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REMOTELY SENSED FRACTURE PATTERNS IN SOUTHWESTERN SAUDI ARABIA AND QUALITATIVE ANALYSIS

CARACTÉRISTIQUES DE LA FRACTURATION DANS LE SUD-OUEST DE L'ARABIE SÉOUDITE ÉTUDIÉES À PARTIR D'IMAGES LANDSAT

M.Y.H.T. QARI*, Z. ŞEN**

Abstract

Remotely sensed fracture patterns from southwestern Saudi Arabia are quantified so as to provide some basic data for engineering and water resources structures in the area. For this purpose, fracture lengths, orientations, frequencies, regional fracture intensities and connected fracture patterns for groundwater movement from two perpendicular directions are either mapped or qualitatively explained. The area has significant permeability anisotropy. Various regional fracture pattern maps help to identify safe sites for engineering activities and potential groundwater recharge and movement. Necessary qualitative rock descriptions are proposed for any infrastructure construction in this area. It is observed that Landsat image processing provides a rather rapid and extremely economical preliminary solution compared to conventional fracture pattern assessment techniques.

Résumé

Les caractéristiques de la fracturation du Sud-Ouest de l'Arabie Séoudite sont quantifiées à l'aide d'images satellitaires, en vue de fournir des données de base pour l'aménagement et les ressources en eau. Les longueurs, orientations, fréquences des fractures régionales sont soit cartographiées soit explicitées qualitativement ; elles sont distribuées selon deux directions perpendiculaires, et la zone étudiée présente une anisotropie significative sur le plan de la perméabilité. La cartographie des fracturations réalisée permet d'identifier d'une part les zones propices à la construction et d'autre part les zones de recharge des nappes souterraines. L'auteur propose également une description qualitative des roches. Le traitement de l'imagerie Landsat fournit une solution rapide et très économique par rapport aux techniques conventionnelles de définition de la fracturation.

1. Introduction

Fractures are essentially present in any rock type and they give significant clues about the structures and tectonic activities in an area. Besides, many human activities require identification, quantification, assessment and interpretation of fracture patterns so as to reach scientific conclusions which furnish basic data for future development and planning in any area. From a geological point of view, their identification gives clues about the tectonic history of the region in relation to the surrounding environment. Engineers try to minimize the undesirable effects of fractures on the stabilization of infrastructures. Also, they provide potential regions for the availability of groundwater resources and suitable sites for waste disposal and nuclear repositories. Whatever the purpose the indispensable step is their quantification in such a manner that future projects can benefit from such studies.

Of course, the most difficult part of such a procedure is the representation of fracture patterns of any region on a piece of paper. Although theoretically it is possible to fix major fracture orientations and lengths to a certain extent by terrestrial methods, reliable results can be obtained by modern remote sensing systems which have the ability to provide instantaneous views of the Earth's surface at different scales. These systems help to identify the most appropriate base for the fracture pattern including macro-scale structures such as folds, faults, dikes and volcanoes, and other features of uncertain origin among which are fracture traces and lineaments.

One of the most significant implications of a fracture pattern is fluid flow through fractured media, interest in which has increased markedly in recent years motivated in part by concerns on the movement of water, petroleum and chemical wastes through bedrock. The permeability of fractured impermeable rock is of prime importance for predicting the groundwater movement in, especially, granitic rocks. On the other hand, the permeability of fractured permeable rocks (sandstone, limestone, shale, etc.) has special relevance to the petroleum industry. Permeability of fractured rocks as well as the

* Faculty of Earth Sciences, King Abdulaziz University, P.O. Box 1744, Jeddah 21441, Kingdom of Saudi Arabia.
** Technical University of Istanbul, Faculty of Aeronautics and Astronautics, Maslak 80262 Istanbul, Turkey.

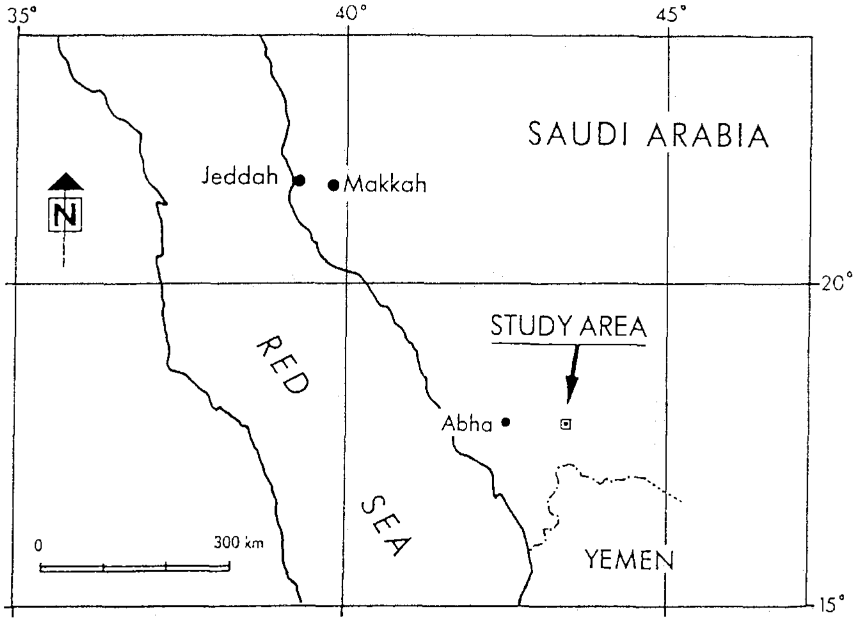


Fig. 1 : Location Map.

recognition of the natural fracture pattern can seldom be examined in detail by direct drilling techniques, and consequently there is a need for reliable regional identification techniques which can be applied through Landsat images. Hence, remote sensing techniques provide perhaps the best tools available to Earth Scientists for mapping structural controls on the Earth's surface at macroscopic scales.

Most hydro- and geo-engineering works invariably depend on either very small scale and local field measurements or over simplified assumptions such as that the fractures are composed of usually orthogonal sets of parallel, infinitely long fractures for which analytical studies could be achieved (Warren and Root, 1963; Deere, 1964; Priest and Hudson, 1976; Şen, 1984; Şen and Eissa, 1991; Şen, 1992).

Natural fracture features such as fracture orientation, length distributions and fracture spatial distributions have been investigated by many researchers (Finch and Wright, 1970; Parizek, 1976; Krohn, 1976; Lattman and Parizek, 1964).

The main concern in this paper will be the Abha region within the southwestern corner of the Arabian Shield. In a fractured aquifer the connected pattern of fractures plays an utmost role in giving direction to the overall groundwater movement. In the present study the identification of fractures from Landsat images is first completed and subsequently fracture density, fracture length, fracture intensity maps and connected fracture map patterns are depicted all of which furnish a base for any future detailed groundwater flow or engineering geological study.

2. Location and geological setting

The study area (Fig. 1) of 225 km^2 is located to the east of Abha city in southwestern Saudi Arabia. The area has excellent exposure of a diverse suite of igneous and metamorphic rocks.

The exposed outcrop of the area is complex due to folding, intense faulting and intrusions. The major lithologies are Tertiary basaltic and Precambrian metamorphic and plutonic rocks (Fig. 2).

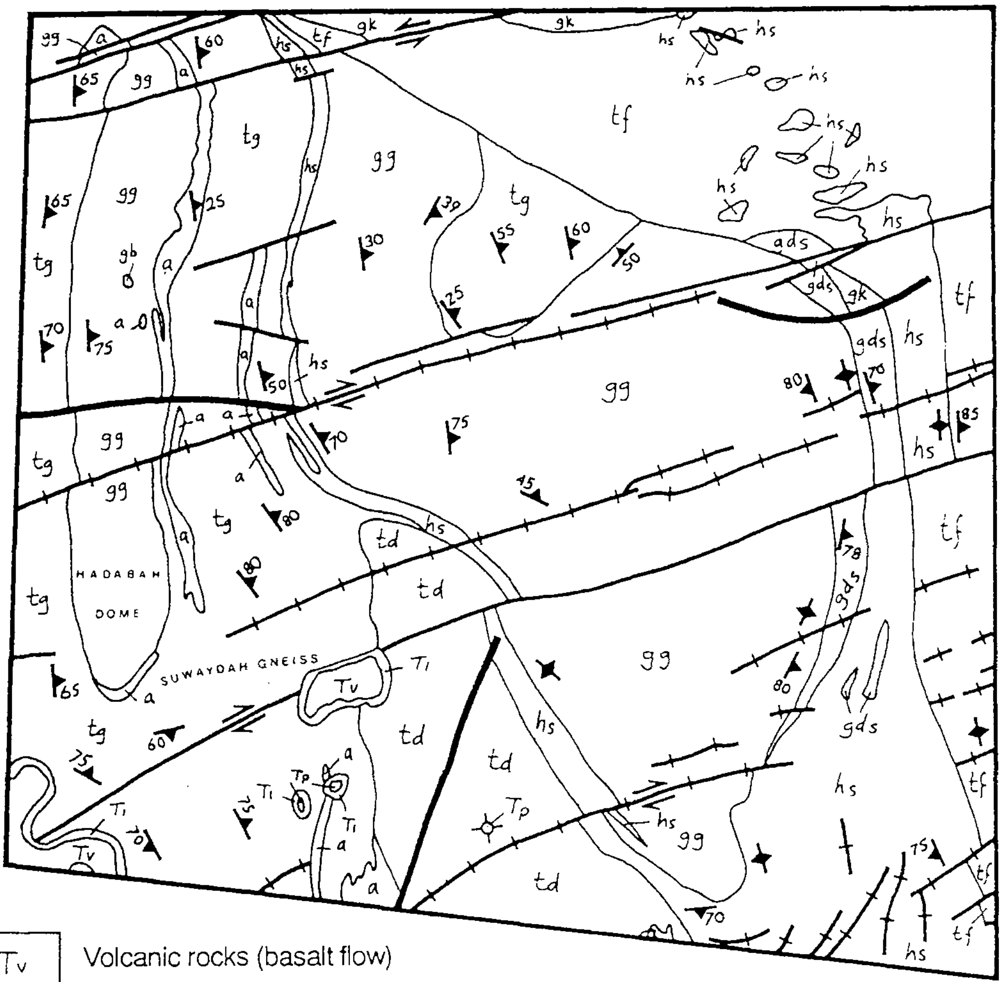
The basaltic flows of the As-Sarat mountains are situated to the west of the area. The metamorphic rocks occupy a small area and are well-foliated Upper Proterozoic metasedimentary rocks assigned to the Halaban Group. The plutonic rocks include granite, tonalite, gneiss and gabbro. A major group of east-west striking faults as well as individual faults extending in some cases for distances over 20 km were observed in the area (Stoeser, 1984).

3. Satellite imagery lineament quantification

A landsat Thematic Mapper (TM) scanner image was obtained for the purpose of the present study. The subscene (Fig. 3) for the selected study area is approximately 15 × 15 kilometres. The TM scanner records six bands of reflected visible and infrared light (0.45 – 2.35 μm), each picture element (pixel) measuring 30 m × 30 m on the ground, plus one thermal infrared band (10.4 – 12.5 μm), 120 m × 120 m on the ground.

Edge enhancement image processing technique was achieved by high-pass filtering, emphasizing higher spatial frequencies, using a convolution operation to increase lineament contrast. TM band 5 (1.55 – 1.75 μm) was selected, and a simple asymmetrical weighted kernel of size 3 × 3 pixels was applied. The resulting image is shown in Figure 4.

The lineaments were identified by visual inspection and recorded on a transparent overlay as ruled lines. A remotely sensed lineament map was constructed (Fig. 5)



Tv	Volcanic rocks (basalt flow)
Tl	Laterite
Tp	Basalt pipes
gb	Gabbro
gk	Khaniqah granite (biotite monzogranite)
td	Mafic tonalite and quartz diorite
gg	Granodiorite gneiss
tf	Al Fayd tonalite
tg	Tonalite gneiss
gds	Granodiorite sills
a	Amphibolite
hs	Metasedimentary rocks (Halaban Group)

Lithological contact

Fault (arrows indicate relative horizontal displacement)

Fault (intruded by mafic dyke)

Vertical foliation

86 Strike and dip of foliation

N

0 km 5

Fig. 2 : Geological Map.

Fig. 3 : TM-band 5 sub-scene.

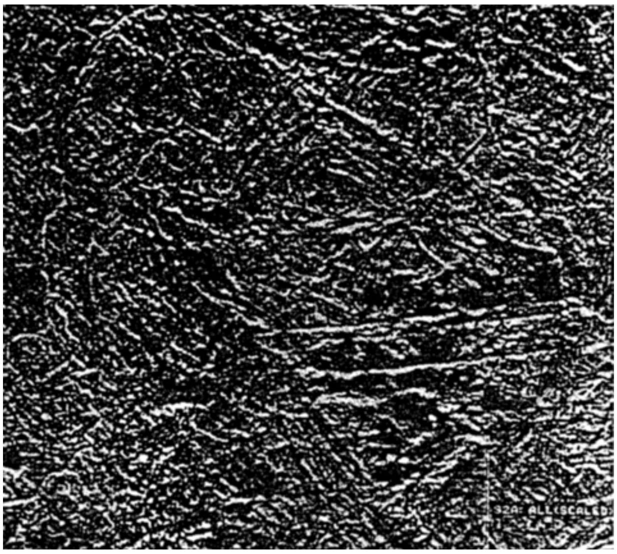


Fig. 4 : Directionally enhanced image.

based on the total knowledge compiled from edge enhancement, principal components analysis and decorrelation stretched images together with ground study (Qari, 1991).

The lineaments shown on Figure 5 were counted on a 2.5 × 2.5 km^{2}grid and the total density contoured (Fig. 6) to examine the pattern of concentration. The number of lineaments/6.25 km^2 varies from 3 to 21. Several concentrations of lineaments are quite apparent throughout the area, particularly in the middle northern and eastern parts of the study area. Additionally, there is an almost planar trend extending in a south-north direction rather linearly.

Comparison of observed lineaments with previously mapped features showed that many of them coincide with mapped faults. However, about 60 % correspond to joint sets that have not previously been mapped in ground surveys (Qari, 1991).

In order to correlate length and density of lineaments in the map (Fig. 5), a contour map of the total length was prepared (Fig. 7) based on the same basic grid size. There is a good correlation between the two maps of density and total length from the point of concentration centres. There appears to be a regional non-linear trend within the study area. The general trend is from SE to NW.

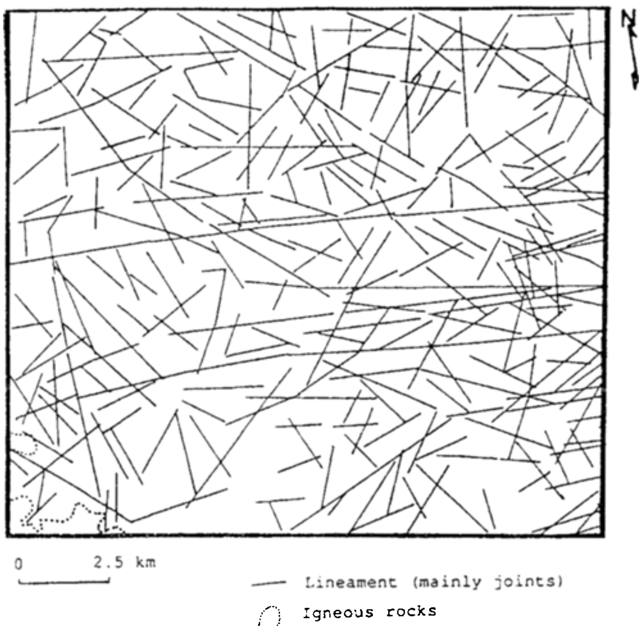


Fig. 5 : Remotely sensed lineament map.

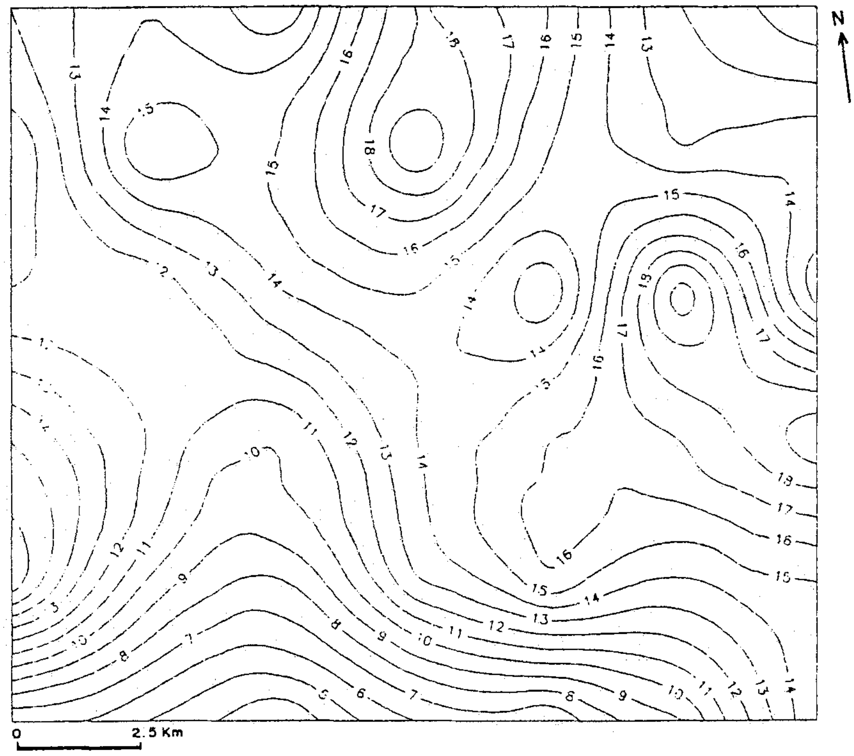


Fig. 6 : Isopleth map of fracture density.

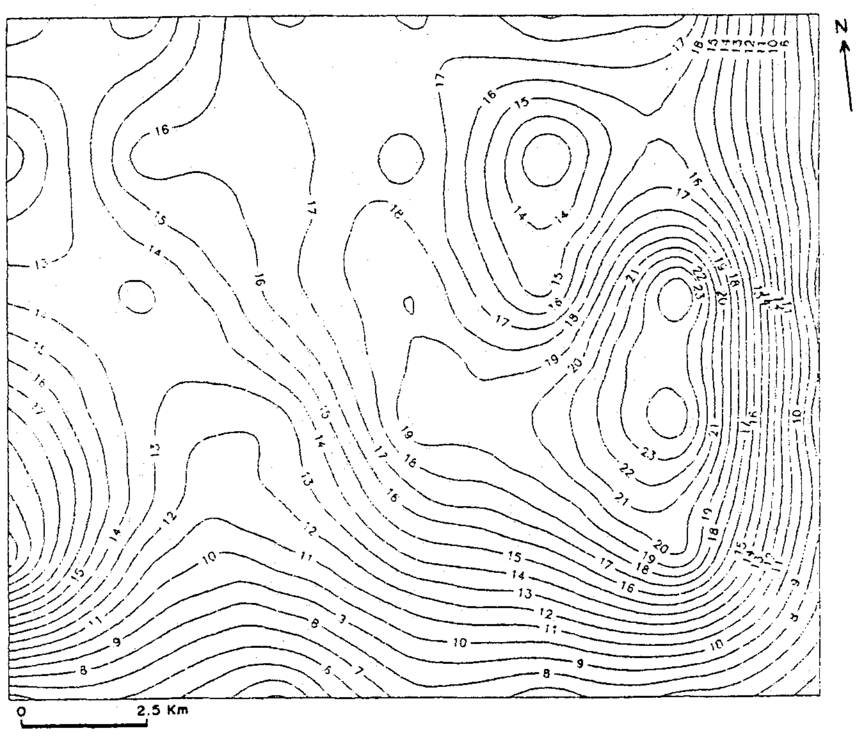


Fig. 7 : Isopleth map of fracture length.

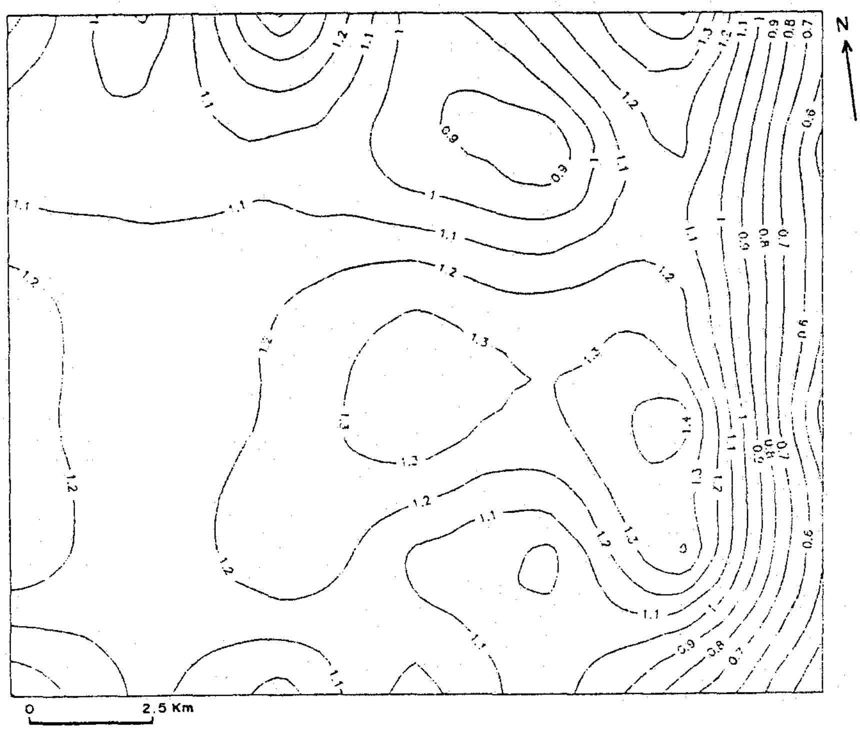


Fig. 8 : Fracture intensity map.

The distribution of the regional fracture intensity (RFI) parameter was obtained by dividing the total fracture length by fracture density and an isopleth contour map of the RFI is presented in Figure 8. This map furnishes a rather different pattern from the previous maps in that the general trend from west to east is rather in a linear form. Western parts of the study area have rather uniform RFI where the intensity change is very slight. On the contrary, the intensity change in the eastern part is comparatively rapid which provides strong evidence that the rock quality in this part is poor. In addition, the groundwater recharge possibilities are quite high. The best rock quality regions have high RFI values which appear in the central part of the study area.

4. Fracture pattern interpretations

The fracture patterns represented in Figures 6-8 imply various geological, hydrogeological and engineering geological implications. The geological interpretations concerning the fracture density isopleth map (Fig. 6) have already been given by Qari (1991). In addition, some of the hydro- and engineering-geological interpretations are given in the previous section.

The same figure shows the potential recharge areas for the surface water. In general, the greater the fracture density the bigger will be the amount of surface water contribution in aquifers of fractured media underlying the study area, especially, high fracture density coupled with low depression gives rise to more recharge possibilities. A quick glance at Figure 6 indicates that the density increases, generally, as a regional trend from south to north and from west to east. However, local fracture density increments appear at central north and mid-eastern locations. These are the places for additional groundwater recharge areas within the study area.

On the contrary, the potential recharge locations present potential hazard regions for engineering activities such as highway, dam and tunnel constructions. These regions possess economic losses prior to or after the construction of engineering structures.

In order to follow the flow pattern of water within the fractures (lineaments) from one edge to the opposite edge, two maps were prepared by considering only the fractures that are connected to each other from one edge to the other. Figure 9 shows the water flow direction (course) from west to east, while Figure 10 shows the flow course from south to north. However, these directions could be reversible in practice. It is obvious that the same study area presents a completely different pattern of groundwater flow lines which are dependent solely on the degree of connection of fractures. This picture presents an entirely different picture of groundwater flow from any classical porous medium. In order to provide a common basis for future groundwater studies within the area, the following interpretations are in order :

(i) the groundwater is compelled to flow through connected fractures in a rather random pattern composed of individual fractures.

(ii) the flow does not meet significant resistance along individual fractures; however, the connection points between two successive fractures, i.e., fracture intersections (energy loss point) give difficulty for groundwater

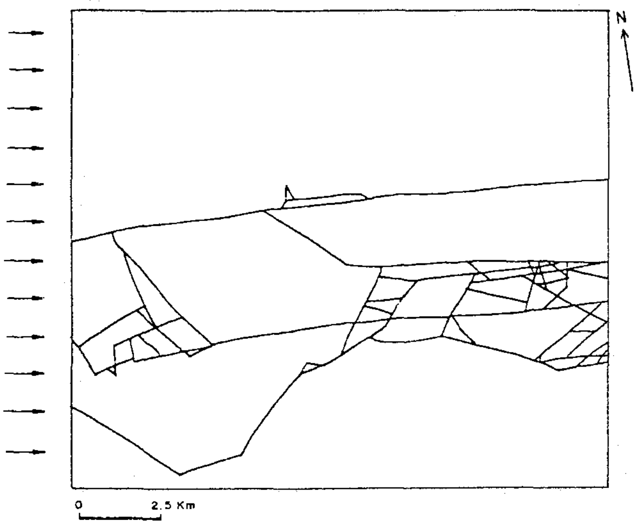


Fig. 9 : Connected fracture net in W-E direction.

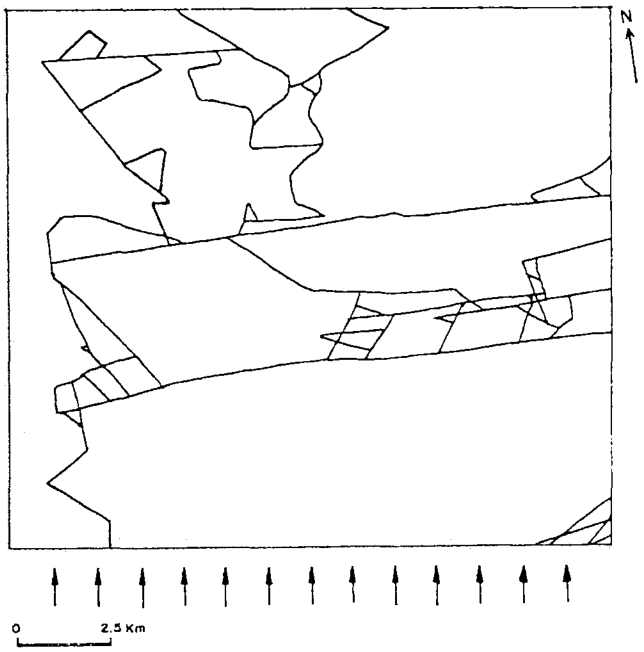


Fig. 10 : Connected fracture net in S-N direction.

flow. This is tantamount to saying that the greater the number of intersections the greater will be the energy loss. Physically, increase of intersections along the flow line causes the hydraulic gradient to be rather steep. This discussion shows qualitatively that by assuming other factors consistant the most resistant region for east-west groundwater flow will be in the lower left portion of the fracture pattern in Figure 9. Consequently, east-west flow will not be isotropic and homogeneous. In comparison, in Figure 10 energy loss points are scattered within the fracture pattern rather uniformly, hence, the groundwater flow will be more isotropic and homogeneous.

(iii) groundwater conducting fracture patterns in Figures 9 and 10 indicate one and two dimensional flows, respectively. In Figure 10 entrance of groundwater from the south ends up in the north and partly in the east.

(iv) along the general flow direction at any cross section, the greater the frequency of fracturing the less will be groundwater velocity. In order to qualify this properly it is necessary to have knowledge of fracture number variations along the flow directions. For such a purpose, Figures 11, 13 and 15 were prepared. Comparisons of these figures indicate that invariably in all the cases there are rather periodic variations of fracture numbers along the flow directions. However, least fracture number variation occurs along the north-south flow direction in Figure 10. There exists a reverse relationship between the number of fractures and the groundwater velocity. At rather dense fracture locations the groundwater velocity is smaller and therefore even

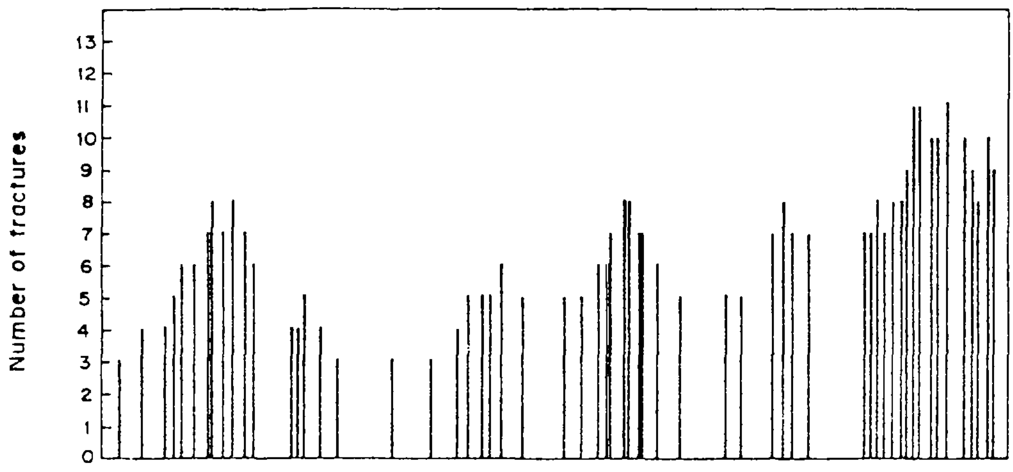


Fig. 11 : Fracture number variation in W-E direction for Fig. 9.

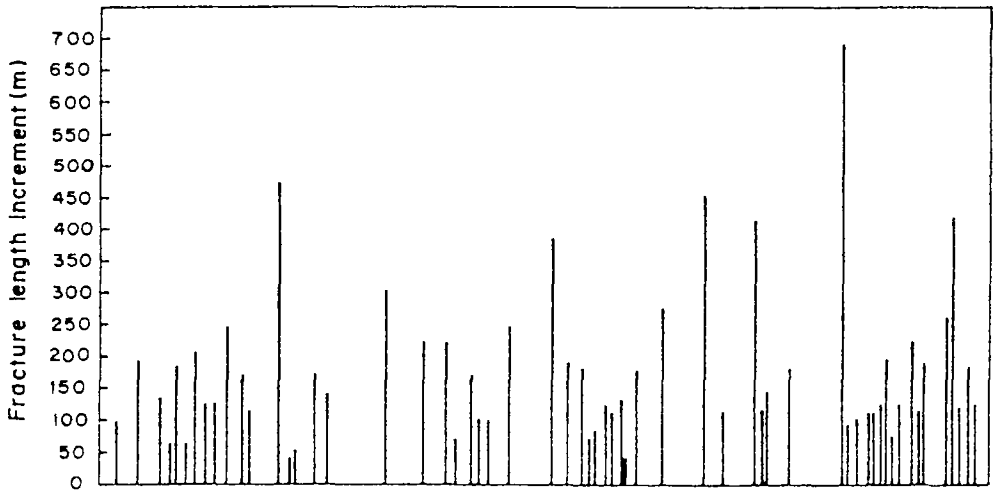


Fig. 12 : Fracture length increment in W-E direction for Fig. 9.

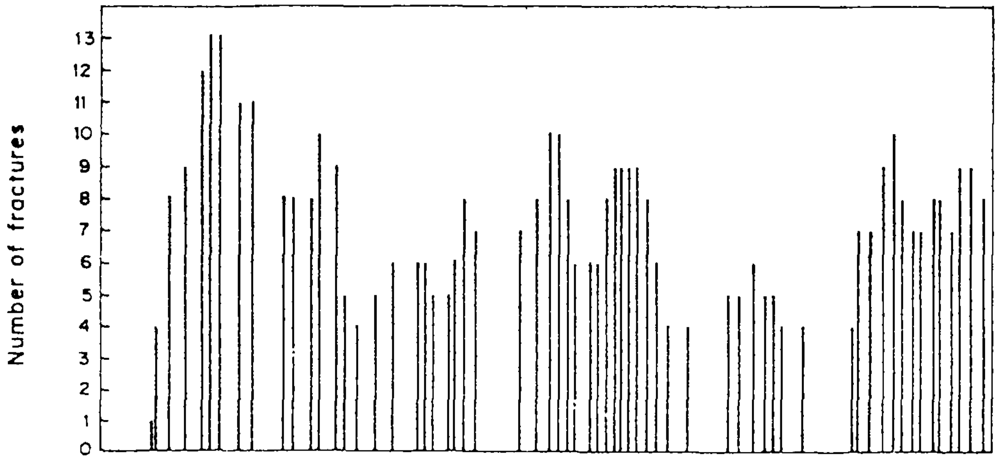


Fig. 13 : Fracture number variation in S-N direction for Fig. 10.

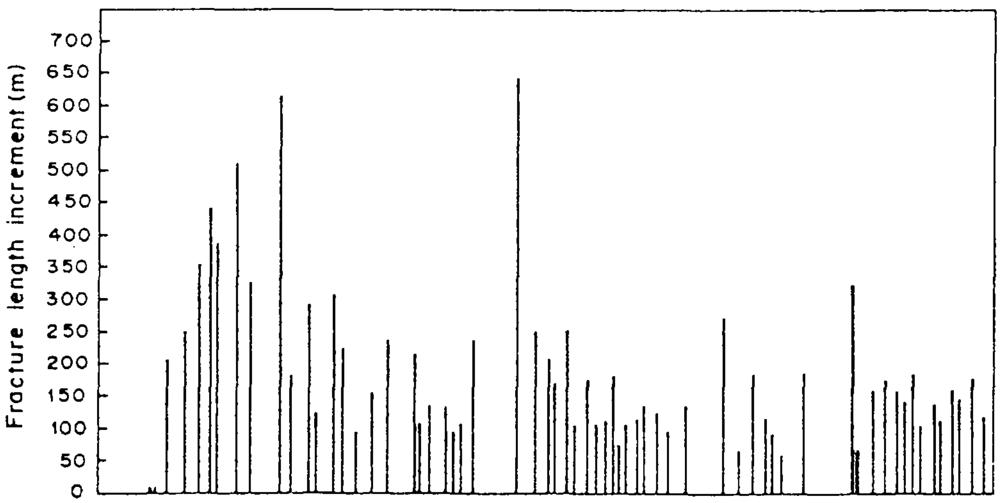


Fig. 14 : Fracture length increment in S-N direction for Fig. 10.

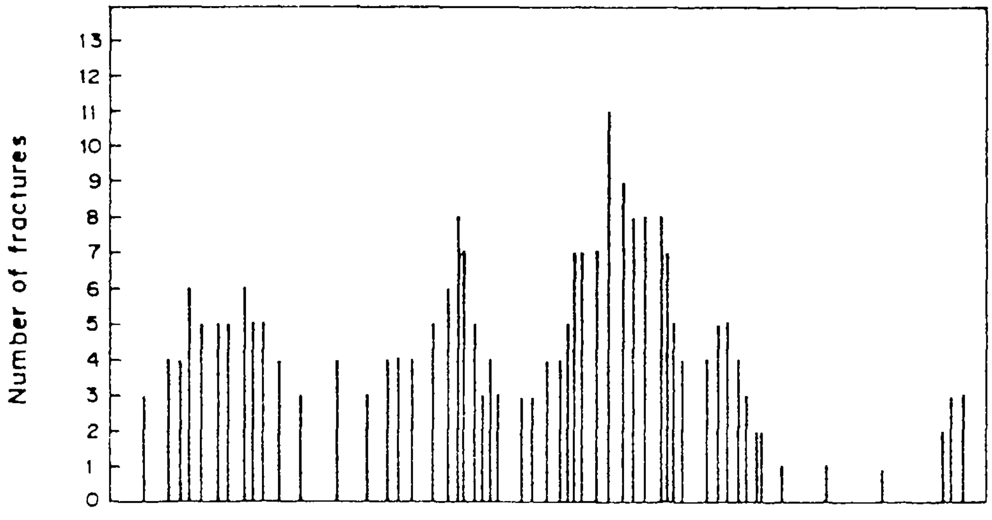


Fig. 15 : Fracture number variation in W-E direction for Fig. 10.

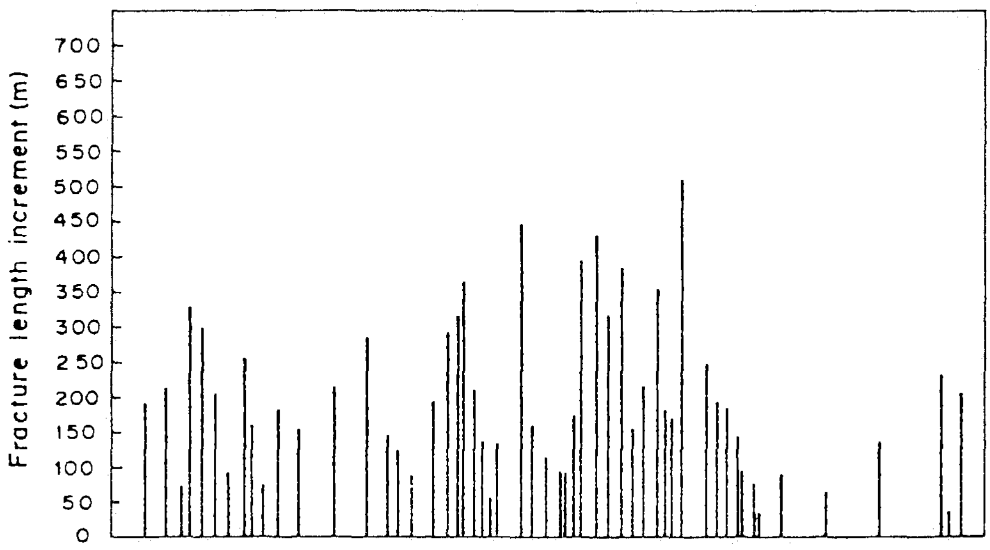


Fig. 16 : Fracture length increment in W-E direction for Fig. 10.

though there might be many fracture intersections the energy loss will be comparatively less than higher velocity locations.

(v) of course, the total length along a flow line (fracture) is directly proportional to the energy loss. The longer the flow path the greater is the hydraulic head loss and consequently the lower is the water quantity. In order to depict the effect of fracture length on the overall groundwater flow, the incremental lengths between two successive fracture intersections along the general flow direction are plotted in Figures 12, 14 and 16.

The quantitative evaluation of all of these figures is outside the scope of this paper. It is hoped that future quantitative studies as a continuation of these qualitative studies will shed light on groundwater flow laws, and contamination transport.

5. Conclusions

The following significant conclusions can be drawn :

(i) A natural fracture pattern exhibits significant anisotropic permeability.

(ii) The flow properties are direction-dependent and show large differences in connectivity of fractures in addition to the geologically more familiar quantities such as fracture orientation, length and intensity.

(iii) East-west flow is almost one dimensional whereas north-south direction flow expands toward two dimensions.

(iv) Since, groundwater flow follows a comparatively longer path for input from the north, the hydraulic gradient is expected to be smaller.

(v) Fracture density map provides information about the vertical movement of water which implies recharge from surface waters.

(vi) Regional intensity map gives potential groundwater recharge locations and rock quality zonation.

(vii) Various fracture number frequency and fracture length increment maps are prepared and necessary qualitative interpretations are presented.

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