J KAU: Earth Sci., **vol. 2**, pp. 69-83 (1409 A.H./1989 A.D.)

Fracture Analysis and Tectonic Implications of Hajjah District, Yemen Arab Republic

MOHAMED T.S. HEIKAL
Geology Department, UAE University, Al Ain, United Arab Emirates.

ABSTRACT. The present study principally deals with quantitative analysis of fractures in both Precambrian rocks including metavolcanics, metagabbros, syntectonic granitoids and late-tectonic granitoids as well as sedimentary rocks of Jurassic Period exposed in Hajjah district located at the northwestern part of Yemen Arab Republic. Aerial photographs and field work were utilized to identify the fractures. 1202 fractures of a total length of 1421.8 kilometers were identified. A multi-stage procedure is adopted for their recognition. The preferred orientations of the fracture pattern are WNW and NW for Precambrian rocks, and ENE and NNE for sedimentary rocks. Highest fracture density is reported in metagabbros.

The structural pattern of the present area is governed mainly by faulting and less by folding. The fracture pattern is compatible to a large extent with the major tectonic trends identified in Yemen Arab Republic. The recognized fracture pattern is believed to belong to two different episodes. The WNW pattern (Red Sea trend) occurred during the Najd Orogeny (Late-Proterozoic-Cambrian). The ENE and NE pattern (Gulf of Aqaba trend) belongs to Post Jurassic Orogeny.

Introduction

The area under consideration comprises about 910 km^2 out of which 700 km^2 are occupied by Precambrian rocks, whereas the rest 210 km^2 are occupied by sedimentary rocks of presumed Jurassic Period (Lamare 1923, 1930, Geukens 1960, 1966 and El-Nakhal 1987). The present area in northwestern part of Yemen is located about 131 km NW of Sana'a (Fig. 1). The chronological sequence of the mappable lithologic units in the studied area is shown in Fig. 1.

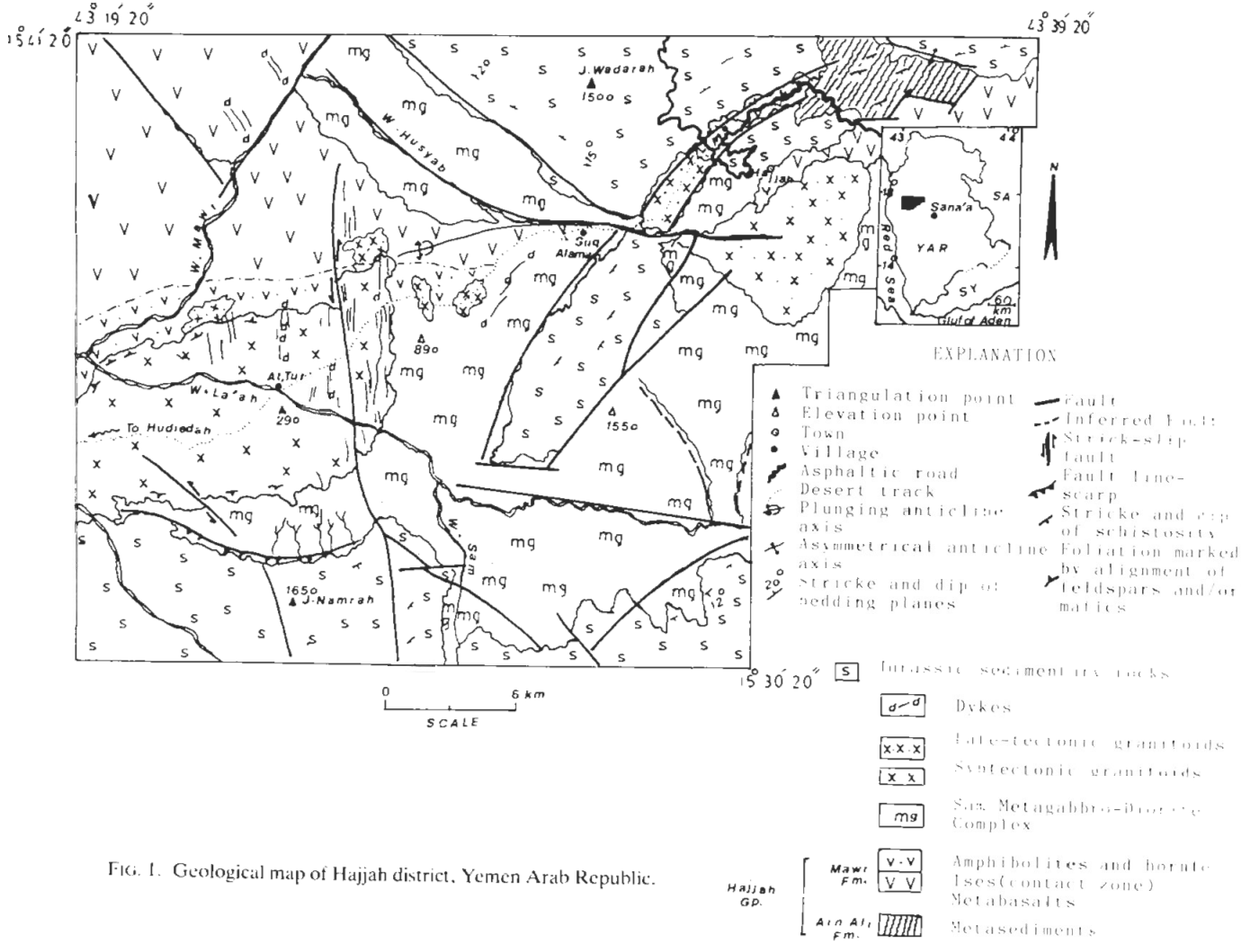

FIG. 1. Geological map of Hajjah district, Yemen Arab Republic.

Only a little geological work has been done on the investigated area. Generalized regional mapping has been carried out by Grolier and Overstreet (1976), who described the Precambrian rocks as consisting mainly of granites, gneisses and mica schists. Kawasaki (1980) in his work on the Master plan study for Hajjah province reported some lithologic units on the basis of the geological map prepared by Grolier and Overstreet *(op. cit.)*.

The present paper deals with quantitative analysis of photo-detected fractures as well as tectonic implications of the Hajjah district, Yemen Arab Republic. The present fracture analysis was performed on exposed Precambrian and Jurassic sedimentary rocks in the area under study to realize the following objectives :

1) Determine the fracture pattern of the area.
2) Detect the differences in the fracture density induced by lithologic variations.
3) Estimate the relevance of the fracture pattern of the structural elements in the area and correlate the recognized fracture pattern with the identified tectonic features in Yemen Arab Republic.

Analytical Technique

In the present study, the term "fracture", and consequently the term "fracture analysis", are used in photogeologic sense to describe any natural linear or curvilinear features that bear overwhelmingly distinctive earmarks of structural control (El-Etr 1976). Accordingly, fracture encompasses faults, joints, and dykes. The principal parameters applied in the present study for the detection and recognition of fractures are abrupt linear topographic change, straight segments of drainageways of structural elements.

The analytical investigation and delineation of fractures were achieved on black and white aerial photographs stereo-pairs at a scale of 1:60,000 and photo-mosaic at a scale 1:100,000 (Fig. 2).

Presentation and Analysis of Fracture Data

The identified fracture pattern (Fig. 3) includes 1202 fractures ranked as first order and/or minor faults. 908 fractures which give a total length (T.L.) of 1066.5 km are detected for the exposed Precambrian rocks with an average length (L/T.N.) of 1.1749 km, whereas 294 fractures from the Jurassic sedimentary rocks give a total length of 353.3 km with an average length (L/T.N.) of 1.209 km.

The pattern is characterized by distinct local density contrast, strong degree of preferred orientation, variation in relative length and the presence of localized belts of clusters of parallel (or en èchelon) fractures. The pattern is best explained reforming to the geological map (Fig. 1).

Length and azimuth of detected fractures (Fig. 3) were measured and recorded. The data was used as a base plot for the analytical treatment. The total number of fracture (N) and their total length (L) in each azimuth class were determined and their respective N% and L% were calculated with respect to the total number and

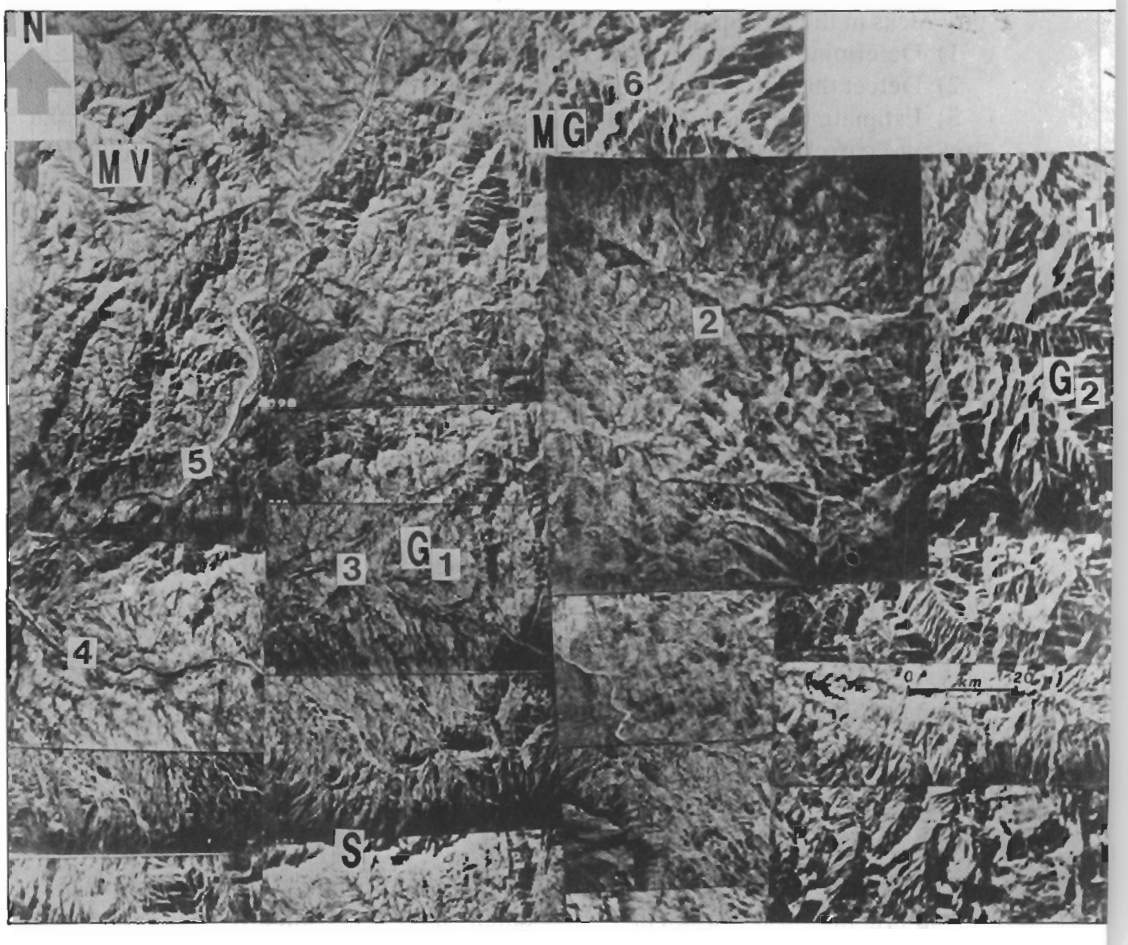

FIG. 2. Uncontrolled mosaic of Hajjah district.
1 = Hajjah town, 2 = Suq Alaman village, 3 = At, Tur village, 4 = Wadi La'ah, 5 = Wadi Mawr, 6 = Wadi Husyab, MV = Mafic metavolcanics, MG = Metagabbros, G_1 = Syntectonic granitoids, G_2 = Late-tectonic granitoids and S = Jurassic sedimentary rocks. Scale 1:100,000.

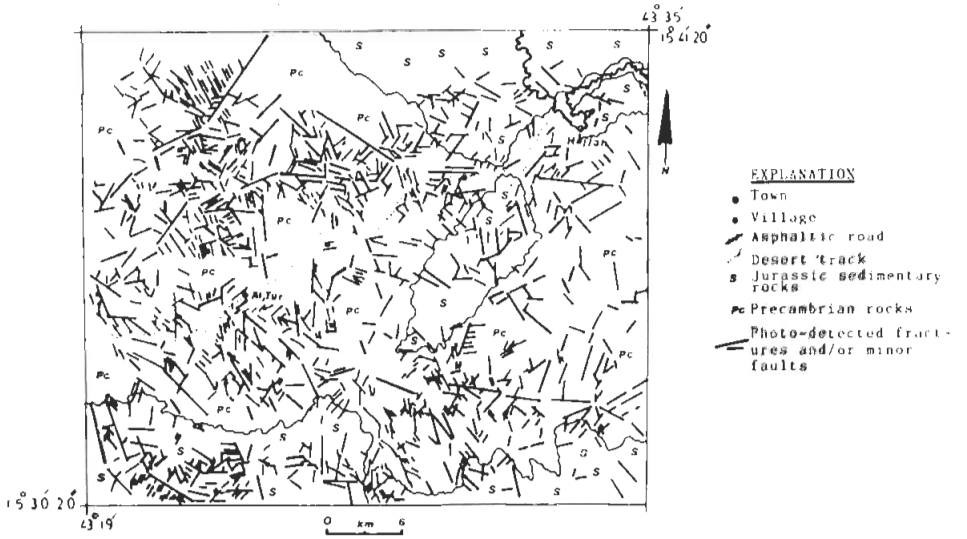

FIG. 3. Fracture map of Hajjah district, Yemen Arab Republic. Based on aerial photographs scale 1:60,000.

length of the total field of fracture pattern. The calculated data is graphically represented in diagrams. The rose diagram of percent of total number of fractures detected in Precambrian rocks in relation to the orientation (Fig. 4) indicates that the regional fracture pattern is generally dominated by WNW and followed by NW. The

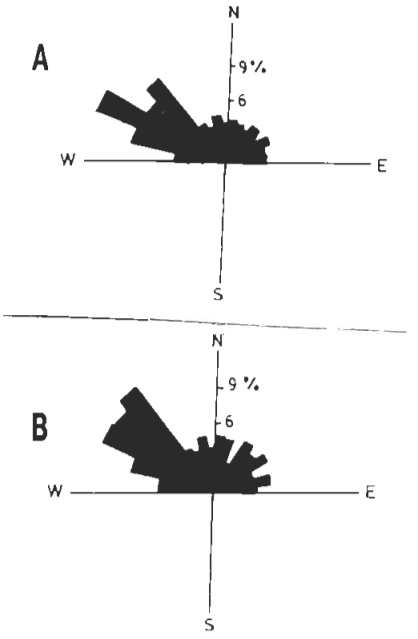

FIG. 4. Rose diagrams of fracture pattern of the studied Precambrian rocks. (A) percent of total number of fractures detected in relation to orientation. (B) percent of total length of fractures detected in relation to orientation.

first range extends from 50° to 70° with maximum peak located in 60°-70° W direction, followed by N 40°-50° W and N 50°-60° W (in decreasing order of significance). The main trend of fracture pattern in sedimentary rocks is ENE and followed by NNE (Fig. 5). The first range extends from 60° to 70° with maximum peak located in N 60°-70° E. The second range lies between 10° to 50° and with relative maximum value in N 20°-30° E direction.

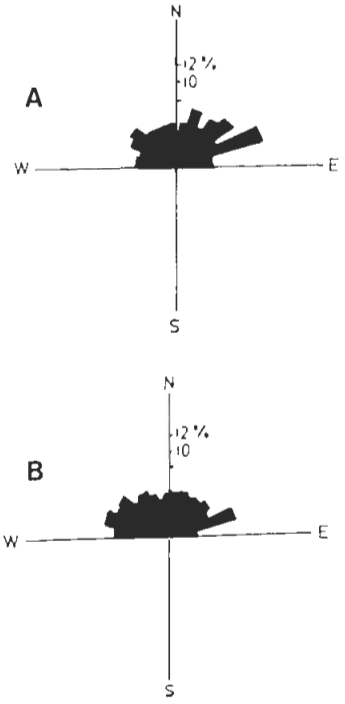

FIG. 5. Rose diagrams of fracture pattern of the studied Jurassic sedimentary rocks. (A) percent of the total number of fractures detected in relation to orientation. (B) percent of the total length of fractures detected in relation to orientation.

The most widespread rock units in Hajjah district are Metavolcanics (MV), Metagabbros (MG), Syntectonic granitoids (G_1), Late-tectonic granitoids (G_2) and Jurassic sedimentary rocks (S). The first four rock units are arranged in decreasing Precambrian age (Zalata *et al.* 1983). The relation between fracture patterns and spatial distribution of fractures in connection with exposures of different lithologic units is well defined and recognized in the present investigation. Possibly a regional criterion may be established to identify rock units on the basis of their photo-detected fractures (El-Etr *et al.* 1979).

The diagrams of fracture pattern of these rocks are shown in Fig. 6 on the basis of N% and L%, respectively. Inserted map at the top right of the Fig. 6 shows the areal distribution of the rocks units. The data on which these diagrams are based on, are shown in Table 1.

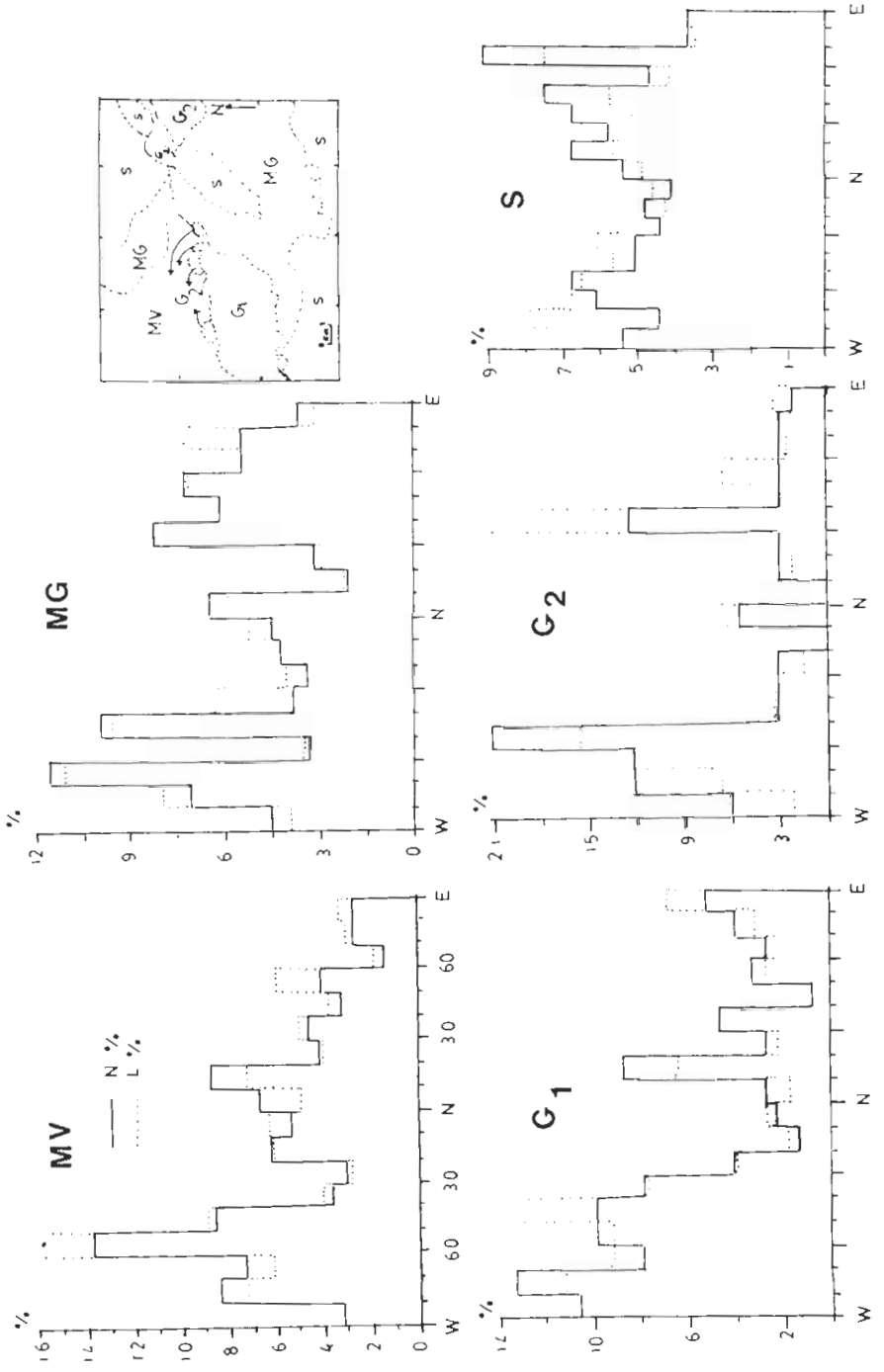

FIG. 6. Histograms of the number in percent (N%) and length in percent (L%) of the total field of fractures sorted out on the basis of both Precambrian lithologic units and Jurassic sedimentary rocks (of parts thereof) exposed. Inserted map shows the spatial distribution of the lithologic units employed. Letters designate as shown in Fig. 2.

TABLE I. Total number (T.N.) and average length (L/T.N.) of the total field of fractures for the major lithologic rock units exposed.

Unit	T.N.	L/T.N. (km)
MV	309	1.2
MG	401	1.1
G_1	151	1.2
G_2	33	1.4
S	294	1.2

The fracture density in the Precambrian rocks is fairly high. It is dominantly concentrated in the outcrops of metagabbros, metavolcanics and syntectonic granitoids. The minimum fracture density is displayed in the low lying disrupted outcrops of late-tectonic granitoids Fractures observed in the field for most rock units are well defined (Fig. 7A,B,C).

The fracture pattern for metavolcanics (MV) (Fig. 6) seems to be bimodal. General trends are mainly WNW and less commonly NNE. For the metagabbros (MG), the diagram indicates no significant trends, but NW and NE trends may be visualized. For the syntectonic granitoids (G_1), the frequency diagram plotted shows a general NW and less common NNE trend. For the late-tectonic granitoids (G_2), the pattern is bimodal with peaks at WNW and NE. For the sedimentary rocks (S), the diagram is bimodal. Main trends are oriented ENE and NE (less pronunced is WNW).

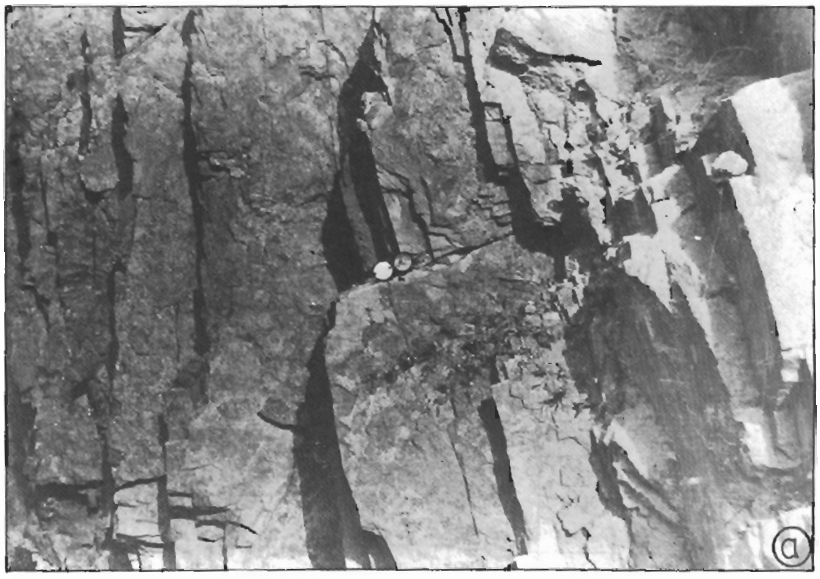

FIG. 7A. Close-up view of metagabbros (MG) showing nearly vertical fractures. Photolooking NNW (near Hajjah town).

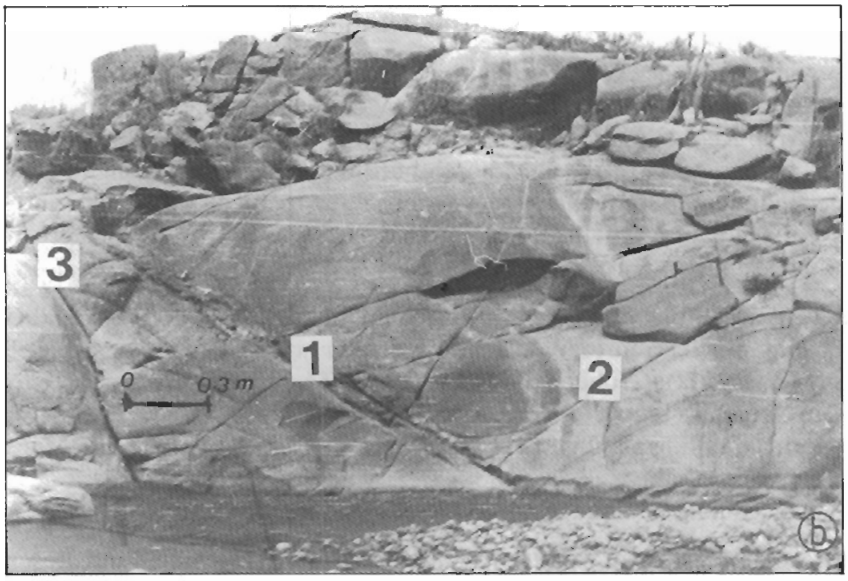

FIG. 7B. Close-up view of syntectonic granitoids showing two sets of joints. The major set (1) is oriented NNW and approximately at right angle to the second set (2).

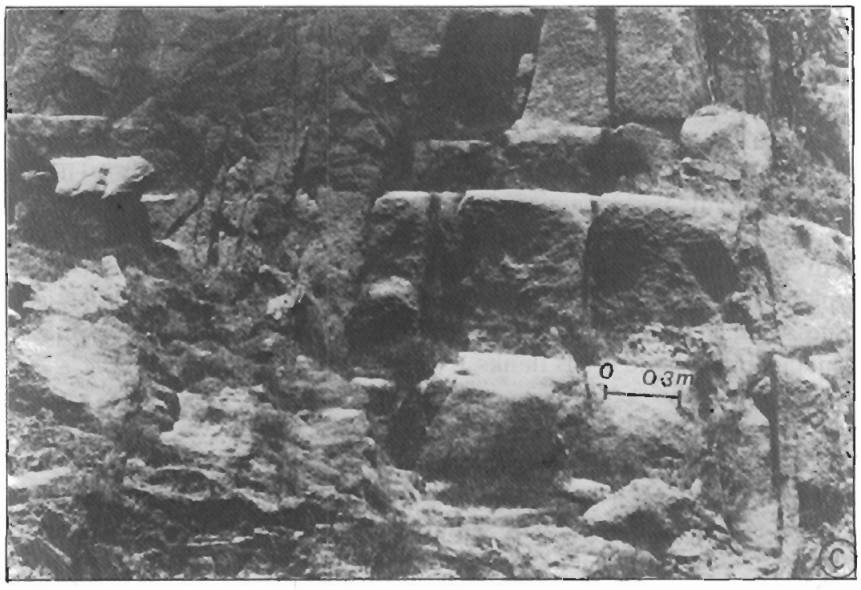

FIG. 7C. Close-up view of late-tectonic granitoids showing vertical joints (near Suq Alaman village).

Structural Setting

The geology of the Red Sea rift was discussed by several authors (Ours 1976, Isayev and Razvalyayeni 1977, El-Shatoury *et al.* 1979, and Ishutin 1982). The Yemen Arab Republic is a part of the original Precambrian Arabian-Nubian massif which is an extension of the shield area but thinly covered with slightly distorted younger sedimentary sequences (Fig. 8). From the highlands of Yemen and southwards to the Gulf of Aden, the Precambrian is partly covered by the Phanerozoic volcanics and sediments.

The tectonic setting of Yemeni rift is mainly related to the Red Sea and Gulf of Aden rifting which is represented mainly by either normal faulting or strike-slip tectonics (Brown 1972). Grolier and Overstreet (1976 and 1978) showed three tectonic trends in Yemen as follows :

1) Normal faulting parallel to the Red Sea with a NNW trends,
2) Transverse to the Red Sea, and
3) Diverse inland oblique features.

The recognized structural pattern of the studied area is assembled and presented in the geological map (Fig. 1). The tectonic events of the investigated area have played an important role in the configuration of the Precambrian exposure. It is made up of a craton of Precambrian rocks occupying most of the mapped area with sedimentary cover bordering it northward and southward. It extends further eastwards outside the boundaries of the mapped area.

Field study indicates that block faulting is a dominant tectonic-style in the area under consideration, where horst blocks of different sizes control the occurrences of the Precambrian rocks, and the intervening graben (structural basins) are filled mainly with the sedimentary rocks of Jurassic age. The demonstrated faults of the gravity type mostly delineate the graben areas of Jurassic sedimentary rocks. The determined fault patterns are of varying magnitude and trends (Fig. 9A). The regional pattern is predominated by major trends that follow northwesterly, west northwesterly, northeasterly and northerly directions. Folding, on the other hand, is less visible (Fig. 9B). Plunging anticlinal folds are recorded and checked in the field. The plunging fold is located at the central part of the present area (see geological map) near Suq Alaman village. It plunges 7° to ENE. Metavolcanics crop out in the core, while metagabbros build up its flanks.

Conclusion

The total number of fractures stereoscopically detected in the Hajjah district is 1202, of which 908 fractures totalling 1066.5 km of Precambrian rocks and 294 fractures totalling 355.5 km of Jurassic sedimentary rocks. The quantitative analysis of the total detected fractures indicates that the major trends of the fracture pattern of Precambrian rocks are oriented west northwesterly and northwest, whereas east northeasterly and subordinate north northeasterly trends are characterized by Jurassic sedimentary rocks.

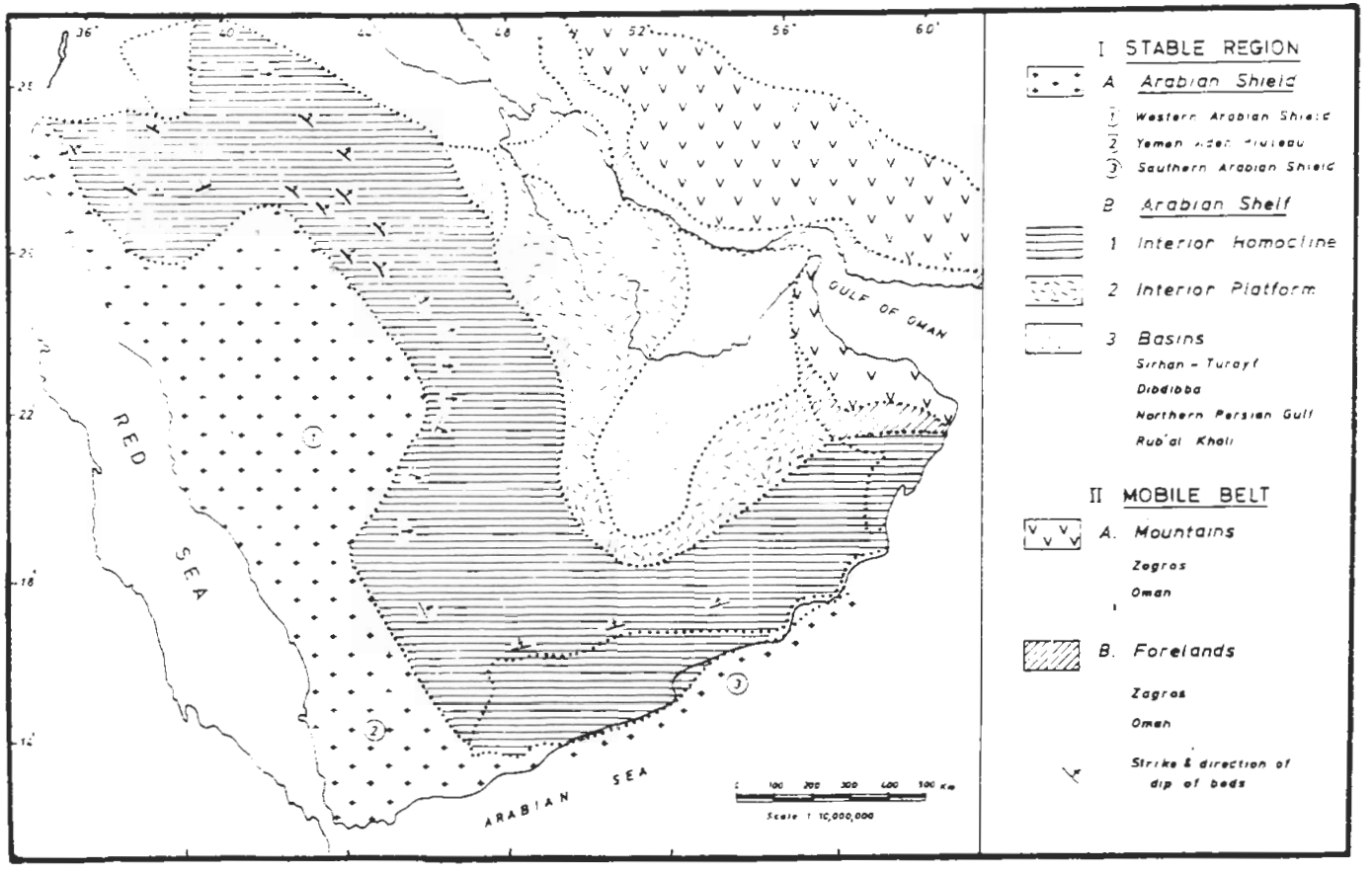

FIG. 8. Map showing structural provinces, Saudi Arabia and adjacent areas (Powers *et al.* 1966).

FIG. 9A. Close-up view of micro-normal fault with very small displacement about 30 cm. The fault plane trends NE (near Ain waterfall, 14 km SE Hajjah town).

FIG. 9B. Close-up view of micro-anticlinal fold of ultramafic schist pertaining to metagabbroid rocks (MG). The axial plane oriented NW (near Hajjah town).

The study showed that the regional fracture signature (west-northwesterly) is quite evident in the fracture patterns of these lithologic units of Precambrian age.

The structural pattern of the study area is effected dominantly by faulting, and subsidiarily by folding. Faults detected in the present area reached several scores of kilometers in length and they control the form and size of the blocks of the Precambrian terrain lying between the said faults. On the basis of the analysis of relative fault ages, it seems that the oldest fault trend extends NW (Red Sea trend), followed by WNW (transverse to the Red Sea) and NE (Gulf of Aqaba trend), and finally N-S (the youngest strike-slip fault trend). The relevance and harmony between fracture and structural patterns of the area under investigation reflect the tectonic pattern and defines the major tectonic trends. The author believes that the fractures occurred in two different episodes. The early phase of fractures having WNW trend (Red Sea trend) is believed to belong to the Najd Orogeny (Late-Proterozoic-Cambrian) described by Schmidt *et al.* (1979). The later phase fracturing that trends ENE and NE (Gulf of Aqaba trend) may have occurred during Post Jurassic Orogeny (Geukens 1966).

It is clear that the recognized major fracture trends are consistent and compatible with the major structural trends identified in Yemen Arab Republic.

Acknowledgement

My sincere thanks are to Dr. M. Yousef, Geology Department, Sana'a University, YAR, for reading and constructive criticism of this work.

References

Brown, G.F. (1972) *Tectonic Map of the Arabian peninsula,* Saudi Arabian Dir. Gen. Mineral Res. Map Ap-2 scale 1:4,000,000.

El-Etr, H.A. (1976) Proposed Terminology of Natural Linear Fractures, *Proc. 1st Internat. Conf. New Basement Tectonics, Utah Geol. Assoc. Pub.*, **5,** pp. 480-489. *Salt Lake City.*

El-Etr, H.A., Shazly, A.G. and **Heikal, M.T.** (1979) Fracture Analysis of Wadi El-Sodmein District, Central Eastern Desert, Egypt. *Delta Jour. Sci.* **2:** 103-138.

El-Nakhal, H. (1987) A Lithostratigraphic Subdivision of Kohlan Group in Yemen Arab Republic, *Iraqi J. Sci.* **28:** 149-180.

El-Shatoury, H.M., Al-Kirbash, S.A. and **Osman, S.** (1979) *Analysis of Lineaments in Landsat-I photographs of Yemen and their Geologic Significance,* Yemen Centre for Studies and Research (Dirasat Yamaniyah) Sana'a, YAR, 3-14.

Geukens, F.P.M. (1960) Contribution a la Geologie du Yemen, *Inst. de Geologie Louvain. Memoire* **21:** 122-79.

————(1966) *Geology of the Arabian peninsula,* Yemen Review of the Geology of Yemen as shown on USGS Miscellaneous Geology Investigation Map 1-270A. Geologic Map of the Arabian Peninsula. U.S. Government Printing Office, Washington, D.C., 560-B: 1-13.

Grolier, M.G. and **Overstreet, W.C. (1976)** *Preliminary and Simplified Geologic Map of Yemen Arab Republic,* Landsat. 1 Image No. 1136-07012. USGS. Open file report, U.S. Government Printing Office, Washinton, D.C.

Grolier, M.G. and **Overstreet, W.C.** (1978) *Geological Map of the Yemen Arab Republic, USGS, Miscellaneous Investigations Series Map 1-1143-B.*

Isayev, N. and **Razvalyayeni, A.V.** (1977) The Relationship between the Rift and pre-rift structural patterns as illustrated in the Red Sea rift, *Geotektonika.* **2:** 39-51.

Ishutin, V.V. (1982) The Red Sea Rift and its Role in the Distribution of Ferromanganese Mineralization, *Geotectonics.* **16:** 3.

Kawasaki, T. (1980) *Report on Master Plan Study for Hajjah Province Integrated Rural Development in the Yemen Arab Republic,* Japan International Co-operation Agency. 1 Main Report, 7. 6, 160.

Lamare, P. (1923) Note preliminaire sur la structure de la Region du Yemen (Arabic). *Société Geologique de France, Sommaire des Seinces, Comptes Rendus,* **23,** 61 p.

Lamare, P. (1930) Resultats Géographiques d'une Mission au Yemen, *La Geographie,* **54:** 393-323.

Ours, P.S. (1976) *Seismic and Volcanic Rocks in the Yemen Arab Republic,* Complied Report; Office of the UN Disaster Relief Co-ordinator, Geneva.

Powers, R.W., Ramirez, L.F., Redmond, C.D. and **Elbery, Jr. E.L.** (1966) *Geology of the Arabian Peninsula, Sedimentary Geology of Saudi Arabia,* Geol. Surv. prof. paper 560-D, US Government Printing Office, Washington, D1-D147.

Schmidt, D.L., Hadley, D.G. and **Stoeser, D.B.** (1979) Late Proterozoic Crustal History of the Arabian Shield, Southern Najd province, Kingdom of Saudi Arabia, *in:* **Al-Shanti, A.M.S.** (Convenor) *Evolution and Mineralization of the Arabian-Nubian Shield,* Vol. 2, *King Abdulaziz Univ., Inst. App. Geol. Bull.* **3:** 41-58.

Zalata, A.A., Shaalan, A.M., Noweir, A.M. and Heikal, M.T.S. (1983) Classification of Basement Rocks of Hajjah District, Yemen Arab Republic. *Fac. Sci. Bull. Sana'a Univ.* **3:** 1-16.

تحليل شروخ منطقة حجة بالجمهورية العربية اليمنية ودلالاتها التكتونية

محمد ثروت صلاح هيكل
قسم الجيولوجيا ، جامعة الإمارات العربية المتحدة
العـــين ، الإمارات العربية المتحدة

مستخلص . استخدمت الصور الجوية والمواقع في التعرف على ١٢٠٢ شرخا في صخور حقب ما قبل الكمبري والصخور الرسوبية الجوراسية لمنطقة حجّة بالجمهورية العربية اليمنية ، وقيست الشروخ طولا واتجاهها ، ورسمت هذه المعلومات في أشكال توضيحية وسُجلت أعلى كثافة للتشرُّخ في المنطقة في صخور الجابرو والبركانيات المتحولة فوق طية غاطسة محدبة . وكان أهم اتجاهات التشرخ السائدة لصخور ما قبل الكمبري غرب شمال غرب وشمال غرب ، بينما كانت اتجاهات التشرخ السائدة للصخور الرسوبية ذات العمر الجوراسي شرق شمال شرق وشمال شرق . وطبقا للوضع التكتوني للمنطقة ، كانت الصدوع هي العامل المؤثر والفعّال في توزيع تلك الصخور ، تليها في الأهمية الطيّات . وعزى المؤلف نظام التشرُّخ في المنطقة إلى حركتين أروجنيتين ، حيث يعتقد أن اتجاهات التشرُّخ في صخور (حقب ما قبل الكمبري) حدثت أثناء حركة نجد الأروجنية (الدهر الفجري - الكمبري) ، بينما نجد أن اتجاهات التشرُّخ في الصخور الرسوبية الجوراسية حدثت أثناء حركة أروجنية ما بعد الجوراسي . ومما هو جدير بالذكر أن الاتجاهات السائدة للشروخ تعكس بوضوح شديد الوضع التكتوني للمنطقة بصفة خاصة واليمن بصفة عامة .