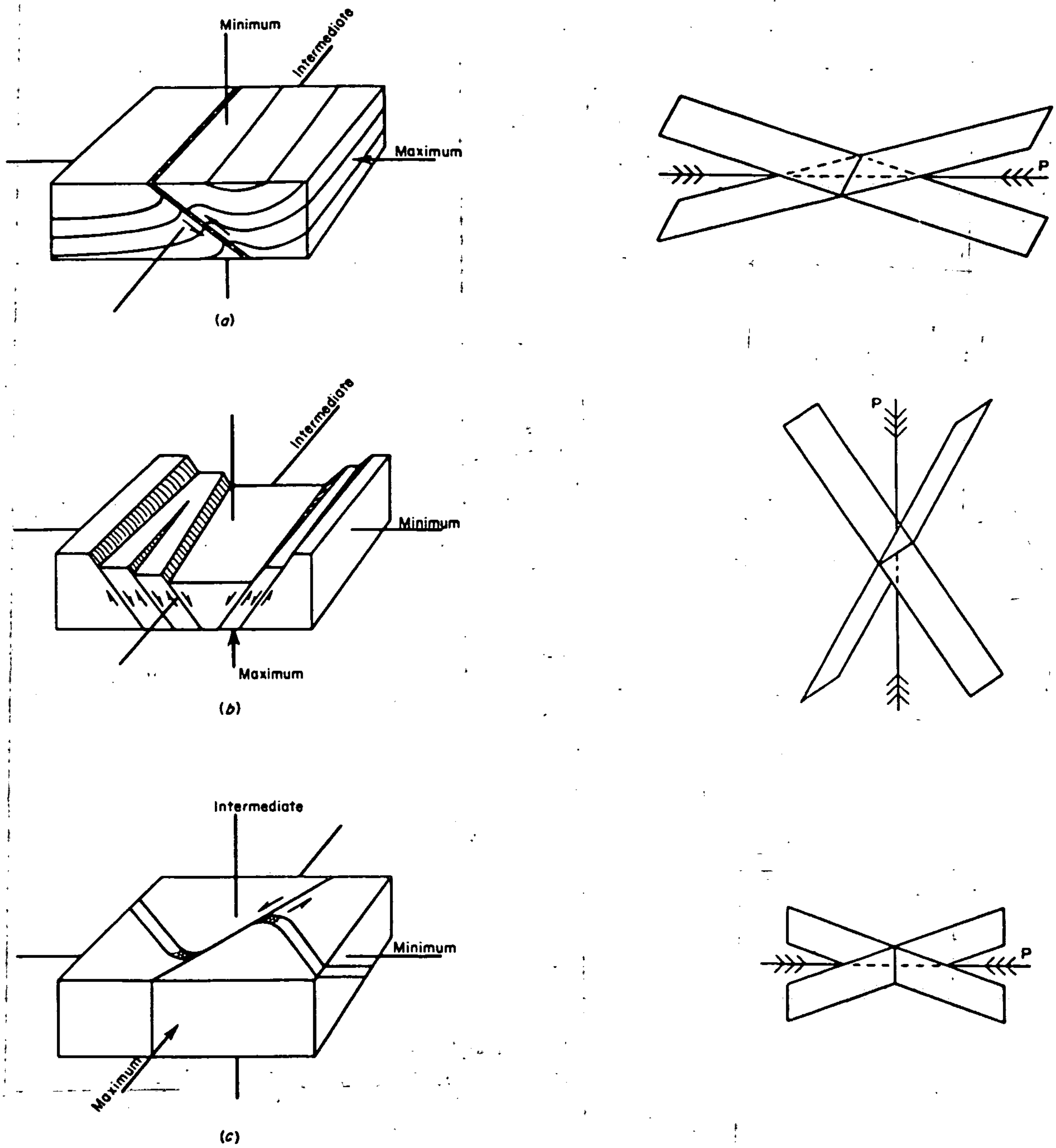
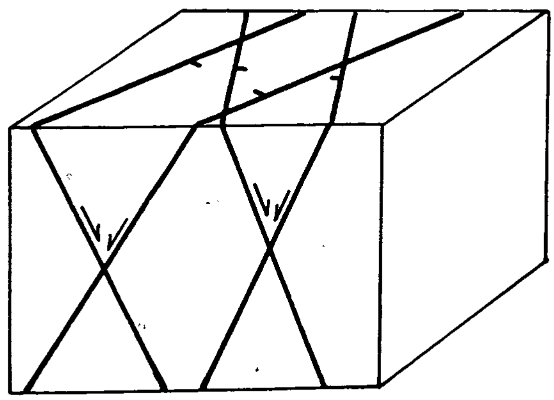
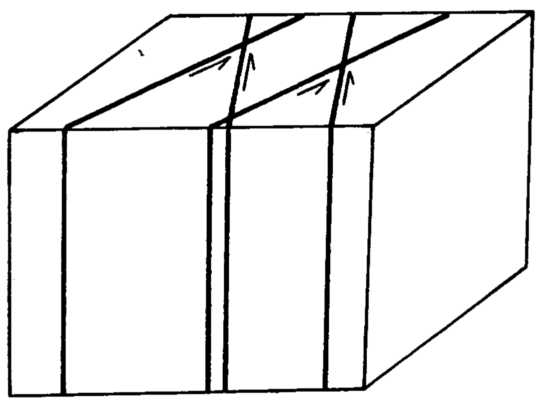


FIGURE 7 Relationship between principal stresses and common fault orientations, for thrust, normal, and strike-slip faults. (*After Anderson, 1951.*)



(a)



(b)

Figure 8: Alternative explanations of intersecting sets of surface lineaments. (a) 2 sets of normal faults formed under different stress configurations (b) conjugate strike-slip faults.

Figure 9 - Plan diagram of the Tectosat Wrench-Fault Model with $2\theta = 80^{o}$.

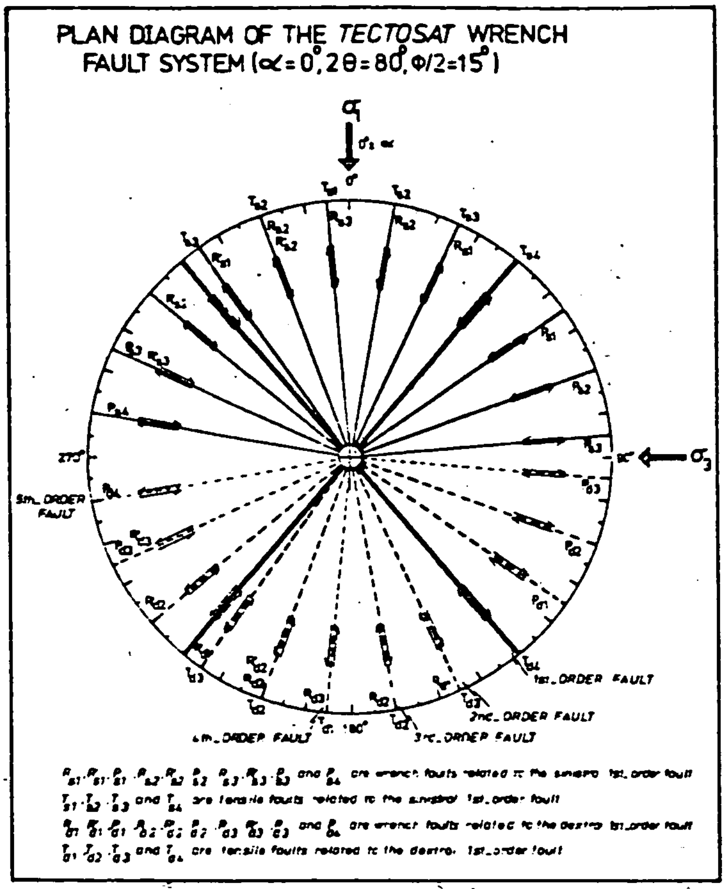
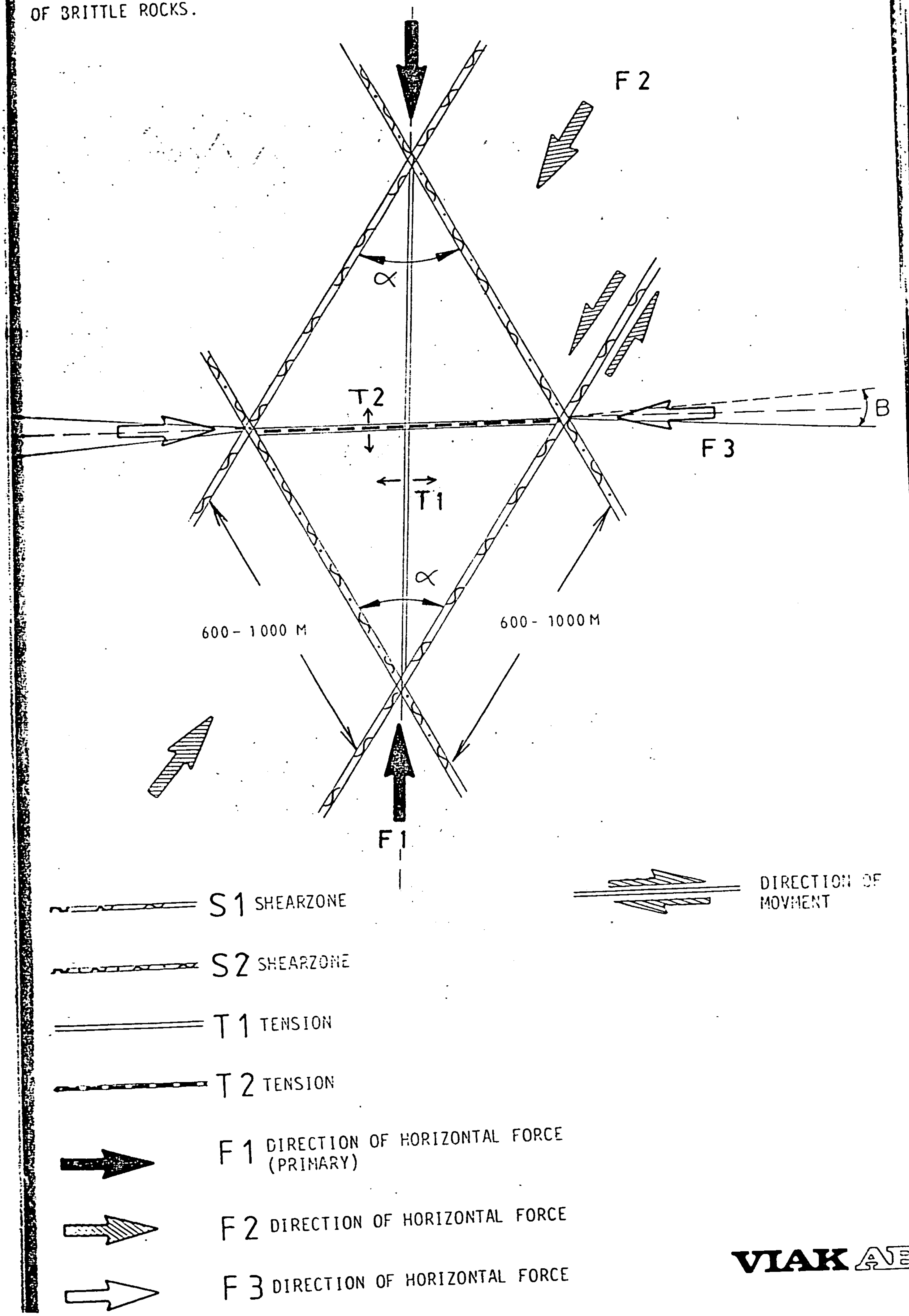


FIG.10

SIMPLIFIED TECTONIC MODEL FOR FRACTURING OF BRITTLE ROCKS.



VIAK AB

these, more irregular, tensional fractures (T1) will develop parallel to the maximum principal stress (F1). The model also involves an unexplained rotation of F1 to F2 and F3 and the formation of a second set of tensional partings (T2). According to them, the rhomb pattern occurs with a regional fracture spacing of 60-100km. Tensional cracks will occur bisecting these shears (evident as weaker lineaments presumably?) but their existence will need to be followed up on aerial photographs or by fieldwork. The example they give is unconvincing. They note, for example, that one of the tension directions was identified from satellite imagery only, whilst the two main shear directions were most prominent on aerial photographs! Moreover, the measured directions provide a poor match for the theoretical model proposed (the shears are almost orthogonal and the tensions do not bisect them). In general, it would seem highly suspect, without extensive field studies, either to attempt to separate lineaments into tensional and shear, or to assume that fractures are necessarily conjugate. Moreover, although tension fractures are perhaps more likely to have good porosity, they would seem less likely to be continuous and might consequently possess low permeability.

It is also interesting to note the difference of approach in studies carried out by the Swedish Nuclear Fuel Supply Company, SKBF/KBS and others. In their work, blocks of country between identified fractures are regarded as having low groundwater flow and thus as possible candidates for radioactive waste disposal.

In conclusion, it would seem that there is no simple route to interpreting the tectonic significance of lineaments from remote sensing studies. Such interpretation must depend on either prior knowledge of the tectonic history of the region or on supporting field work.

5.3 Regional tectonic controls affecting groundwater

As noted above, the regional view provided by satellite images makes them ideally suited to observing large-scale structures, such as major lineaments, that would not be detected at a more detailed scale. Such data can provide evidence of the major tectonic controls affecting the basement and cover materials that could have significance in understanding regional groundwater supply.

Several hydrogeological studies touch on this subject and many other remote sensing papers deal with general tectonic models developed from a study of LANDSAT imagery. Though few of these directly concern the question of groundwater in basement or regolith they demonstrate the usefulness of the regional tectonic approach (Kogbe, 1983a; 1983b).

Kruck (1981) reports on a hydrogeological study using LANDSAT imagery carried out over the aeolian and laucustrine Kalahari Beds of northern Botswana. The swamp area has a complex geological history and, according to Kruck, comprehension of the hydrogeological conditions depends on the reconstruction of the tectonic, paleogeographical and climatological development of the region in the younger Quaternary in connection with known groundwater data. A reconstruction of recent tectonic events was achieved through an interpretation of satellite-derived lineament data in conjunction with facies distribution data and seismicity records - a result which would have been virtually impossible by other means. It was concluded that the Okavango delta is situated in a embryonic graben-structure which has controlled sedimentation in several localised depressions by repeated jostling movements along a number of major and antithetic faults. This interpretation and the understanding of tectonic relationships provided a basis for explaining the regional hydrogeological conditions such as groundwater flow, salinisation and regeneration.

The importance of regional faults in controlling the location and discharge of groundwater in the western desert of Egypt has been demonstrated in several studies by El Shazly and coworkers (1977; 1982). LANDSAT interpretation was carried out over an area including Siwa, Kharga and Dakhla oases. The influence of major structural lineaments identified during this work on the locations of these surface discharges was apparent in all three cases. It was concluded that major faults controlled both the configuration of the oasis depressions and the upward flow of groundwater in the region from the more extensive aquifer below.

In Upper Volta, Amesz and Lausink (1984) note that in the hard rock, which is only permeable through fractures, lineaments represent potential zones of infiltration and groundwater percolation. Lineament patterns can therefore provide a good indication of how an aquifer functions, describing recharge and storage areas, and providing a guide to the direction of groundwater flow.

As indicated previously a great many remote sensing studies have been carried out that demonstrate the value of large though subtle lineaments in interpreting regional tectonic events (e.g. Viljoen and Viljoen, 1973). Whereas it is not appropriate to review such studies here, it is worthwhile noting that satellite imagery often affords the best, or indeed, only approach towards interpreting such regional features.

Despite few hydrogeological examples, the potential importance of this approach in areas of Basement Complex and associated regolith where tectonic control is suspected, seems clear. For example there is a strong possibility that many basins of weathering are structurally controlled. LANDSAT studies should make it possible to detect the presence of either major boundary fractures or of fractures along which deep weathering developed. Reconstruction of the development of an area of regolith may provide information on existing hydrogeological conditions, and the existence of major structures may themselves relate to aquifers or channels for water movement.

One example of the type of regional application envisaged concerns the origin of inselbergs. According to Dr MacFarlane, these landscape features are important from a groundwater point of view since they frequently border enclosed basins of deep weathering. The two commonly considered theories of bornhardt (or domed inselberg) development are 'denunation', according to which the bergs represent the more resistant kernals of an uplifted landscape originally formed by deep weathering, and 'scarp retreat' which regards their origin as due to normal, sub-aerial erosional processes. Regardless of these uncertainties, it is apparent from several reviews (e.g. Thomas, 1974; Whitlow, 1978) that both theories rely heavily on the existence in the basement of major fractures along which weathering proceeded more quickly thereby isolating a number of structurally-controlled compartments which subsequently developed as bornhardts. The general concept is illustrated in Fig. 11. The scale of LANDSAT imagery would seem to be particularly suited to detecting the presence of such major fractures which might relate to the development of intervening regolith basins.

5.4 Lineaments and well production

The occurrence of groundwater in fractured rock has been referred to repeatedly in foregoing sections, and groundwater literature contains abundant references to this association (e.g. Fetter, 1980; Stevenson, 1982). Whereas the theoretical basis of this association would seem well-founded, some consideration of the field evidence in support of it seems appropriate. In this section, studies that have sought to examine quantitatively the relationship between well production and remotely sensed lineaments (from aerial photographs and satellite images) are briefly reviewed.

A number of reports show a statistical correlation between lineaments detected on aerial photographs and the occurrence of groundwater in dense, fractured limestone. For example, Lattman and Parizek (1964) reported that an aerial photograph fracture study found that wells located on or near single fractures, or at the intersection of two fractures, gave yields 10 to 100 times greater than wells placed between fractures (Fig. 12). Similar conclusions were reached in a subsequent study (Siddiqui and Parizek, 1971); Figure 13 from their paper, illustrates how the productivity of wells sited on fractures, either intentionally or accidentally, is well above that of wells not on a fracture trace. In detail they found that those wells on fracture traces had a median productivity 55 times greater than wells between fractures and nearly 10 times greater than randomly located wells. In the Piedmont area of Delaware, Woodruff et al (1974) showed that 14 wells drilled on fractures or fracture intersections mapped from aerial photographs showed average yields more than 10 times the average historic yeild.

Comparable studies over sandstone areas, correlating aerial photograph-derived lineaments to the presence of groundwater, were carried out in Arizona by Akers (1964), Cooley et al (1969) and Huntoon (1970), and showed that water well production is heavily dependent to the presence of deep fracturing. More recently, Foster et al (1980) carried out an investigation in NE Arizona using LANDSAT imagery to examine the statistical correlation between satellite-derived lineaments and water well data in study sites situated in their vicinity. The model compared lineament density within a specified radial distance from each well with hydrologic parameters using linear regression analysis. Figure 14 and Table 2 from their report show that at Flagstaff the high positive correlation between lineament density and specific capacity, transmissivity and temperature support a strong relationship between fracturing and water movement. Comparable results were obtained at the Springfield site. However, at Snowflake a negative correlation was noted. The authors suggested that this may have resulted from the inappropriate use of satellite imagery in a situation where higher resolution aerial photography would be more applicable for detecting smaller fracture traces. A similar cautionary note was sounded by Rauch (1984) in a study in Kentucky using both aerial photographs and satellite

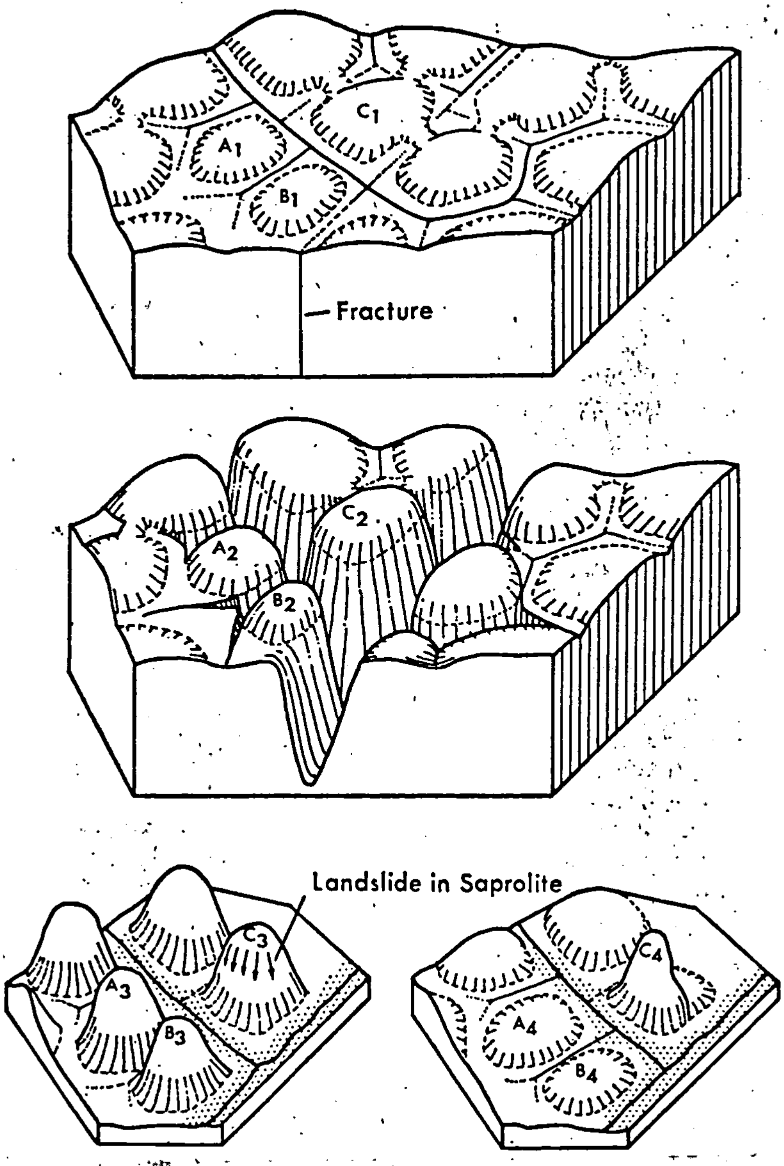


Figure 11. Formation of rocky inselbergs in the forest zone (after Hurault 1967).

A, B, C, indicate massive granite blocks, divided by major fractures followed by drainage lines. Stages in the development of the inselbergs are shown: A_1 B_1 C_1 landsurface formed on regolith (saprolite); A_2 B_2 C_2 incision of drainage along fracture zones forms cupola-shaped hills still mantled by regolith; A_3 B_3 C_3 further weathering and erosion reduce hills in size; rock is exposed on C_3 as a result of landslide; A_4 B_4 these hills are continuously reduced by weathering beneath saprolite mantle; C_4 rocky inselberg (dome or bornhardt) emerges from exposure created by landslide.

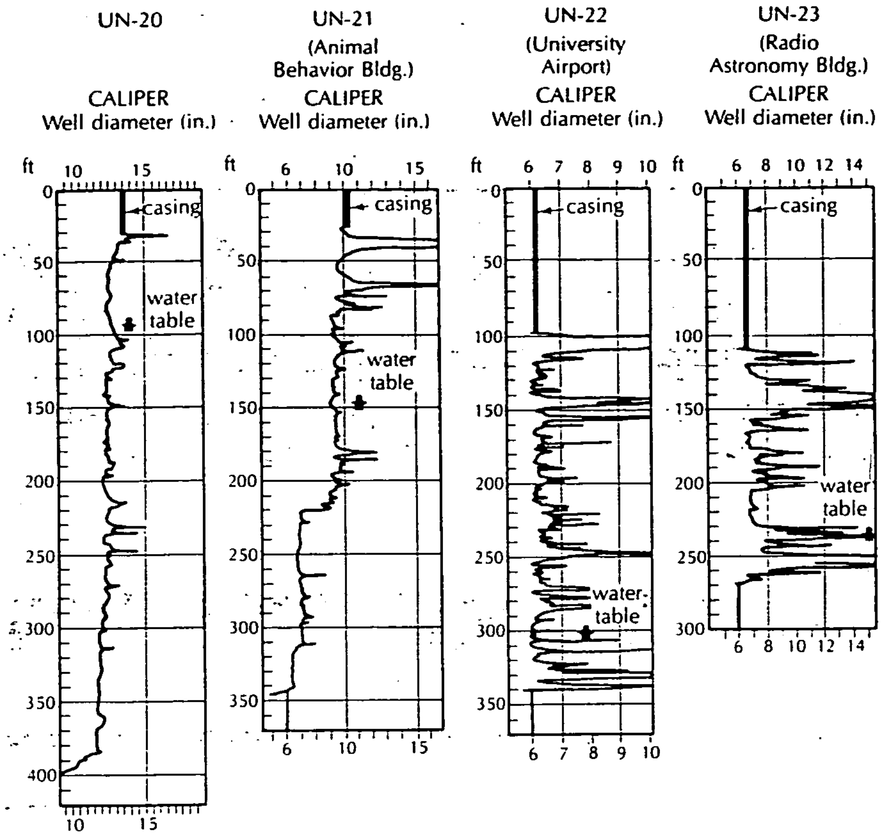


FIGURE 12: Caliper logs of wells in an area of carbonate rocks in central Pennsylvania. Wells UN-20 and UN-21 were drilled in interfracture areas; Wells UN-22 and UN-23 were located on fracture traces. SOURCE: L. H. Lattman and R. R. Parizek, *Journal of Hydrology* (Elsevier Scientific Publishing Company) 2 (1964):73–91. Used with permission.

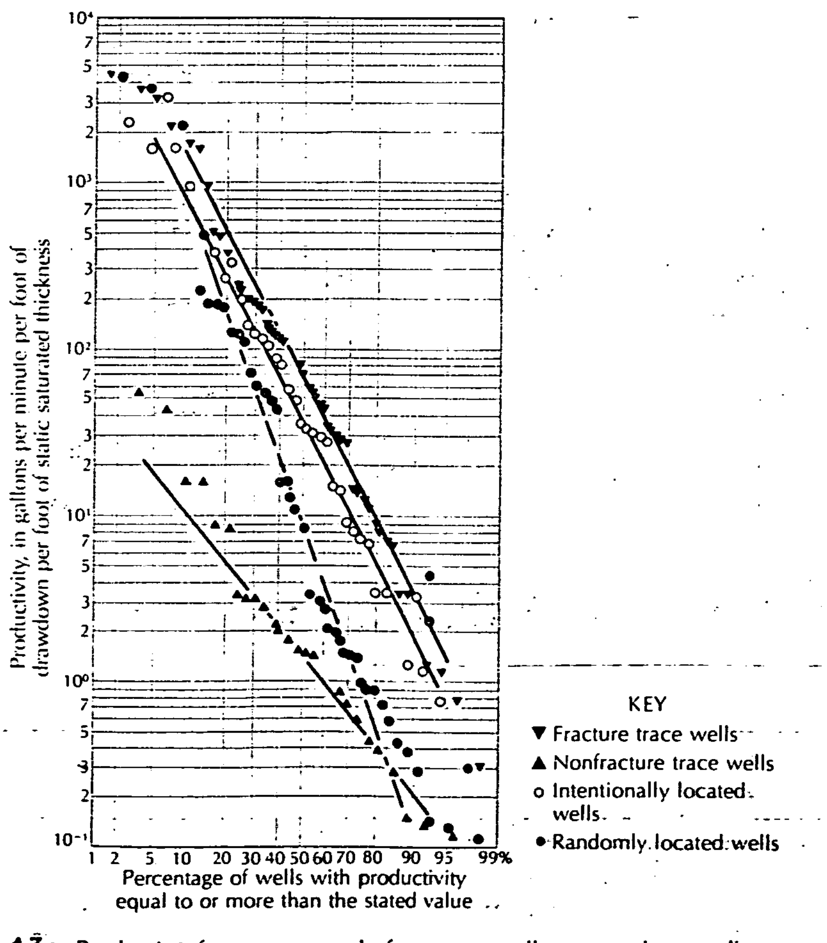


FIGURE 13: Production-frequency graph for water wells grouped according to whether or not they fall on a fracture trace. SOURCE: S. H. Siddiqui and R. R. Parizek, *Water Resources Research*, 7 (1971):1295–1312.

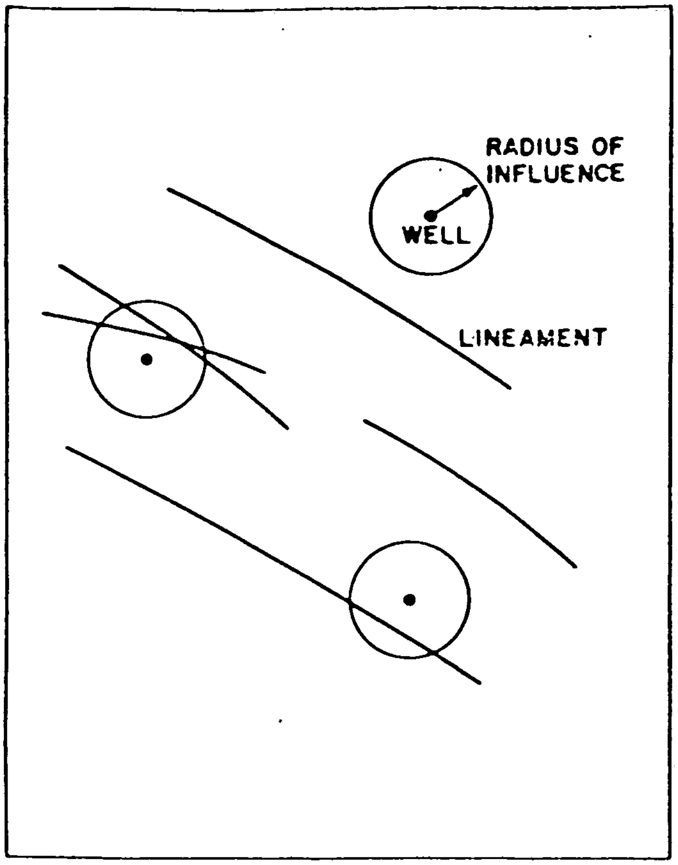


Fig. 14: Well Centered Model for Data Correlation.

TABLE 2. Correlation Coefficients.

Site	Hydrologic Parameter	Number of Wells	Correlation Coefficient	Well Radius of Influence (km)
Site A. Flagstaff	Specific Capacity	5	0.64*	0.8
	Transmissivity	6	0.99	0.8
	Temperature	4	0.78	0.8
	Specific Conductance	4	0.04	0.8
Site B. Snowflake	Specific Capacity	42	−0.14**	2.4
	Transmissivity	14	−0.67	2.4
	Temperature	74	0.09	2.4
	Specific Conductance	82	0.02	2.4
Springerville	Specific Capacity	5	0.79***	1.6
	Temperature	10	0.61	1.6
	Specific Conductance	12	−0.64	1.6

*1:24,000-scale structure maps (Harshbarger and Associates, 1973).
**1:250,000-scale enhanced Landsat imagery.
***1:48,000-scale structure maps (Harshbarger and Associates, 1976).

images. He noted that whereas photolineaments, representing linear stream channels or valley segments 0.5-3.0 km long, showed a strong positive correlation with yields from wells sited with 0.1km of them, curvilineaments and LANDSAT lineaments related poorly to water yield.

Stephouli and Osmaston (1984) point out that permeability and porosity along LANDSAT linear features depend fundamentally on their geological nature. They note for example, that in Crete mylonite zones formed along one particular set of faults, behave as unpermeable zones retarding groundwater movement, whilst other similar-looking LANDSAT lineaments of another generation coincide with high-yield springs. Follow-up field work or published structural geological studies may help determine the nature of a population of lineaments as a guide to their hydrogeological characteristics.

Among other studies of well production and LANDSAT-derived lineament data, those reported by Moore and Hinkle, 1977 and Drahovzal et al (1973) provide further examples of the applicability of this approach. The latter authors investigated well production along a 4km wide lineament in limestone terrain in Alabama. Nearly 80 wells and springs were located within the lineament with well yields as high as $1144m^3/h$ and averaging $115m^3/h$, as compared with only about $36m^3/h$ in wells located outside the zone. They further showed that in certain places streams associated with lineaments had increased flows over 70 times normal due to outflow from fracture zones. A similar situation would appear to exist in Upper Volta. Here also Berard (1976) reported that the highest well yields were obtained from lineaments corresponding to deeply-weathered fracture zones. At Kou springs in western Upper Volta the flow from springs was reported by Zall and Russell (1981) to be as much as $14000m^3/h$. Near the town of Kongoussi, Armesz and Lausink (1984) reported that well drilled to 70m on satellite-identified lineaments yielded flows of 2 to $7m^3/h$.

5.5 Lineament pattern/density analysis

It has been shown that lineaments are important both as structures capable of storing and transmitting groundwater, and as indicators of rock type and physical properties. Data generated in lineament studies require the use of appropriate manipulation and analysis techniques as a prerequisite to geological interpretation. Qualitative assessment of lineament plots may be carried out visually, but for most purposes this approach is inadequate since patterns and distributions are often complex and require systematic analysis. Although manual processing of smaller datasets is feasible, problems concerning the manipulation of large amounts of directional data arise which can only be solved at a practical level by the use of a computer.

Computer-aided lineament analysis may involve a number of stages and these are summarised in Figure 15. The essential aspects of these techniques involve the establishment of methods for the computer handling of the data (e.g. digitisation), the development of the software to reduce and summarise this information, and the availability of plotting routines for the presentation of the results of the analysis in the most appropriate format for interpretation.

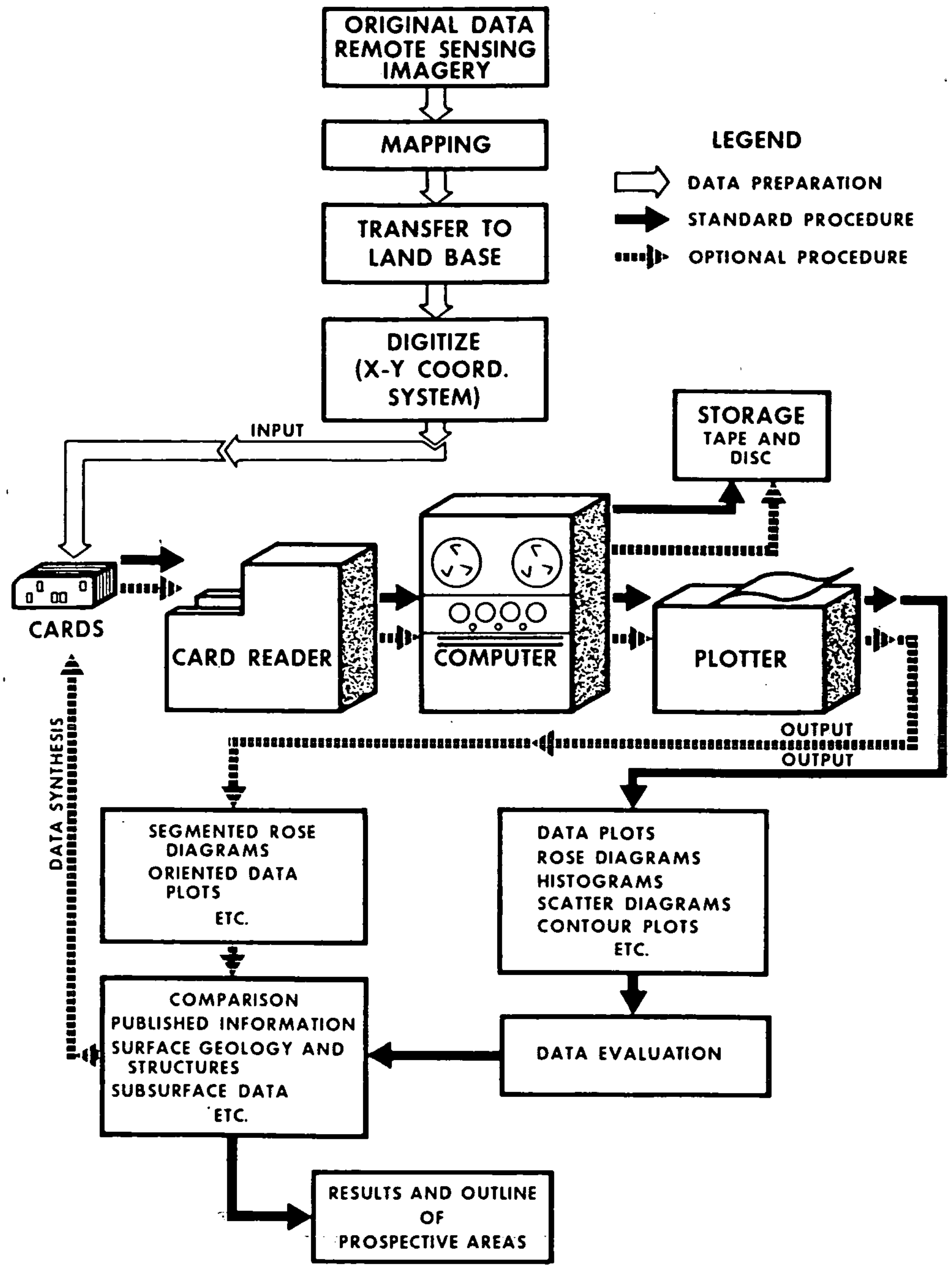


Figure 15: Schematic drawing showing the various stages of computer-aided analysis of of lineament data sets.

Lineaments interpreted from LANDSAT imagery, aerial photographs or even geophysical maps will initially be plotted on transparent overlays to the original source. Where significant, unsystematic distortions are present on the original datasource (e.g. the radial distortions on aerial photographs) a preliminary stage might require the transference of lineament data to a standard base map. In the case of internally consistent data (e.g. satellite imagery) rectification of the map projection can be achieved, if required, at a later stage by computer processing.

The principal phase of data preparation involves the conversion of analogue data to a computer compatible format. The process of digitisation is carried out over a magnetic table and involves the careful positioning of a moveable cursor over data points which are then automatically recorded as co-ordinates relative to a pre-set, though arbitary, origin. Lines may be registered either as continuous streams of co-ordinate pairs, whereby the cursor is used to trace the entire lineament whilst the 'entry' button is depressed, or merely as pairs of end-point co-ordinates. If the latter technique is used, which is generally much quicker, it may be necessary to approximate long curvilinear traces as a series of contiguous straight line segments. Companion computer files containing, for example, topographical and locational data including textual information (e.g. town names), may be digitised in a similar way. If required, this data may subsquently be added to computer-plotted output to produce annotated maps.

The digitisation phase is labour-intensive, slow and extremely tedious. The rate at which data can be digitised will depend on the experience of the operator, but is never rapid and, in any case, speed is less important than accuracy in the long run; more time can be lost through errors and time-consuming editing than might be initially gained through hurrying. Experience has also shown that it is often better to digitise data in small blocks. This allows the operator a brief respite, and the resulting small files can be more quickly corrected, or even re-digitised, at the editing stage. These sub-sets of data can be readily concatenated on the system to form a single data file at the data reduction stage, as described below.

An on-line plotter may be used to produce an initial playback plot at the same scale and projection as the source map. This is used to check accuracy and errors. Files may generally be corrected interactively except where extensive errors occur, in which case it is usually quicker to re-digitise the entire offending data file.

Once rectification of data files is complete, the total data is 'reduced' to a single file. At this stage also control points (e.g. UTM, latitude/longitude) are used to transform the digitised co-ordinates to map co-ordinates. The data is now ready for plotting or further processing.

Tables 3 and 4 indicate some of the choices available for analysis of lineament data. Not all of these will be relevant to groundwater studies and the choice of processing will depend on the particular study. Nevertheless, one of the main advantages of having digitised data is that many types of data manipulation can be carried out rapidly and with minimum effort or cost, subject only to the availability and sophistication of software.

Techniques of lineament analysis can broadly be divided into those aspects related to either orientation or distribution. Most structural geology

TABLE 3

Summary of Kinds of Computer-Plotted Displays[1]

I. DATA PLOTS may be made for each of the following:
  A. Original data set
  B. Modified data set(s)
  C. Selected data (from original or modified data) - e.g. based on:
    1. Arbitrarily chosen size subdivisions
    2. Arbitrarily chosen orientation subdivisions
    3. Geographic location subdivisions
    4. Measures of confidence
    5. Measures of importance
    6. The individuals who selected the original data set
    7. Tectonic or lithologic setting

II. ROSE DIAGRAMS AND ROSE PUB DIAGRAMS - based on:
  A. Length vs. orientation
  B. Number vs. orientation

III. HISTOGRAMS - based on:
  A. Number vs. length cells (show how many lines there are with specific lengths within the specified cell limits)
  B. Total length per cell vs. length cells (shows the total length of all lines within the specified cell limits)

  ORIENTATION BAR DIAGRAMS - based on:
  A. Length vs. orientation
  B. Number vs. orientation

IV. SCATTER DIAGRAMS (not widely used) - number and length vs. orientation

V. TREND ORIENTATION PLOTS - depicts the major orientation cells (up to 5) based on cumulative length for subsets of the linear data within each increment of area (domains of specified size) on a map

VI. CONTOUR MAPS - based on:
  A. Line density
  B. Length density
  C. Intersection density

[1] A summary of the use of these computer displays is included in Table 4

TABLE 4

SUMMARY FOR USE OF COMPUTER DISPLAYS

ILLUSTRATION	TYPE DATA OR PARAMETERS	DEPICTS	USE	USEFUL COMPARISONS	INTERPRETIVE USE AND REMARKS
Data Plot	All kinds of data (i.e., original, modified, intersection, and selected)	Data in actual geographic location with length and direction shown	To observe the actual map of the data	With all plots, diagrams and maps	Data plots "tell it like it is" and provide a check for interpretations based on other plots, diagrams
Rose Diagram (Rose Pub Diagram)	Number, length, orientation cells	The association between number of length and direction	To determine preferred directions and the angles between them	Scatter diagrams, orientation histograms, trend orientation plots, data plots	The same as scatter diagrams but not so accurate and do not show length number and direction on one plot
Histogram (Orientation Bar Diagram)	All kinds of data; all parameters	The frequency distribution of the data or parameters	To determine trends in the data or parameters.	Scatter diagrams, rose diagrams, orientation plots, data plots	Graphically depicts trends in the data and of individual parameters which permit refinement of hypotheses
Scatter Diagram (not widely used)	All kinds of data; all parameters (i.e., number, length, direction, confidence, importance, and their combinations)	The simplest diagram depicts number, length and direction on one plot (more sophisticated plots are possible)	Clusters of points show preferred length-direction associations. Density of clusters shows the intensity or degree of preference	Histograms, rose diagrams, and data plots	Show preferred lengths, directions, and the degree of preference which can be checked by comparison to other illustrations and which can lead to construction of interpretive hypotheses, like the stress distributions in the area
Trend Orientation Plots	Number, length orientation cells	A rose diagram for each small area on a map	Shows the variation of preferred directions and the angles between them from place to place on the map	Data plots, scatter diagrams, rose diagrams, and contour maps	Show how interpretive hypotheses involving direction change from place to place for the whole geographic area under study
Contour Maps	Density of all parameters	Variation of parameters with change of geographic location for the map area	To determine geographic areas where parameters are the most or least dense or where they deviate the most from an established norm	Data plots; all other illustrations	Show "hot spots" and "cold spots" which indicate where to go on the ground to test hypotheses; useful in predicting fluid migration routes and where traps or deposits are located

studies are more concerned with the orientation of lineaments (e.g. as evidence of tectonic stresses) whereas from a hydrogeological viewpoint distribution studies (e.g. lineament density) may be more important. Nevertheless, both approaches can provide valuable information for groundwater studies. Initially, it may be desired to produce a simple data plot at an appropriate scale for visual inspection and comparison with other available data (e.g.geological, geophysical, geochemical, borehole data etc.) The usual first stage of orientation analysis is the generation of one or more diagrams on which frequency distribution of either accumulative lineament lengths or of numbers of lineaments is represented in a circular, windrose diagram. In general, cumulative length rose diagrams are the more informative as there may be a large range of individual lineament lengths. Problems also arise on number-frequency plots if long curved lineaments have been digitised in several segments. On both types of plot the user can choose the segment size: a 10° sector is appropriate for most analyses. An example of a length frequency rose diagram derived from a satellite lineament study of eastern central Greece is shown in Figure 16. Note maxima at 65° and 105° and an absence of NW-SE directions. For more detailed analysis to study local variations rose diagram plots of small sub-areas may be produced (Figure 17).

Using the information on dominant directions obtained from a study of rose diagrams it may be helpful to generate maps of lineations having a specified range of directions, or 'sector plots'. This could have value, for example, where it was known from other information that faults having a particular trend were open, tensile features with good groundwater storage potential. Alternatively, sector plots sometimes help identify very large compound fracture zones, observed as discrete segments, but which exhibit regional alignment and perhaps relate to some buried structure. An example of a sector-plot is given in Figure 18.

A potentially more useful approach for groundwater studies is lineament distribution analysis. Some indication of intensity of fracturing will be visually evident from lineament maps and sector plots. A more objective approach involves the preparation of lineament density maps. These can be constructed using several different, though related, criteria including length-density, line-density and intersection density (McGuire and Gallagher, 1979) as well as average-length density (Silva et al, 1983). For groundwater studies, length-density and intersection density would seem likely to have most significance (Figure 19).

The calculation usually involves subdivision of the map into a grid of small square domains, within each of which either the cumulative length of lineaments or number of lineament intersections are determined etc, as an input to a plotting routine. Data may be plotted in either raster or contour format. The fundamental method described will produce an essentially unsmoothed density plot. By using a counting window larger than the grid cell, a smoothed version of the data is produced. This 'moving average' is analogous to the use of a two-dimensional low pass filter, and for highly variable data may yield a more readily interpretable result. Other variants of the approach include the generation of density plots of data subsets derived from sector plots. These could be used, for example, to identify areas of highest fracture intensity along a hydrogeologically favourable

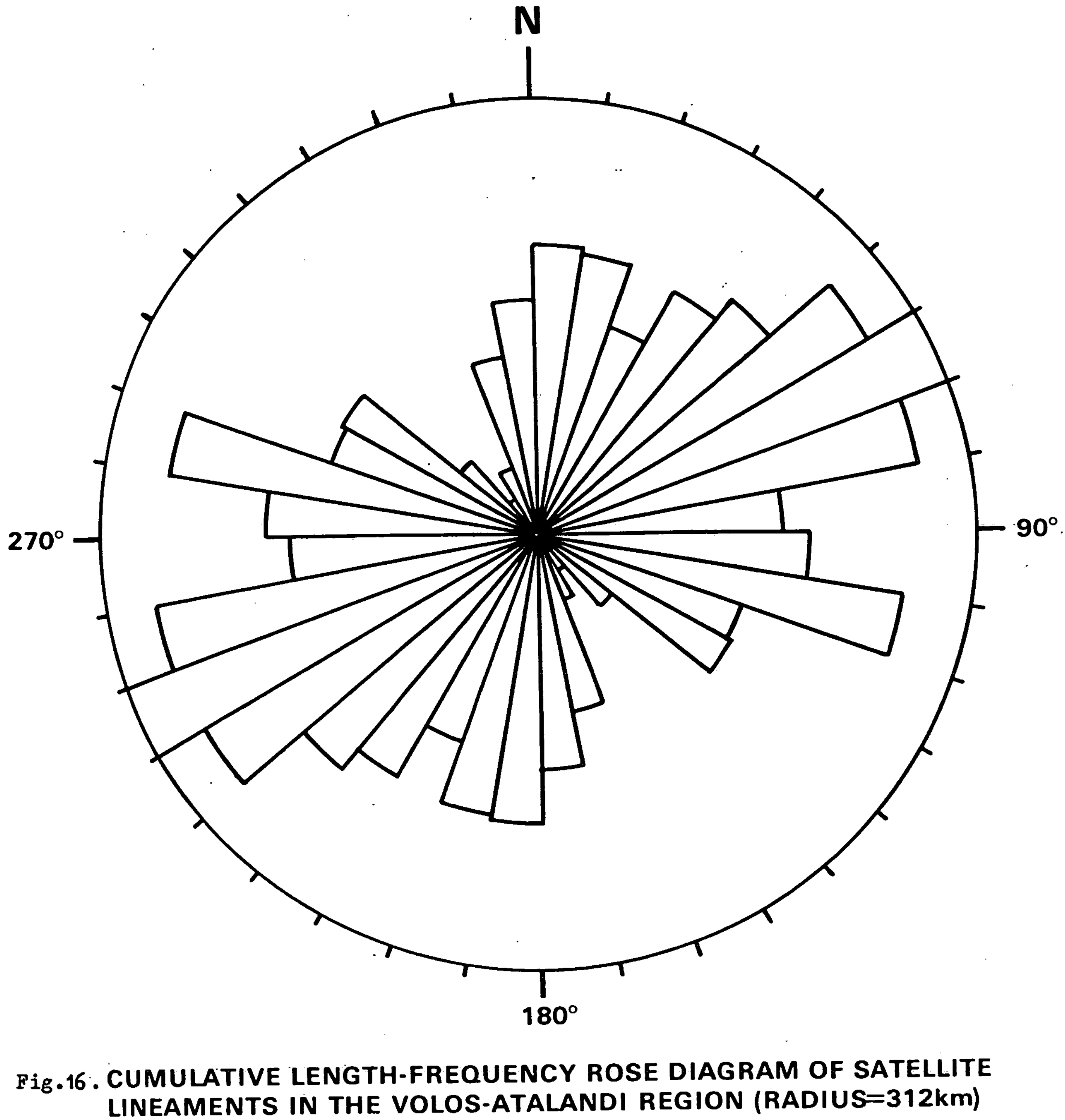


Fig.16. CUMULATIVE LENGTH-FREQUENCY ROSE DIAGRAM OF SATELLITE LINEAMENTS IN THE VOLOS-ATALANDI REGION (RADIUS=312km)

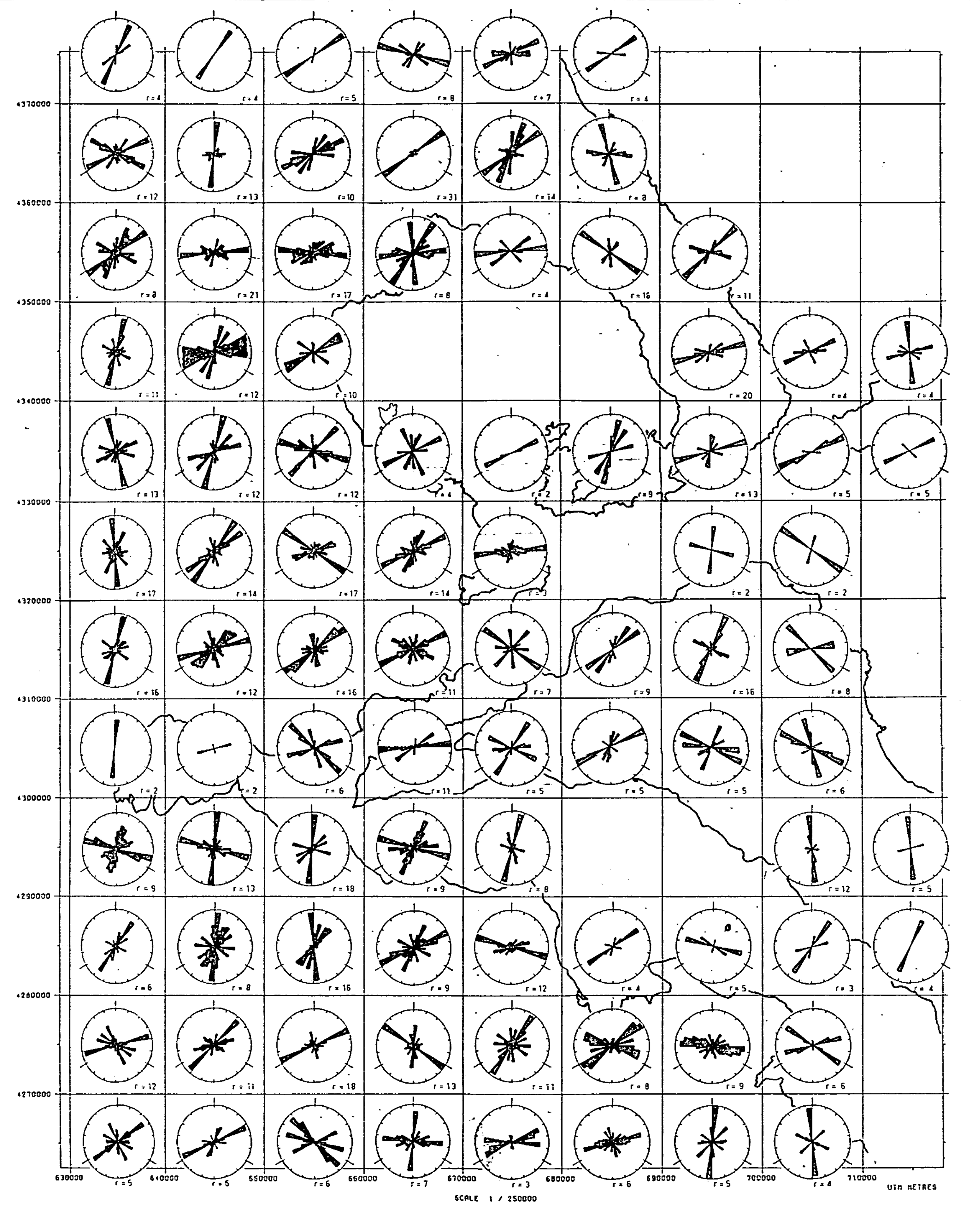


Fig. 17

LENGTH-FREQUENCY ROSE DIAGRAMS FOR SATELLITE LINEAMENTS IN THE VOLOS-ATALANDI REGION, GREECE. (SAMPLE BLOCK SIZE = 10 KM SQUARE; SECTOR SIZE = 10°; SCALE RADIUS IN KM SHOWN ALONGSIDE EACH ROSE).

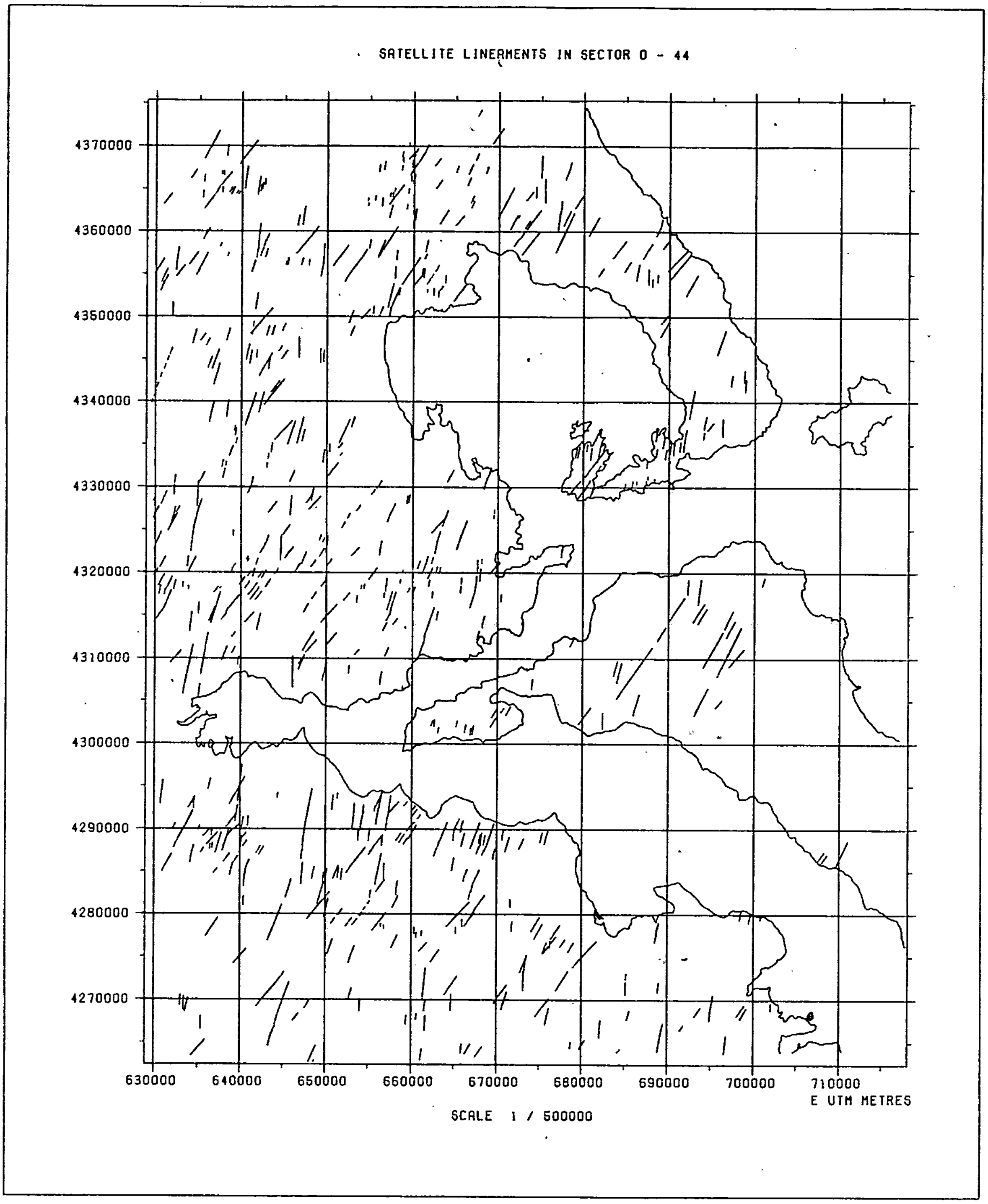


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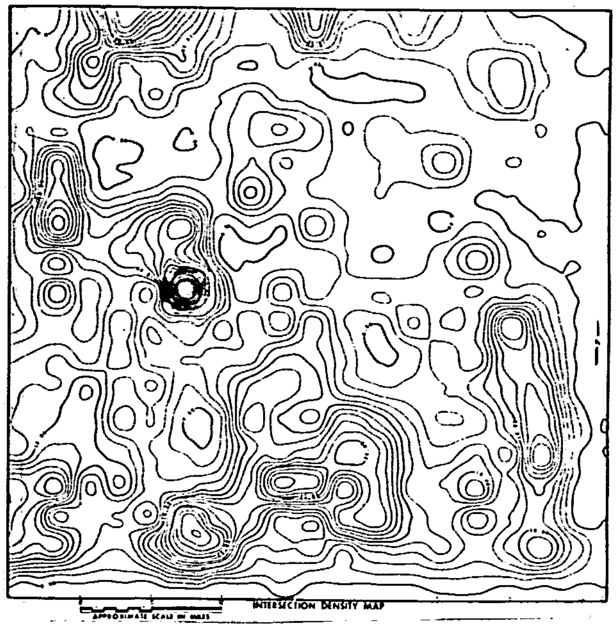
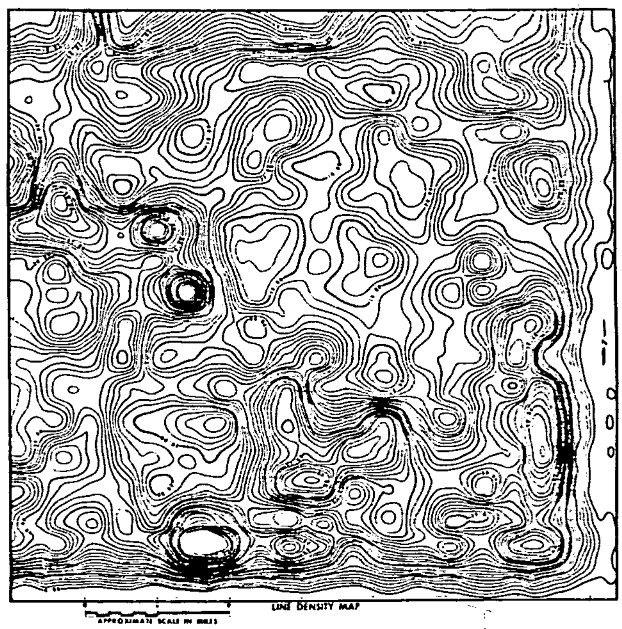
Fig. 18. Satellite-derived lineaments falling within the 0 - 44 degrees sector, Volos-Atalandi region, eastern Greece.

A



B



C

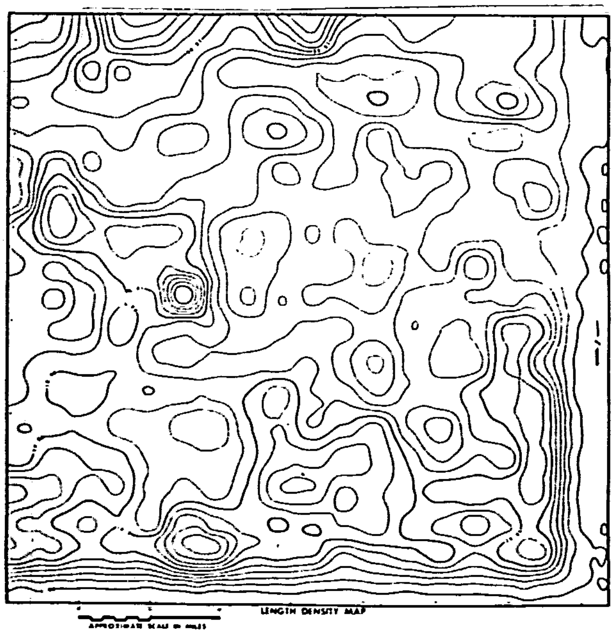


Figure 19. Examples of computer-generated CONTOUR MAPS for the sample lineament data set illustrated in Fig. 18. The parameters illustrated here are for (A) intersection density, (B) line density, and (C) length density.

fracture direction. An example of this technique from Sawatzky and Raines (1981), who refer to this plot as a 'linear feature concentration map', is shown in Figure 20.

Fracture density plots often provide a good general correlation with lithology. In the Suez region of Egypt, for example, El Etr and Yousif (1979) found that lineament density was high over Eocene limestone and low over Nubian sandstone and wadi alluvium. Similarly in Sri Lanka, Silva et al (1983) found a correlation between areas of highest lineament density and the central fold belt. The relationships will, of course, vary, but in general will be dependent upon the age and history of rock with as well as on the competence and cohesion of the material concerned as well as the degree of exposure.

In the context of cystalline basement and regolith, fracture density analysis may be expected to have application in two areas: first, in distinguishing between areas of outcropping basement and regolith, and second in the estimation of relative depth of weathering within the regolith. Initial results of a test study conducted by Dr B J Amos suggests that the method works satisfactorily in the former case. The relationship between the density of lineaments detectable within regolith and depth to basement is more speculative and is considered further in the following section.

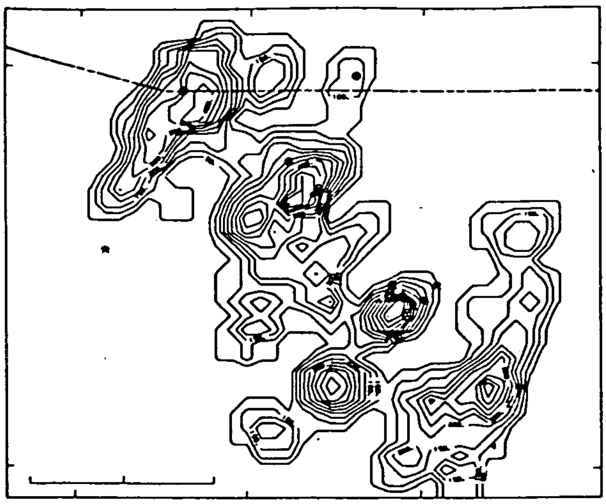
In a more general way fracture density may provide a guide to groundwater potential in crystalline areas, by identifying fractured zones of higher permeability. Kruck (1981) states "The goal of hydrogeological interpretation using Landsat imagery was therefore to map lineations as indications of the fracture pattern. With the aid of this evaluation a density map was compiled separating areas with high, medium or low concentration of lineations ... The different areas of fracture density provide a relative criterion of probable groundwater occurrences ..."

Computer techniques used for the analysis of lineament data can similarly be applied to drainage patterns. Here, one would be particularly concerned with drainage density based on total length of stream channel. Due to the irregular nature of drainages, continuous digitisation would be used initially. The plot would be produced using the same computer routines as for cumulative lineament length.

5.6 Structural controls in basement and regolith

In this final section concerning lineaments further consideration will be given to those aspects concerning fracturing in basement and regolith not already covered in previous discussion.

Basement Complex is a general term applied to areas of Precambrian metamorphic rock including schists, gneisses, migmatites and granite, forming the crystalline basement. Overlying this in places are areas of extensive and relatively thick, deeply-weathered overburden, termed regolith, or saprolite. This weathered mantle is important from a hydrogeological viewpoint since it is capable of possessing a high capacity of water storage and ingress (e.g. Omorinbola, 1982). He notes that in Nigeria deep



SONORA LINEAMENTS E20-E57 TREND
ISMINT=1,DELXY=.3

Figure 20. Linear-feature concentrction map of north-east-trending linear features of Sonora, Mexico.

weathering of Basement Complex to produce regolith is the single most important factor in the location of groundwater. Cratchley (1958) states that in the Kankara district of Nigeria "groundwater is held in the decomposed layer lying above the hard unweathered rock, and in fissures and joints within the bedrock. Local supplies are drawn almost exclusively from the decomposed layer which varies in depth between 80-100ft." The role of bedrock fractures is, however, stressed by other writers. Pathak (1981) considers that in hard-rock areas of India the fracture system may provide a more reliable source of groundwater than the weathered zone to furnish substantial yields down to 200m. Similarly, in western Niger and Upper Volta, Kruck (1981) notes that because of the low yield fromtraditionally exploited aquifers in alluvial deposits and weathered mantle, water exploration in recent times has concentrated more on fractures in basement rocks. Clearly conditions vary from one region to another, though the fundamental importance of both fractures in basement and of zones of deep regolith is apparent. (See also Zall and Russell, 1981; Cooley and Turner, 1982; Kogbe, 1983a, and Amesz and Lausink, 1984).

Tropical weathering in a humid climate over a long period of time would appear to be the fundamental requirements for production of thick regolith. Other things being equal, this would appear to be favoured by structural anisotropy such as the presence in the crystalline basement of faults, joints and fissures which serve to increase the permeability in such zones and promote rock decomposition. Thomas (1966, p 178) provides an example from northern Nigeria where he says "... a fair correspondence exists between the orientation of the basins of weathering and dominant joint directions". Comparison of his two figures (here Figs. 21 and 22) shows that the lineaments obtained from basins are derived primarily from the outline of the basins and are a function of their elongate morphology. The inference presumably is that parallel joints within the basins were instrumental in their formation. The arguments raised by Dr MacFarlane, in her recent review of tropical weathering, concerning Thomas' study would appear not to invalidate the more general argument that structural anisotropy influenced the weathering pattern. Thomas's statement in his 1974 book (p 93) concerning "lineations in mapped weathering troughs" is possibly just an unfortunate turn of phrase that does not appear in his original description (Thomas 1966). In this he states "The major joints show a dominance of bearing ... that accords well with the elongation and arrangement of the deeper basins of weathering ... Since it is scarcely possible to observe jointing directions within the weathered area the apparent correspondence between joints and weathering pattern must rest on circumstantial evidence alone". (Thomas, 1966, p 180). Nevertheless, it is perhaps surprising that his aerial photograph lineaments do not reflect these presumed structures that controlled the weathering of basins. It is possible that the scale of aerial photographs was inappropriate to detect larger features; indeed had satellite imagery been used the elongation of basins or alignment of several basins might have in itself "produced" a lineament, perhaps reflecting a more subtle deep-seated structure that is relatively poorly expressed at the surface.

Despite Thomas's comment that it is not possible to detect jointing within weathered zones, there is considerable evidence, both theoretical and observational, to suggest that basement structures may be propogated through overlying consolidated and unconsolidated materials, and be evident on

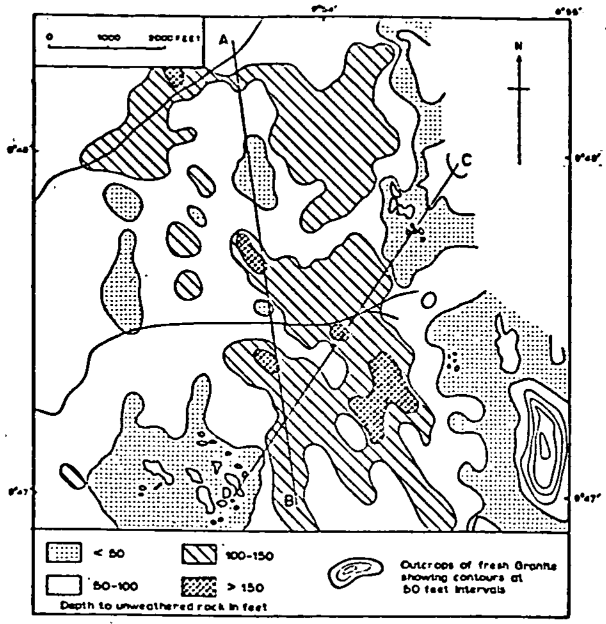


FIG 21 .—Deep weathering patterns near Jos, Northern Nigeria. The map shows depth to unweathered rock rather than true depths of weathering, because the *in situ* weathering profiles are overlain by varying thicknesses of alluvium.

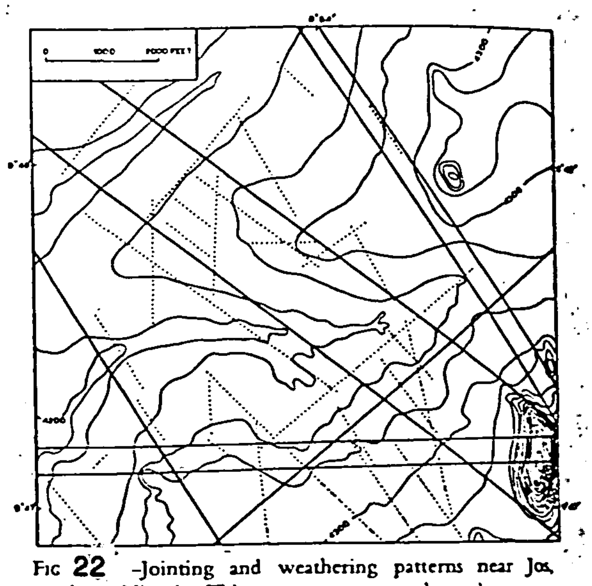


FIG 22 —Jointing and weathering patterns near Jos, northern Nigeria. This map attempts to show the correspondence between major joint directions and lineaments in the weathering patterns in the same area as Figure 15. Joints have been mapped from air photographs and their bearings extrapolated across the deeply weathered area. They are shown by ruled lines. Lineaments in the deep weathering pattern are derived from Figure 15 and are indicated by dotted lines. Contour interval 20 feet.

imagery. (Mollard and Carr, 1974; Drake and Vincent, 1975; O'Leary and Simpson, 1975; Norman, 1976; Mallick et al, 1979). Obscured and buried structures are represented on imagery by structurally controlled streams and lineaments, by brightness and spectral variations, and by topography (Berger, 1982). This may result from such causes as differential loading and compaction of the underlying materials, minor post-tectonic movements on deep faults and disruption of the flow of near-surface groundwater (Gallagher and McGuire, 1979; Berger, 1982; 1984). This in turn causes differences in the water table which produce observable surface expressions such as changes in soil moisture and vegetation type and density, or zones of more advanced weathering, made conspicuous by subtle vegetation changes, as noted by Dr MacFarlane. Gallagher and McGuire (op cit) describe laboratory and field examples to show the effects on accumulating sediments of repeated movements along basement faults. In this situation, deep fractures may be evident only as diffuse surface manifestations, e.g. drape folds.

An important implication of the concept that some fractures have exerted an influence on sedimentation during depositional periods, is that, if the same lineaments controlled stream-channel positions in the past as at present, then coarse river-deposited gravels may be found at depth in alluvium filled valleys (Salomonson, 1983). A possible example of this type of situation comes from Egypt where Salman (1983) states: "the interpreted major fractures in the area... often play an important role in the localisation of groundwater ... most of these structural lineaments are major gravity faults controlling the course of many master streams. These faults are characterised by relatively wide fracture zones which are often filled with thick sands and gravels. This association is very promising since a remarkable amount of groundwater is found where alluvial deposits are relatively thick and coarse-grained sediments occur at depth. Moreover, these fracture zones can act as suitable channels for migration of underground water from the deep aquifer ... to the shallow aquifer". Even where the rejuvenation of basement fractures post-dates the overlying sediments, dissipation of the structures in less brittle rocks may result in diffuse surface effects, as indicated in Fig. 23 (Wunderlich, 1957; Whittle and Gutmanis, 1983).

Published case studies refer to the detection of structures buried beneath both consolidated, and hence comparatively brittle sediments (e.g. Podwysocki, 1979) and unconsolidated deposits, notably glacial drift (e.g. Wobber, 1967). From a theoretical viewpoint there is good reason to suppose, in view of the essentially autochthonous nature of the regolith (conforming closely to the Glossary of Geology's definition of 'saprolite' - "characterised by the preservation of structures that were in weathered rock"), that these materials will display relict structures to a still greater degree than drift. Initial inspection of LANDSAT imagery of Malawi indicates that this supposition is well founded (B J Amos, personal communication). This conclusion has a number of important implications for groundwater exploration.

Consider, for example, the case where development of a basin of weathering is controlled by rock decomposition along a major inactive fracture zone. The lineament detected on imagery may here relate to a zone of more advanced weathering as illustrated by Dr MacFarlane in her recent review, and will perhaps also correspond to a deeper zone of the basin. In this way it may be possible to pinpoint zones of deeper weathering connecting with an underlying major structure. Such a situation would seem to provide an ideal set of conditions for sustained yield, combining the high storage capacity of theoverlying regolith with the recharge capability and transmissivity of the fracture system. Fig. 24 illustrates this concept.

Corroborative evidence related to buried fracture systems might also be expected to come from the study of lineaments in outcropping areas of basement enclosing basins of deep weathering. Thumult (1984) describes the results of a LANDSAT imagery study of the Athabasca Basin in the Canadian Shield where, not only did he find that basement fractures could be detected through several hundred metres of sandstone and several metres of drift, but that many major regional lineaments were continuous across the basin margins. Such data could support the validity of more subtle lineaments observable through regolith; the concept is illustrated in Fig. 25.

In addition to the circumstances already referred to it is likely that other factors will also affect the propogation and detectability of fractures through the regolith, and some of these are likely to have an opposing effect in their relationship to depth. Consequently, it might be expected that the propogation of basement fractures through overburden will be greatest where the thickness of cover is least. In a somewhat comparable situation, Wobber (1967) found that bedrock fracture traces, recognisable as lineaments on aerial photographs, could be indentified through up to 150 feet of glacial drift, but that a higher occurrence of such lineaments could be detected where the overburden was thinner. Clearly differences exist between glacial deposits and regolith but it is not unreasonable to expect that similar conditions apply, perhaps influenced by groundwater flow patterns, for example. If so, zones of low lineament density may correlate with thicker parts of the regolith filled basin.

It is not possible at this stage to be more positive as to which theoretical controls will dominate and it is likely in any case that these will vary from one location to another. As remarked earlier, however, lineaments - however formed - do appear to be observable through regolith and this fact in itself is the important point. Hopefully, data from the project areas in Malawi will enable conclusions to be drawn regarding the correlation between depth of weathering and surface lineament density. It may also help to decide the value of targetting boreholes in 'intermediate' depth regolith where surface lineaments indicate the presence of buried fracture zones.

Finally, as described elsewhere, the identification of major lineaments or lineament intersections in exposed basement rocks can be used directly to locate areas for follow-up work and eventual drilling. Larger LANDSAT lineaments often represent zones of highly fractured rock with sufficient permeability and porosity for reasonable, sustained groundwater yield. Amesz and Lausink (1984) note, however, that fracture zones are commonly quite narrow (10-20 m) and steeply dipping so that the precise siting of wells is important. They recommend that satellite imagery studies are followed up by aerial photograph study and geophysical prospecting (EM). Following this approach good drilling success rates (up to 80 per cent) and high yields were reported.

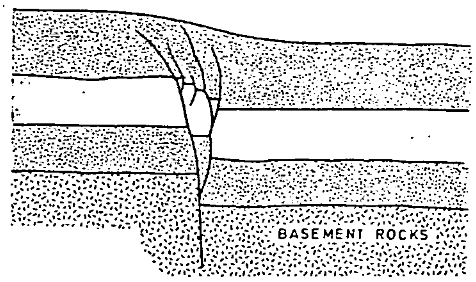


Fig23 Dissipation of the effects of basement fault displacement in overlying less rigid rocks (after Wunderlich, 1957)

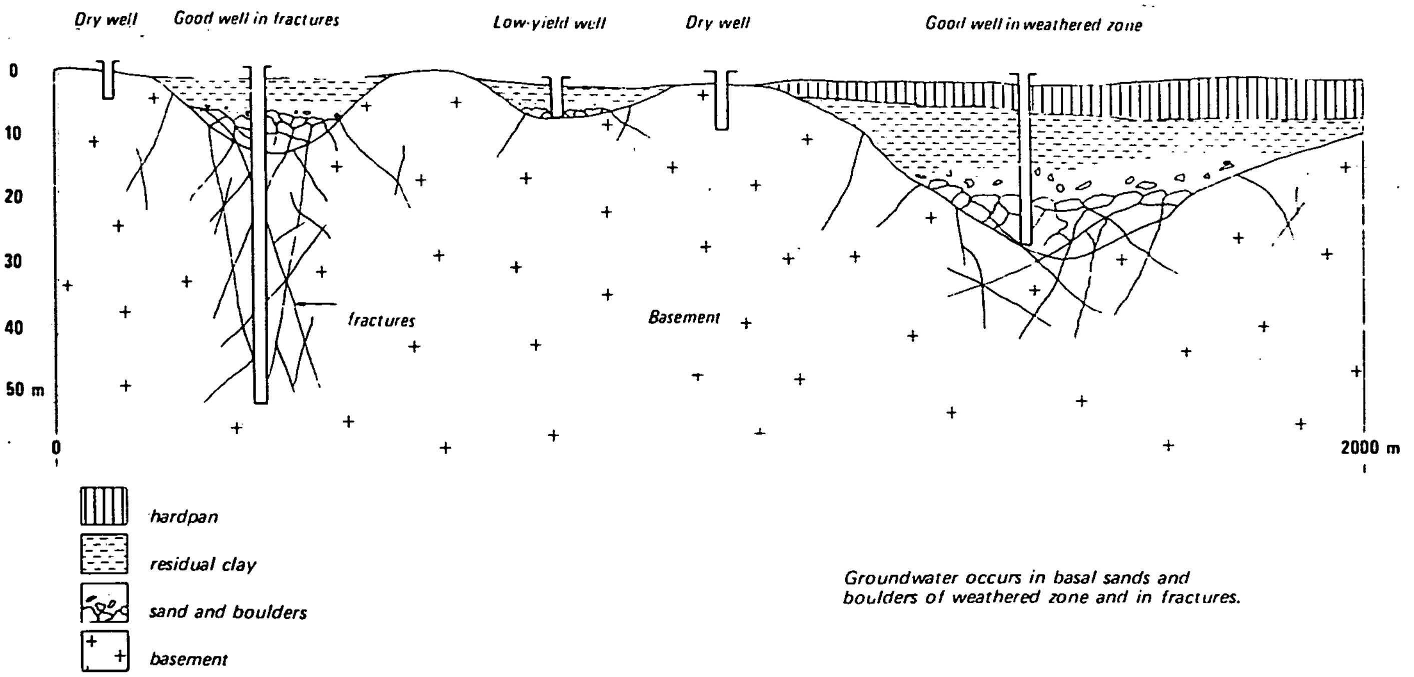


Fig. 24. Ground Water Occurrence in Basement, Typical Cross Section (after TAMS, 1978).

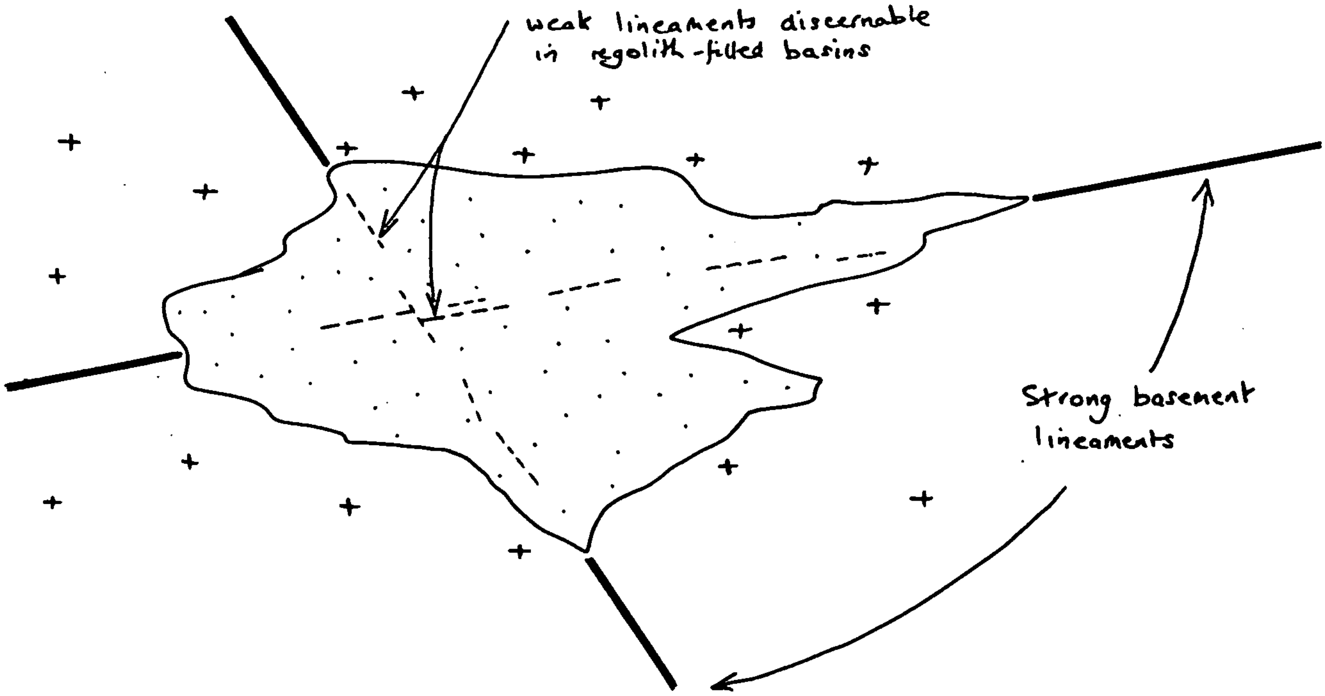


Fig. 25. Strong basement lineaments used to corroborate presence of more diffuse lineament patterns discernable through regolith.

6. CONCLUDING REMARKS

This review has attempted to outline some of the main techniques and applications of remote sensing to groundwater exploration over areas of fractured basement and weathered overburden. In the limited time available it has not proved possible to cover any single aspect in detail. Moreover, difficulties encountered in assembling a representative reference list and in obtaining several obscure publications may have led to omissions or an imbalance of emphasis in certain areas.

The main conclusions of this review may be summarised as follows:

(1) Several forms of remote sensing imagery have important applications to groundwater exploration studies. The more commonly used techniques of LANDSAT imagery and aerial photography are of wide-ranging use at the regional and local levels respectively. Other types of imagery, such as thermal IR and radar, have more specialised uses.

(2) The use of remote sensing at an early stage in a groundwater study can significantly reduce overall effort, especially in regard to costly ground work. The use of such techniques is thus highly cost effective.

(3) The apparent lack of significant applied research into groundwater-related applications of remote sensing in basement areas is a serious omission and suggests that the potential of remote sensing techniques in this area has not been fully investigated or exploited.

(4) An appropriate methodology and expected output of a typical remote sensing study may comprise:

- preparation of a general hydrogeological guide map showing the location of all near-surface and buried groundwater-related features

- generation of spatially- and contrast-enhanced imagery. Interpretation of lineament and drainage pattern data. Digitisation and use of computer-aided analysis to prepare a range of orientation and distribution plots.

- interpretation of the above data products to provide information on:

    - surface permeabilities
    - distribution of basement outcrop and regolith
    - regional fracture pattern and origin; important fracture zones and fracture intersections
    - relationship between important fractures, basins of weathering and other features (e.g. bornhardts)

- depth distribution within regolith
- location of basement fractures underlying regolith.

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