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Study of fractures network in the basement of Socotra Island – Yemen - by using remote sensing and GIS techniques

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Abstract

Fractured basement rocks have become an increasingly common target for hydrocarbon production in the Republic of Yemen, where the oil is in production from the deeply buried fractured basement. These basement reservoirs underlie a thick sequence of Mesozoic to Tertiary sediments and in order to study the characteristics of this buried basement, indirect methods must be used. The present work deals with the production of structural maps of basement of Socotra Island, and the extraction of lineaments from remote sensing data (satellite imageries and aerial photographs) as well as the analysis of these extracted lineaments by using GIS. The numerous fractures detected in the basement are characterized by consistent variations in trend, length and density when they affect the different lithological units out cropping in the study areas. The granitic basement is expected to have the best fractured reservoir potential. The dominant fracture trends in the basement of Socotra Island are NW-SE and NE-SW. The presence of this fracture system is thought to be due to major tectonic activity which formed new fractures and also reactivated older fractures.

1. Introduction

The occurrence of naturally fractured basement reservoirs has been known within the hydrocarbon industry for many years. Reservoirs in fractured basements, where the oil and gas in place may be within an extensive fracture network on variety of different scales. Fractured basement rocks have become an increasingly common target for hydrocarbon production in the Republic of Yemen, where the oil is in production from the deeply buried granitic/gneissic fractured basement. These basement reservoirs underlie a thick sequence of Mesozoic to Tertiary sediments and in order to study the characteristics of this buried basement, indirect methods must be used.

Remote Sensing and Geographic Information System (GIS) techniques help to identify the fractures that effect basement outcrops. Generally the fractures of basement outcrops reflect the characteristics of the buried basement. Therefore a greater understanding of fracture distribution within basement reservoirs using Remote Sensing and GIS techniques may prove to be the key tool for improved exploration and management of this hidden resource.

Socotra Island (Yemen) is located in the northwest Indian Ocean near the Gulf of Aden (Fig. 1). Socotra is about 120 by 40 km and covers an area of 3625 km². It is composed of a basement complex of igneous and metamorphic rocks of Pre-Cambrian age overlain by sedimentary rocks, mainly limestone and sandstone.

The main aim of this study is to explore the fracture network in the Pre-Cambrian rocks of Socotra Island from remote sensing data (satellite imageries and aerial photographs). Remote Sensing and GIS techniques were used to produce structural maps of the basement areas.

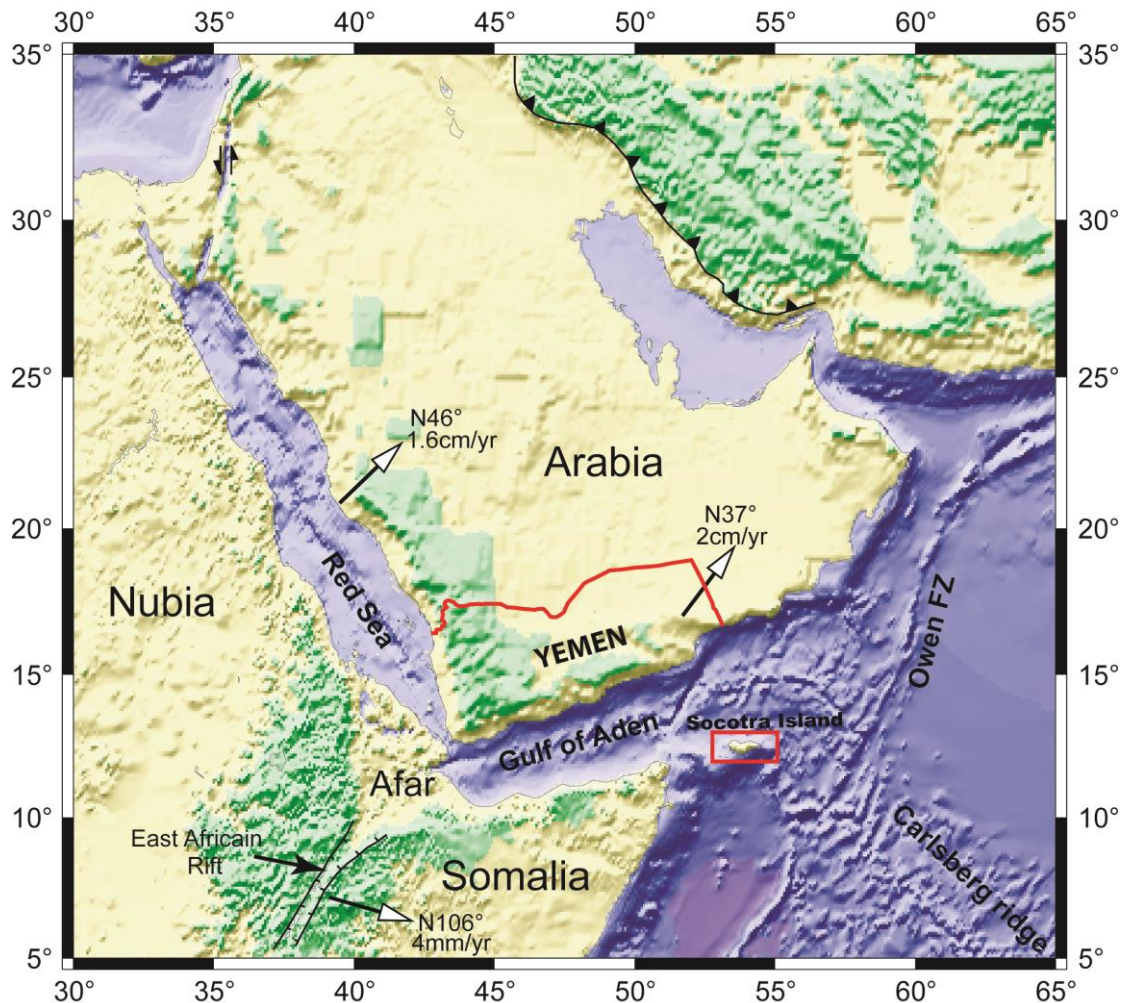


Figure 1: Topographic and bathymetric map of the Gulf of Aden and surrounding regions showing the location of Socotra Island and the direction and rate of motion of Arabia and Somalia with respect to Africa (Nubia and Somalia)

2. Tectonic and Geological Setting

The Socotra Island belongs to the southern continental margin of the Gulf of Aden (Fig. 1) which corresponds to an active oblique rift system with young margins along the Arabia-Somalia plate boundary connects to the Indian Ocean to the east and to the Red Sea to the west. This rift separates the Somalia plate to the South and the Arabian plate to the North. Rifting history started around 35 Ma and oceanic accretion is recorded since 17.6 Ma to the east^{1 2}. The oceanic floor becomes younger in the westernmost part of the Gulf of Aden,

¹ Leroy, S., Gente, P., Fournier, M., d'Acremont, E., Bellahsen, N., Beslier, M.-O., Patriat, P., Maia, M., Blais, A., Perrot, J., Al-Kathiri, A., Merkouriev, S., Ruellan, P.-Y., Fleury, J.-M., Lepvrier, C., Huchon, P., 2004. From rifting to spreading in the eastern Gulf of Aden: a geophysical survey of a young oceanic basin from margin to margin. *Terra Nova*, 16, 185-192.

² Fournier M., Chamot-Rooke N., Petit C., Huchon P., Al-Kathiri A., Audin L., Beslier M.O., D'Acremont E., Fabbri O., Fleury JM., Khanbari K., Lepvrier C., Leroy S., Maillot B. and Merkouriev S., 2010, Arabia-Somalia plate kinematics, evolution of the Aden –Owen–Carlsberg triple junction, and opening of the Gulf of Aden, *J. Geophys. Res.*, V. 115, B04102.

where the oldest magnetic anomaly corresponds to 3 Ma³. This gulf results from an oblique rifting characterized by a direction of extension N20° and a rift oriented N70°⁵. The Socotra Island has occupied, prior to the Oligo-Miocene Gulf of Aden opening, a position between the proto-East Gondwana and the Arabian Nubian Shield⁷.

Socotra Island composed of a basement complex of igneous and metamorphic rocks of Pre-Cambrian age overlain by sedimentary rocks, mainly limestone and sandstone (Fig. 2). It is covered by a carbonate-dominated Cretaceous and Tertiary succession unconformably overlying a Proterozoic and Paleozoic basement. Triassic and Jurassic deposits are locally preserved in a fault bounded area at the eastern end of the island.

Basement is exposed in three main areas of Socotra. The basement mainly includes Pan-African granites, which make up the 1500m-high Haggier massif (Fig. 2). The oldest basement lithologies, metamorphosed to amphibolites facies, are metasediments, amphibolites and acid orthogneisses. These are intruded by gabbros, acid volcanics and a variety of acid plutons, including granodiorites, adamellites and peralkaline granites^{8,9}.

On the island of Socotra, the southern passive margin of the Gulf of Aden displays along its strike two different types of asymmetric structures. Western Socotra is made up of a series of southward tilted blocks which are bounded by consistently northward dipping normal faults. Eastern Socotra consists of a broad asymmetric anticline with a steep northern limb and a gently dipping southern limb. A zone of NE–SW striking strike-slip and normal faults separates the two areas. The overall structure is interpreted as representing two rift segments separated by a transfer zone which is called Hadibo transfer zone¹⁰.

Three main outcrops of basement can be observed in Socotra Island (Fig. 2): Mont – Haggier area, Sherubrub area and Qalantssya area which is small and diffuse¹¹. In this study, Mont – Haggier and Sherubrub areas which represent the major outcrops of the basement, have been studied.

³ Cochran, J.R., 1981. The Gulf of Aden: Structure and Evolution of a Young Ocean Basin and Continental Margin. *J. Geophys. Res.* 86 (B1), 263-287.

⁴ Audin, L., 1999. Penetration de la dorsale d'Aden dans la depression Afar entre 20 et 4 Ma. PhD Thesis, Paris 7 University, France. 278 pp.

⁵ Dauteuil, O., Huchon, P., Quemeneur, F., Souriot, T., 2001. Propagation of an oblique spreading center: the western Gulf of Aden. *Tectonophysics* 332, 423-442.

⁶ D'Acremont, E., Leroy, S., Beslier, M.-O., Bellahsen, N., Fournier, M., Robin, C., Maia, M., and Gente, P., 2005. Structure and evolution of the eastern Gulf of Aden conjugate margins from seismic reflection data, *Geophys. J. Int.*, 160, 869–890.

⁷ Denele Y., Leroy S., Pelleter E., Pik R., Talbot JY., Khanbari K., 2012, The Cryogenian arc formation and successive high-K calc-alkaline plutons of Socotra Island (Yemen), *Arab J Geosci* 5(5):903–924.

⁸ Beydoun Z.R., Bichan H.R., 1970, The geology of Socotra Island, Gulf of Aden. *Quarterly J Soc Lond* 25:413–446.

⁹ Denele Y., Leroy S., Pelleter E., Pik R., Talbot JY., Khanbari K., 2012, The Cryogenian arc formation and successive high-K calc-alkaline plutons of Socotra Island (Yemen), *Arab J Geosci* 5(5):903–924.

¹⁰ Fournier M., Huchon P., Khanbari K., Leroy S., 2007, Segmentation and along-strike asymmetry of the passive margin in Socotra, eastern Gulf of Aden: Are they controlled by detachment faults?, *G3*, Q03007.

¹¹ Denele Y., Leroy S., Pelleter E., Pik R., Talbot JY., Khanbari K., 2012, The Cryogenian arc formation and successive high-K calc-alkaline plutons of Socotra Island (Yemen), *Arab J Geosci* 5(5):903–924.

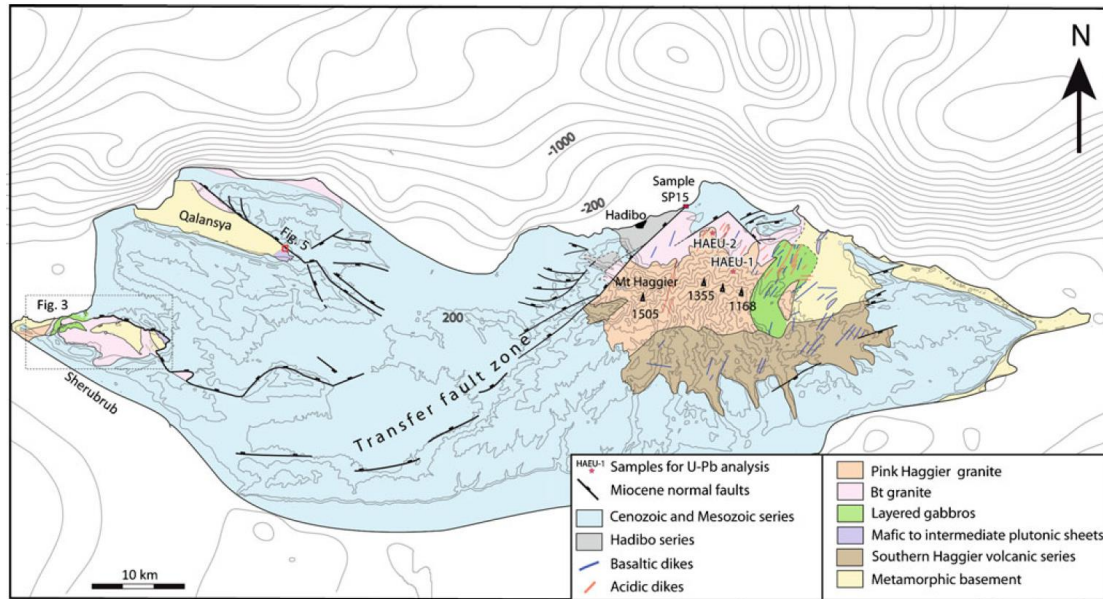


Figure 2: Geological and topographic map of Socotra Island showing the location of basement exposures in three main areas on Socotra

3. Study of fractures network by remote sensing data

Aerial photo interpretation technique was used for mapping the small fractures which effect the basement of Socotra Island, while Landsat-ETM image is used de identify the main structures such as major faults. Aerial photo mosaic with resolution of one meter and Landsat-ETM image have been interpreted by visual method in order to delineate the structures in the study areas (Mont-Haggier and Sherubrub area).

All structures derived from aerial photos and Landsat-ETM have been implemented in a GIS in order to obtain the related fracture maps, useful for the tectonic interpretation. The recognized structures have been analyzed by their trend. The numerous fractures detected are characterized by consistent variations in trend, length and density when they effect the different lithological units outcropping in the study areas.

3.1. Mont-Haggier area (Eastern outcrop)

Haggier mountains are located in eastern –central part Socotra Island (Fig.2). This basement massif occupies area of 662 Km² with the highest altitude in the Island (1500m). The oldest basement rocks in Mont – Haggier area are the metamorphic basement which comprise Paragneisses and Micaschists, Orthogenesis, Amphibolite and Quartzites. The Metamorphic basement is overlain by Metavolcanic series which corresponds to an association of pyroclastic and effusive rocks¹³.

Structural map of Mont-Haggier area (Fig. 3) shows that the basement is effected by different type of geologic structures (fractures, faults, dykes) which have different trend, length and density. The rose diagram (Fig.4) shows that the dominant trends of fractures in Mont -

¹² Denele Y., Leroy S., Pelleter E., Pik R., Talbot JY., Khanbari K., 2012, The Cryogenian arc formation and successive high-K calc-alkaline plutons of Socotra Island (Yemen), Arab J Geosci 5(5):903–924.

¹³ Denele Y., Leroy S., Pelleter E., Pik R., Talbot JY., Khanbari K., 2012, The Cryogenian arc formation and successive high-K calc-alkaline plutons of Socotra Island (Yemen), Arab J Geosci 5(5):903–924.

Haggier area are NE-SW and NW- SE. Some other trends: N-S and E-W have been observed. The density map of fractures (Fig. 5) shows that the fracture density is high in the west and central parts of the study area which represent per-alkaline granites, while the other rock units are less affected by fractures.

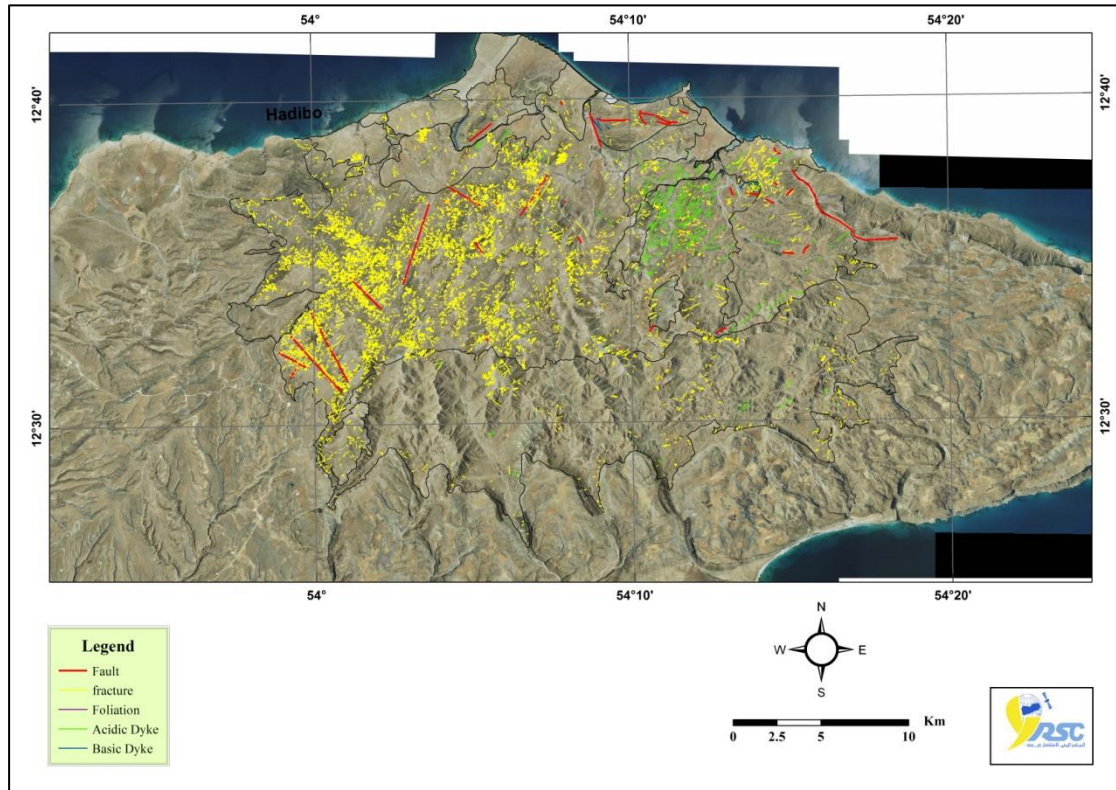


Figure 3: Structural map of Mont- Haggier basement (the background is aerial photo mosaic with resolution of one meter)

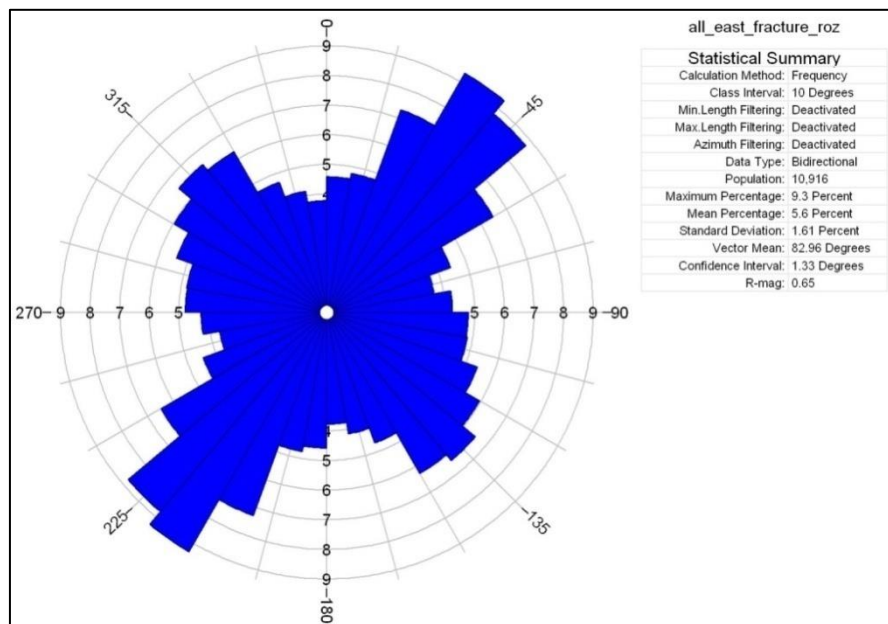


Figure 4: Rose diagram showing the trends of fractures in Mont -Haggier basement

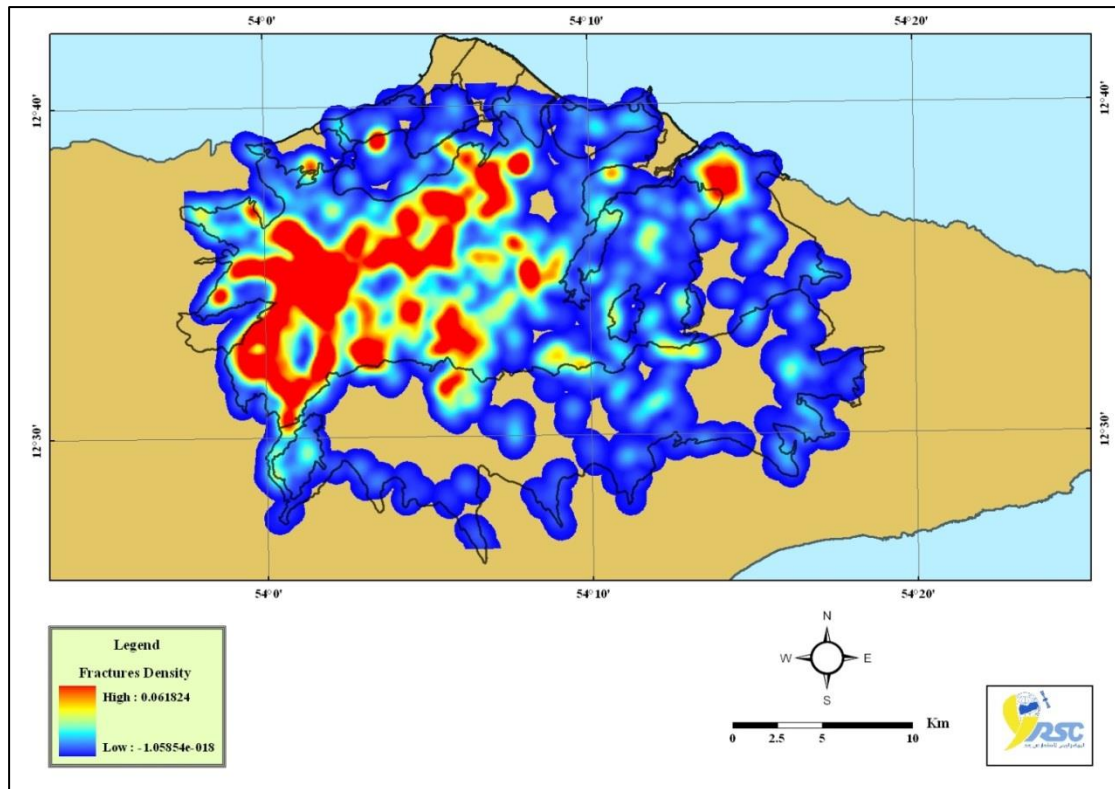


Figure 5: Density map of fractures in Mont -Haggier area

3.2. Sherubrub area (western outcrop)

Sherubrub basement is located in the western part of Socotra Island (Fig. 2). The basement occupies area about 53 Km². Sherubrub area is covered mainly by Granitic pluton which is constituted mainly by a pink Biotite-Hornblende granite. The pink granite and Gabbro are intended the metamorphic basement (Orthogenesis, Paragneisses, Quartzites). The volcanic dykes cut all petrographic formations in Sherubrub area. These dykes correspond to basaltic dykes with a microgranular porphyric texture¹⁴.

Structural map of Sherubrub area (Fig. 6) shows that the basement is effected by different type of geologic structures (fracture, faults, dykes, floatation) which have different trend, length and density. The rose diagram (Fig. 7) shows that the dominant trends of fractures in Sherubrub area are NW-SE and NE- SW. All other trends such as N-S and E-W have been observed. The density map of fractures (Fig. 8) shows that the fracture density is high in the west and central parts of the study area which represent Paragneisses and Biotite-Hornblende granites, while the other rock units are less affected by fractures.

¹⁴ Denele Y., Leroy S., Pelleter E., Pik R., Talbot JY., Khanbari K., 2012, The Cryogenian arc formation and successive high-K calc-alkaline plutons of Socotra Island (Yemen), Arab J Geosci 5(5):903–924.

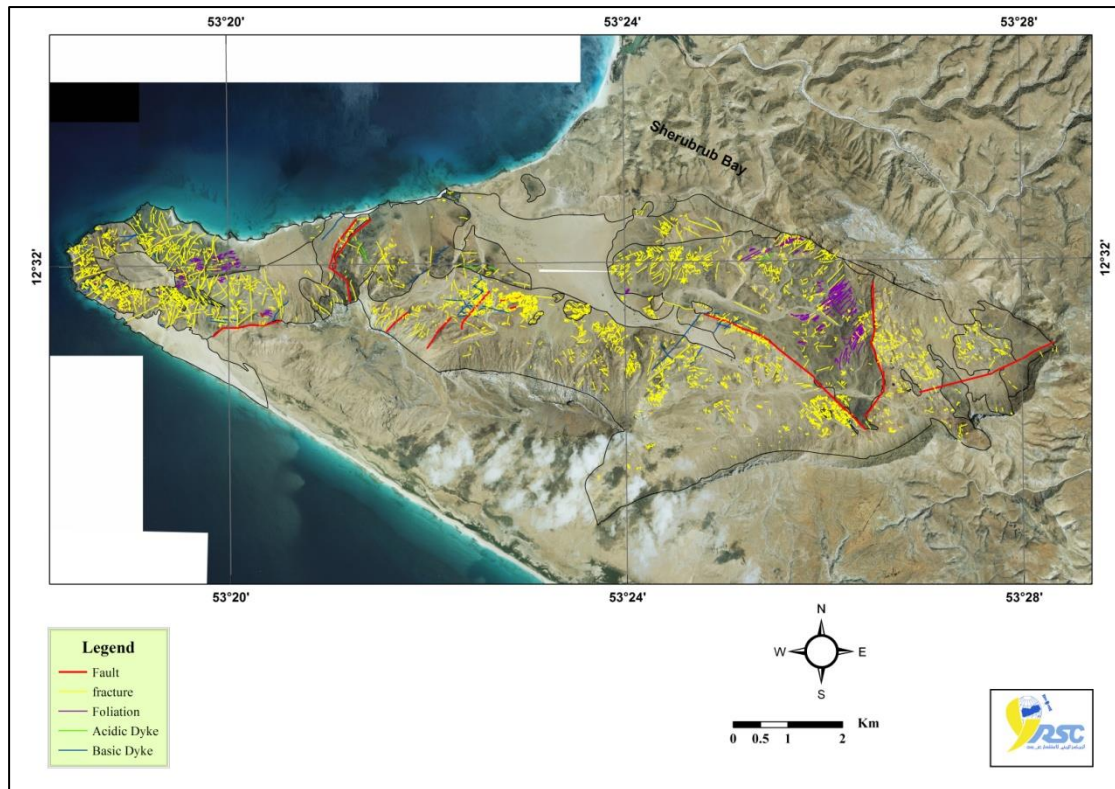


Figure 6: Structural map of Sherubrub basement (the background is aerial photo mosaic with resolution of one meter)

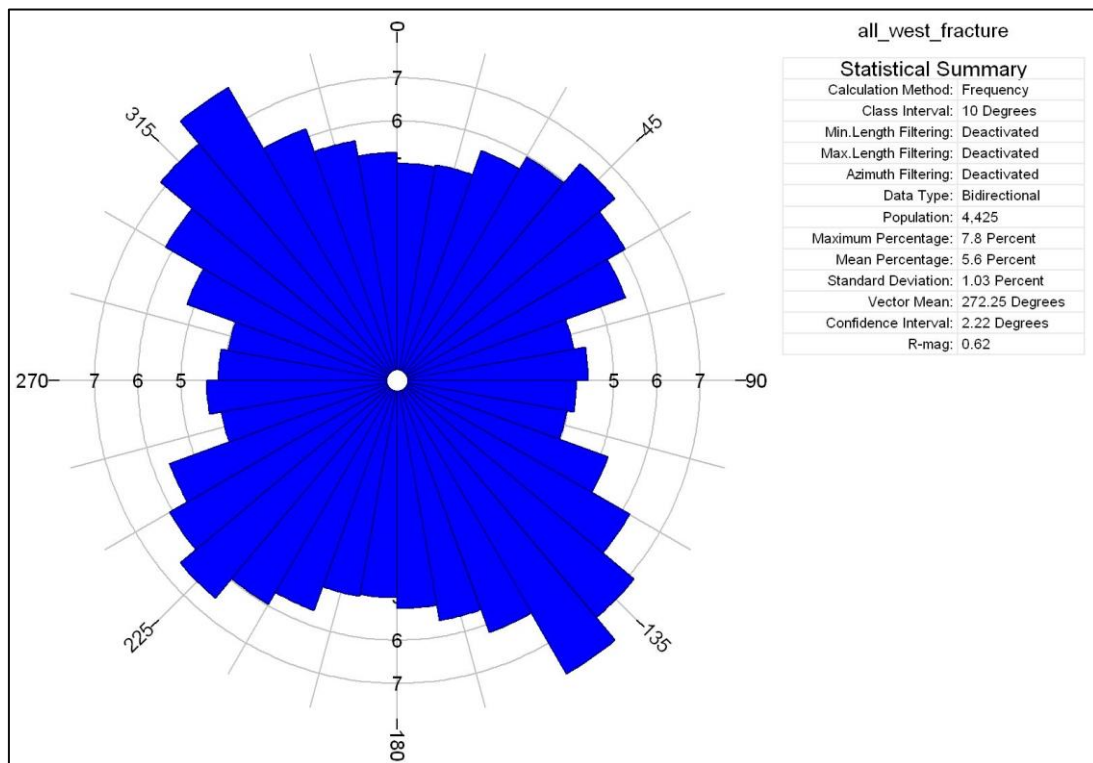


Figure 7: Rose diagram showing the trends of fractures in Sherubrub basement

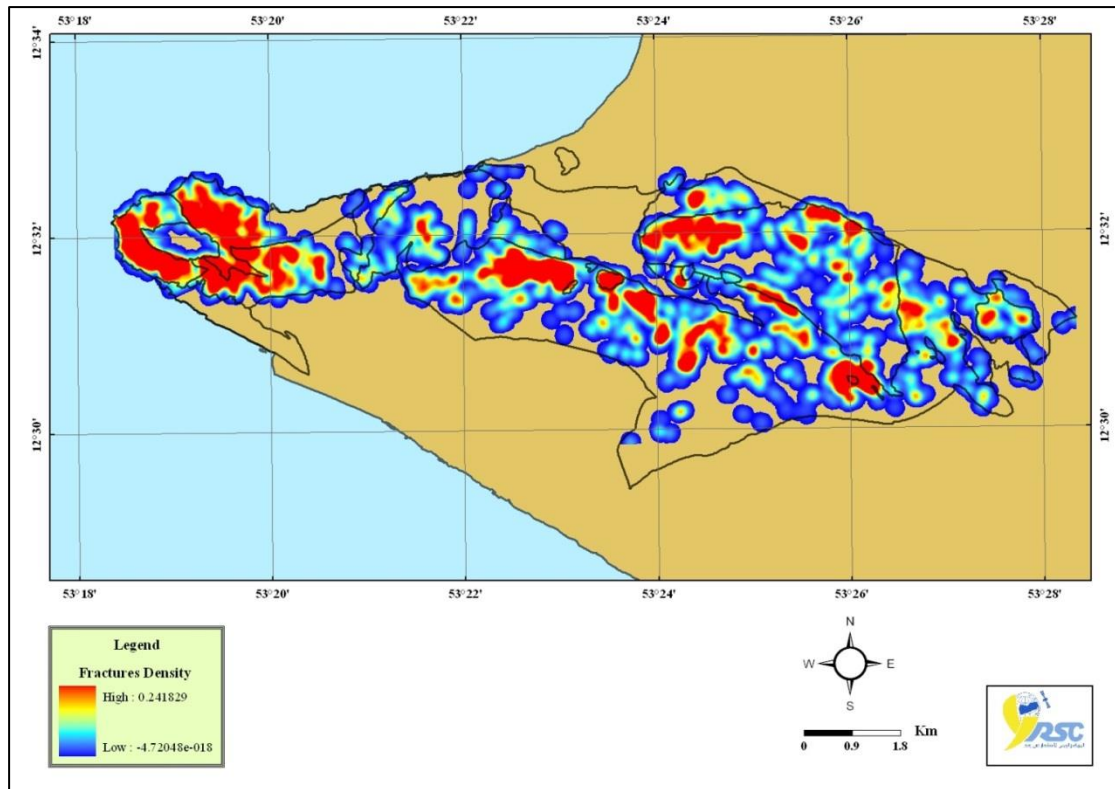


Figure 8: Density map of fractures in Sherubrub area

4. Discussion and Conclusion

Basement of Socotra is correlated with Proterozoic basement of Arabian plate (especially Yemen and Oman). The construction of the Gulf of Aden shows that the Socotra Island has occupied, prior to the Oligo-Miocene rifting, a position close to the Precambrian Mirbat and Al-Halaaniyat Islands outcrops in Oman^{15 16}. The Socotra Island has occupied, prior to the Oligo-Miocene Gulf of Aden opening, a position between the proto-East Gondwana and the Arabian Nubian Shield¹⁷.

The present work deals with the production of structural map of basement of Socotra Island, and the extraction of fractures from remote sensing data (satellite imageries and aerial photographs) as well as the analysis of these extracted fractures. The basement is exposed mainly in eastern Socotra (Mont-Haggier) and also in several western localities such as Sherubrub area. Basement of Socotra displays a great variety of metamorphic, plutonic and volcanic rocks.

¹⁵ Denele Y., Leroy S., Pelleter E., Pik R., Talbot JY., Khanbari K., 2012, The Cryogenian arc formation and successive high-K calc-alkaline plutons of Socotra Island (Yemen), Arab J Geosci 5(5):903–924.

¹⁶ Leroy, S., Razin, P., Autin, J., Bache, F., d'Acremont, E., Watremez, L., Robinet, J., Baurion, C., Denele, Y., Bellahsen, N., Lucazeau, F., Rolandone, F., Rouzo, S., Kiel, J.S., Robin, C., Guillocheau, F., Tiberi, C., Basuyau, C., Beslier, M.O., Ebinger, C., Stuart, G., Ahmed, A., Khanbari, K., Al Ganad, I., de Clarens, P., Unternehr, P., Al Toubi, K., Al Lazki, A., 2012. From rifting to oceanic spreading in the Gulf of Aden: a synthesis. Arab. J. Geosci. 5 (5), 859–901.

¹⁷ Denele Y., Leroy S., Pelleter E., Pik R., Talbot JY., Khanbari K., 2012, The Cryogenian arc formation and successive high-K calc-alkaline plutons of Socotra Island (Yemen), Arab J Geosci 5(5):903–924.

The numerous fractures detected in the basement are characterized by consistent variations in trend, length and density when they affect the different lithological units out cropping in the study areas (Mont-Haggier and Sherubrub area). Fractures networks have been observed in all rock units. They exist over a wide range of scales from micro-fractures to largest faults. The fracture analysis shows two principal structural trends: NW-SE and NE-SW with less expressed trends around N-S and E-W. The average length of the fractures is about 25-100m.

Basement in Socotra Island is intensely fractured. The nature of fracture network varies with lithology. It appears that more homogeneous lithologies of magmatic origin have been better fracture properties than the layered formations of metamorphic origin. Therefore the granitic basement is expected to have the best fractured reservoir potential. Basement variations in Socotra Island are influenced by a number of factors including basement lithology and tectonic factor.

The dominant fracture trends in the basement of Socotra Island are NW-SE and NE-SW. The presence of this fracture system is thought to be due to major tectonic activity such as Tertiary opening the Gulf of Aden and Mesozoic break-up of Gondwana. These tectonic events formed new fractures and also reactivated older fractures.

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