Geological and Structural Evolution of the Sharab area, Southwest Yemen

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Abstract— This paper presents the first attempt to give insight background on the lithological units and their structural evolution in the Sharab area of Yemen, based on the field work, satellite image analysis and available secondary data sources. Accordingly, geological map is constructed. Lithologically, the Sharab area is occupied by a few thousand meters thick of Precambrian basement rocks overlain by thick Mesozoic marine sediments (limestone and shale) and clastic sediments (sandstone, siltstone, mudstone and conglomerate). The Precambrian basement and Mesozoic sediments are coated by huge amounts of Tertiary basalts intercalated with acidic and volcaniclastic strata and injected by several types of igneous dykes, sills and plugs. Structurally, the study area is affected by six phases of deformations (D_1-D_6) took place in three stages; during the Precambrian (D_1: D_4), through Mesozoic (D_5) and in the Cenozoic (D_6). D_1 of the Precambrian is characterized by penetrative linear foliation (S_1), lineation (L_1) and isoclinal, intrafolial folds (F_1), while D_2, D_3 and D_4 are characterized by a series of major and minor anticline and syncline folds (F_2), ductile left-lateral shear zones, and right lateral ductile-brittle shear zones respectively. D_5 generated during Mesozoic is represented by the obviously observed folds in the Jurassic limestone. The latest phase of deformation (D_6) in Cenozoic is characterized by horizontal extension and vertical thinning, which led to wide fragmentation by E-W, NE-SW, WNW-ESE and NW-SE conjugate system of high-angle brittle normal faults and several distinctive horsts and grabens.

Index Terms— Sharab, basement; sandstone, limestone, basalt, deformation

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1 Introduction

THE study area falls in the northwest of Taiz city, located in the central mountain region of Yemen (Yemen Highlands and High Plateau). It is bounded between the latitudes 13º 42\ 12\\ and 13º 55\ 00\\ and longitudes 43º 35\ 51\\ and 43º 52\ 11\\ and covering area725Km2 (Fig.1).

Geologically, the study area represents part of the western part of Yemen occupied by Precambrian rocks, Paleozoic sedimentary rocks (Akbara formations), Mesozoic (Kuhlan formation, Amran and Tawilah Group), Cenozoic volcanic rocks and Quaternary to recent deposits.

The geological evolution of Yemen was driven by the plate motions that broke Pangea apart in the Mesozoic and formed the Gulf of Aden, Red Sea, and the Arabian Peninsula in the Cenozoic. The contributions in the form of detailed work of [1]–[6] for better understanding of the stratigraphy and regional geology of Yemen are noteworthy.

The geological evolution of Precambrian rocks was studied by [7]–[16]; while the Mesozoic rocks by [17]–[23] and Cenozoic igneous rocks by [24]–[34].

In the studied area, only two geological study works were performed, the first was concerned with the joints [35] and another with organic matter in limestone [36]. The present work gives reconnaissance geology and mapping of the Sharab area on a scale of 1: 60,000 based on field works, interpretation of Landsat Imagery and compilation of published and unpublished maps. They discriminated the study area as occupied by three main categories of rocks, namely, Precambrian Basement, Mesozoic Sediments and Cenozoic volcanic rocks.

The scarcity of geological data on the area under study pushed the authors to insight background on the general classification, distribution, characteristics, contact relations, of the rock units and their structural evolution based on the field work, satellite image analysis and available secondary data sources.

2 Materials and Methods

The present study is based on the geological field work, ETM+ Landsat images analysis and other collected data sources. The field work was achieved by field trips meant to identify the lithostratigraphical units, structural features and to make relationships between them by the direct field observations. A satellite imagery over the Sharab area covering about 725 km2 was acquired from Landsat Enhanced Thematic Mapper Plus (ETM+) data in 2000 and processed by ILWIS 3.7 software. The geological map of the study area is modified after [37] based on the analysis of ETM+ Landsat image and field observations. In analysis of ETM+ Landsat image, the combinations of bands 7, 2 and 1 were used in order to color enhancement and this facilitated visual discrimination of various lithological units. Five different lithostratigraphical units were mapped and could be distinguished by distinct colors in the processed image. These are from older to younger: the Precambrian basement associations, Jurassic Limestone (Amran Group), the Cretaceous sandstone (Tawilah Group), the Tertiary volcanic sequence and Quaternary deposits.

The delineation of lineaments initiated by the digital processing of Landsat ETM+ images, creating relations between bands and using various Red–Green–Blue color combinations using also ILWIS software (version 3.7). After that, the lineaments were extracted over digitally processed images in the form of segment map at 1:60,000 scale. 147 lineaments were detected and statistically analyzed according

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to their azimuth (relative to the true north), number and length (in kilometers). The number percent (N %) and length percent (L%) for the lineaments were calculated, tabulated and then represented as graphical histograms. The outline of the methodology is shown in the flow diagram (Fig. 2).

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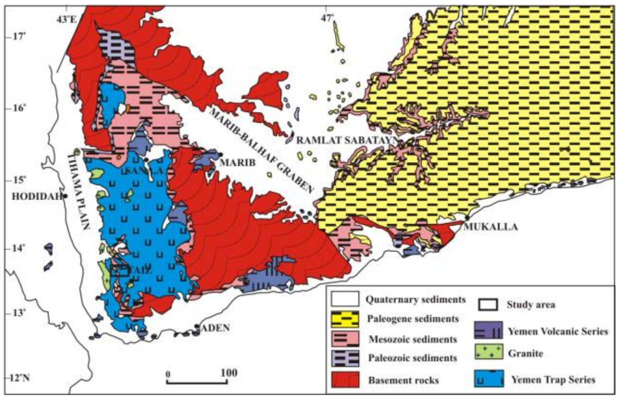


Fig. 1: Simplified geological map of Yemen (modified after [37]) showing the relationship between main rock types and principal grabens. The bold-line rectangle marks the location of the Taiz area..

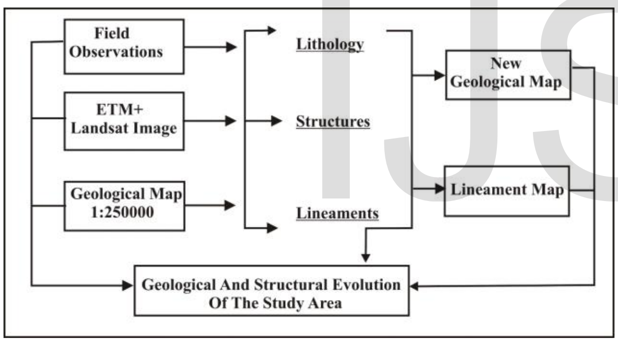


Fig. 2: Flow diagram represents the methodology in this work.

3 Geological Background

The southwestern part of Yemen is occupied by the succeeding four basic tectonic category rocks viz., early Precambrian Basement rocks, Mesozoic sedimentary rocks, Cenozoic volcanic rocks and Quaternary recent sediments (Fig. 1). The early Precambrian Basement forms part of the Arabian Shield, and occupies approximately one fifth of the total area of Yemen and occur as separated fault blocks exposed in the northwestern, central, southwestern and southern parts of Yemen. It consists of different lithological units having various tectonic features, includes metamorphic rocks (gneisses, schists, amphibolites, migmatites, quartzite, marble and mylonites) and igneous intrusions. The metamorphic rocks originated from two origins comprise, continental origin (continental gneissic terranes) undergone to the metamorphosis under conditions up to upper amphibolite facies and island arc origin commonly metamorphosed under conditions of greenschist facies [7], [9], [10], [16]. These rocks were later affected by mylonitic metamorphism and were injected by multi-phases of igneous intrusions (e.g.[11], [13], [14]. The Precambrian basement in the southwestern part of Yemen is unconformably overlain by Mesozoic sedimentary rocks. The first Mesozoic sedimentary succession rocks in this part of Yemen are represented by marine sediments (limestone and shale) that followed by clastic sediments (sandstone, siltstone, mudstone and conglomerate). They formed associated with rifting during the break-up of Gondwana affected Yemen. The fluctuations in sea level occurred during the Jurrasic, causing the deposition of a transgressive series composed of relatively thin beds of clastic (Kohlan), carbonate and marly sediments (Amran Group) [18]. Uplift and erosion of Pre-Cretaceous rocks was followed by the deposition of shallow-marine to continental siliciclastic sediments (Al-Tawilah Group) during the Cretaceous time [18].

The Cenozoic evolution of Yemen is affected opening of the Gulf of Aden and the Red Sea. The western part of Yemen and parts of the coastal plain of the Gulf of Aden as well as some islands in the Red Sea and Gulf of Aden are mantled by extrusive lava flows known with Traps of Yemen or Yemen Volcanic Group covering an area of about 45,000 km2 with maximum thickness up to, 2,500m [26], [32], [33], [38]. The intrusions of plutonic alkali granite, syenite, diorite and gabbro massifs were accompanied the eruption of Traps of Yemen [24], [39], [40].

4 Geology of the Study Area

The diversity of geological structures and lithological characteristics in the studied area is due to its location at the intersection of two major depressions; Taiz depression (WNW-ESE) and Al-Barh depression (N-S) (Fig. 3).

The geological map of the study area is modified after [37] based on field observations and satellite image analysis (Fig. 4a). It's displays different lithostratigraphical units exposed at the ground surface, which include from older to younger: the Precambrian basement associations, Jurassic Limestone (Amran Group), the Cretaceous sandstone (Tawilah Group), the Tertiary volcanic sequence and Quaternary deposits (Fig. 4b).

The oldest Precambrian Basement rocks are exposed in different localities and along NNW- SSE normal faults, having various tectonic features. They crop out mainly in two regions, the Al-Amgod region and Alqihaf region in the northeast and southwest of mapped area respectively. In addition, there are numerous unmappable small outcrops are found as scattered sites throughout the studied area. All these exposures represent part of deeply eroded folded horsts belt or footwall structure bounded from SW margins by high angle normal faults dipping toward the SW.

The Precambrian basement rocks have been recognized as gneisses, schists, amphibolites, migmatites and granite (Fig. 5a), which are mainly originated from sedimentary porotolithes, including pelitic, semipelitic, psammitic and calc-silicate rocks. Mineral assemblages observed in hand specimens as well as the migmatization identified in the field indicate that the metamorphism take place under upper amphibolite facies conditions.

The contacts of these rocks against Mesozoic sedimentary succession (Amran limestone and Al-Tawillah sandstone) are usually unconformable, where the Mesozoic sedimentary successions occurring in the upthrown blocks are unconformably overlie the intensely folded metamorphic sequence of the basement rocks. In some places the contacts are tectonic, which marked by its downfaulting along a narrow fault zone consists of subparallel stepped high- angle normal faults dipping at 60°-75° away from the neighboring basement rocks. On the other hand, the contacts against downthrown blocks consist of Tertiary basalt rocks and their cover Quaternary sediments are tectonic.

The Mesozoic sedimentary rocks are essentially represented by two NW-SE linear exposures in the middle parts of the mapped area extending over 31 km with an average width of 5 km and separated to each other by Cenozoic volcanic rocks. They are deposited in two different deposition environments viz; marine environment and transitional to shallow marine environment and are separated by an unconformity contact (Fig, 5b). In the investigated area, the lower marine sedimentary rocks are belonged to the Jurassic Amran Group, which mainly consists of limestone rock types intercalated with shales and randomly evaporates with clearly defined beddings (Fig. 5c &d). The limestone is characterized by dark to light gray color, silicification phenomena and by its little contains of fossils. The silicification process of the limestone in Sharab area is probably attributed to metasomatism caused by a volcanism during Tertiary Time.

The limestone beds show locally affected by mesoscopic folding with fold axes trending in NE to SE direction

The upper terrigeneous clastic sedimentary sequence rocks rest unconformably over the Precambrian basement or Amran limestone. They are formed mainly from sandstone rocks alternated with mudstone, siltstone and conglomerate (Fig. 5e). The sandstones are predominant characteristics by variable color, mostly white to light yellow, medium to fine grained texture, and by cross-bedding and graded bedding structures. The sequence appears as an elongated beds strike on the rate trend of N40°W with dips ranging from 25° to 66° on the average direction N50°E. The contact relations between this sequence and both Precambrian basement rocks and Amran limestone rocks are clearly seen in Al-Amgod, and Al-Hosia, Al-Karabah and Jurayah respectively. The sandstones at the contact with above volcanic rocks and basaltic dykes become more cohesive (Fig. 5f).

The Cenozoic igneous rocks (volcanic and intrusions) in the study area display considerable variations in their mineral composition, texture, structure and contact relationships with the underlying rocks. The volcanic rocks in the area considered the part of the Yemen volcanic group. They are predominantly represented by basic volcanic rocks (basalt flows) capped by silicic volcanic rocks (rhyolite and pyroclastic). The basalts are characterized by thick lava flows, microcrystalline; sometimes porphyritic with plagioclase and/or olivine phenocrysts texture and massive to vesicular structures. The secondary minerals such as quartz and calcite are sometimes filled fractures and vesicles forming veined and amygdaloidal structures respectively. In some places such as Jabal Tharai and Khuala both basaltic and rhyolitic rocks show well developed columnar jointing features in the colonnade or entablature form.

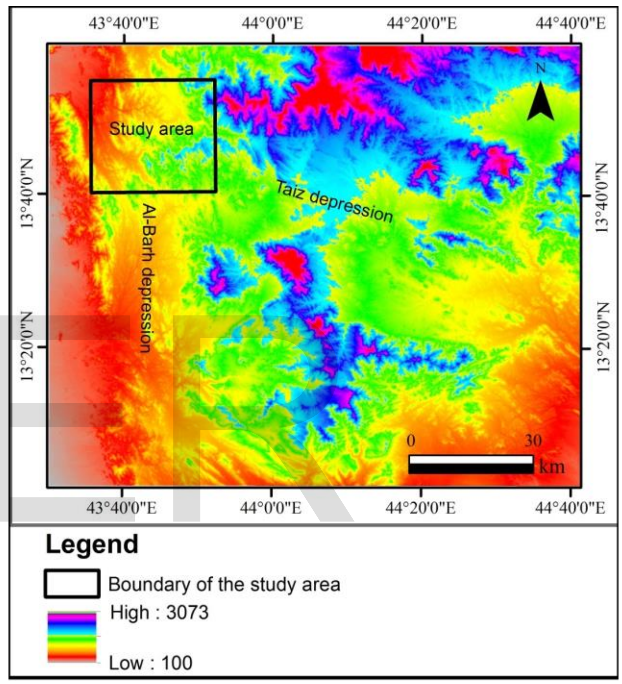


Fig.3: Physiographic provinces of southwestern Yemen , showing the geomorphological and structural features of Sharab area

5 Tectonic Framework

Opening the Red Sea and Gulf of Aden between the Arabian Peninsula and Africa and the formation of Afar depression east Africa at the triple junction above a mantle plume (~30 Myr) produced extensional forces that proceeded to oceanic spreading [41], [42]. These forces led to the progression of border normal faults associated with flowing of flood basalt [26], [43]–[45]. The faulting caused the uplifting and falling of blocks and juxtaposes the older rock units in the footwall with younger in the hanging wall, that kept varieties of structural features (as folds, faults, dykes, joints, and unconformities), which have been formed from various stress and strain conditions in response to different tectonic events.

The lithological units and their structural features in the studied area are briefly described in the following subsections:

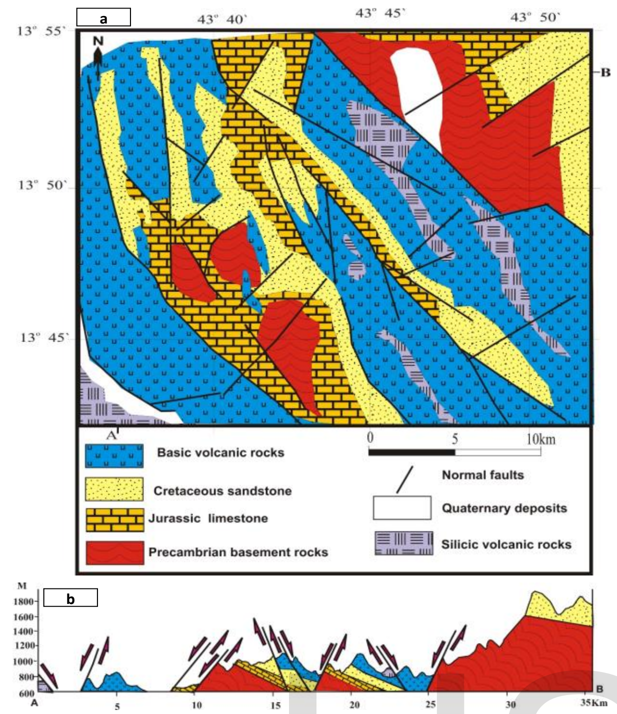


Fig. 4: (a) Geological map of Sharab area and (b) Geological cross section along A-B.

5.1 Precambrian structures (D_1 to D_4)

In the study area, the mesoscopic features of Precambrian basement bearing signs of metamorphism and deformation events. The superimposed relationships of the structures lead to discern at least two events of metamorphism (M_1 and M_2) and four phases of deformation (D_1 to D_4) happened during Precambrian time associated with the Pan African Orogeny. Brittle faulting and joints may be formed later, associated with subsequent events.

D_1 deformation phase

The relict primary depositional layering (S_0) in the metamorphosed rocks is conformable and generally runs NW-SE direction. It's commonly observed as alternating laminae of different mineral composition originated from deposition of pelite, semipelite, psammite and impure calcareous sediments, which then regionally metamorphosed (M_1) and partially migmatized under amphibolite facies conditions. The secondary penetrative planar structure of metamorphic foliation (S_1) formed during this deformation phase runs generally parallel to the primary depositional layering (S_0) and is characterized by a extending foliation marked by the strict parallel organization of the mafic minerals such as biotite and/or amphiboles, alternated with felsic bands, lenses and/or laminae in the gneisses and metatexites. The accompanying lineations (L_1) are marked by the subparallel alignment of amphiboles and others elongate minerals run generally NW-SE and plunge to the NW and in some cases SE. The isoclinal interafolial to tight reclined folds (F_1) are frequently observed within the metatexites, with axial planes run corresponding to the prevailing S_1 foliation, and hence they are considered as products of cogenetic magmatic processes (Fig. 6a). The axes of some intrafolial folds (F_1) are also extending subparallel to L_1 alienation.

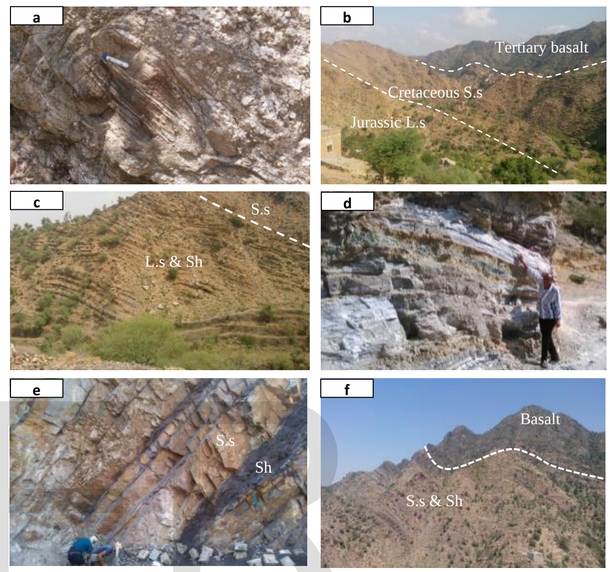


Fig. 5: The field photographs showing: (a) biotite schists intercalated with gneisses. Note the distinct S0 foliation (bedding); (b) A general view showing the unconformity surfaces between the Jurassic limestone and Cretaceous sandstone and between Cretaceous sandstone and Tertiary volcanic rocks; (c) limestone (L.S) beds alternating with thin layers shale (SH) and overlained by sandstone (S.S); (d) the gypsum layers intercalated with shales and limestone; (e) General view of thick sandstone beds alternating with thin layers of shale; (f) the original bedding within the sandstone succession and unconformably overlying by basalts.

D2 deformation phase

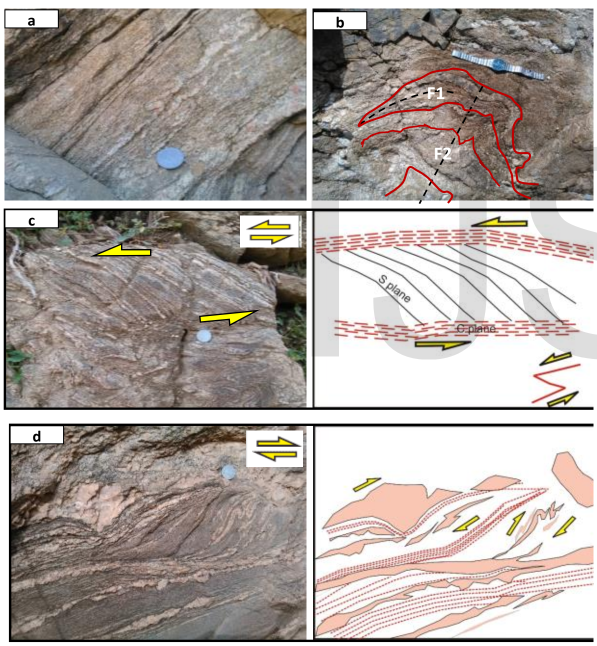
This deformation phase is appeared with well-developed minor mesoscopic folds (F_2) emerged from bending of S_1 foliation, which trend NW-SE and plunge NW. They are represented by a series of synclines and anticlines that are largely exposed in the different exposures within the studied area. Minor F_2 folds occur as tight to open, and box folds with axial planes generally extend NW-SE and dip to NE indicating a NE stress direction. The stretching lineation (L_2) generally runs parallel to the F_2 fold axes. Also, during D_2 deformation phase, the intrafolial folds F_1 formed during D_1deformation phase are refolded into tight to open folds.

D_3 deformation phase

The third phase of deformation (D_3) in the Sharab area is represented by NW-SE narrow shear zones accompanied by a strong mylonitization as well as retrogressive metamorphism (M_2). In these shear zones, the rocks exhibit extensive planar foliation (S_3) and mylonite lineation (L_3) transposed the earlier S_1 penetrative planar foliation. This deformation phase is marked by strong alignment of mica flakes, which occasionally alternate with quartz ribbon bands and stretched and rounded feldspar porphyroclasts formed during M_1 regional metamorphism. The shear zones generally exhibit a left - lateral sense of movement as deduced from S-C fabrics, feldspar porphyroclasts, pressure shadows and Z-folds (Fig. 6c).

D_4 deformation phase

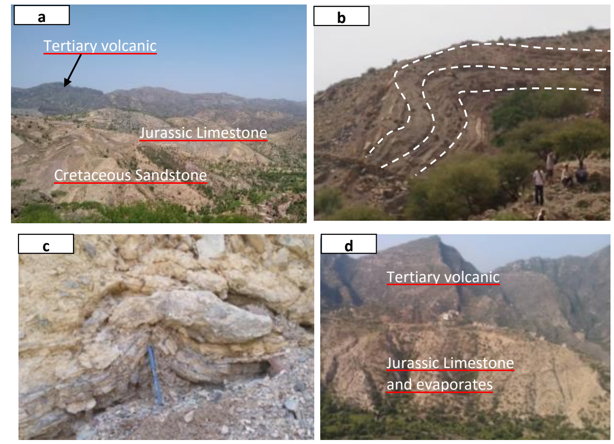
After the folding and the ductile shearing phases, the Precambrian basement and shear zones could be overprinted by changing their sense of movement to become right-lateral under conditions of ductile-brittle manner (Fig. 6d).



Fig,6: The field photographs displaying: (a) intrafolial fold (F_1) in the migmatitite; (b) a tight intrafolial minor fold (F_1) refolded by a box fold (F_2) in migmatitic biotite gneiss; (c) S/C fabric and S folds in mylonite rocks show left-lateral sense of movement where S is represented by sigmoidal folaiton and C is represented by shear planes; (d) asymmetric rigid relict and Z folds showing right-lateral shear sense of movement.

5.2 Mesozoic structures (D_5)

During the Mesozoic Era, the deeply eroded Precambrian rocks were unconformably overlain by thick sedimentary section. Meanwhile the study area was dissected by a series of horsts and grabens most probably along rejuvenated fractures pertaining to the earlier faults. Some of these grabens are filled with Jurassic limestones followed by Cretaceous sandstones (Fig. 7a). The major folds are entirely absent, whereas the minor folds are only observed in a few limestone outcrops and absent in sandstone (Fig. 7b, c, d).



Fig,7: The field photographs displaying: (a) Tertiary volcanic rocks directly over Jurassic limestone; (b) overturned folds in Jurassic limestone;(c) tight, upright fold in Jurassic limestone; (d) domal structure in Jurassic limestone.

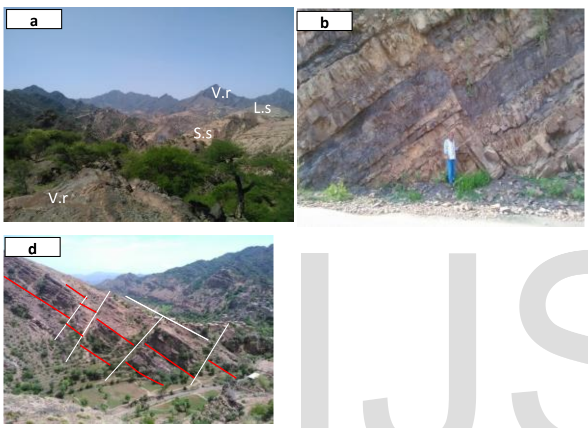
5.3 Cenozoic structures (D_6)

During the Cenozoic, the area was affected by severe tectonics generated breakdown of the crust in the two main trends probably related to the opening of Red Sea and Gulf of Aden. The active volcanic eruptions originated contemporaneous with two groups of normal faults trending NW-SE to WNW-ESE and NE-SW to E-W with dips vary from 25^{o} to nearly vertical [46], [47]. The downthrown of the NW-SE to WNW-ESE normal faults are mostly to SW and some to the NE, whereas NE-SW to E-W normal faults are commonly to S. The area also experienced intense vertical tectonism during the Cenozoic with the formation of NW-SE and WNW-ESE trending horst and graben structures.

Some horsts are occupied by basement rocks, Amran limestone and Al-Tawillah sandstone beds which are locally unconformably overlain by the Tertiary volcanics (Fig. 8 a). In some localities, the sandstone beds are sliced along dipping steeply normal faults toward the NE (Fig. 8b, c). The other faults are represented by high-angle step normal faults which formed the feeders for the basic dyke swarms trending NW-SE and extending for a few of kilometers. The rocks along the fault planes are highly fractured, cataclased and sometimes lost cohesion.

6 Lineaments

Lineaments or linear features of the area were traced from the Landsat ETM+ images using Ilwis 3.7.software. 147 lineaments were detected and mapped at 1:50000 scale (Fig. 9). The mapped lineaments or linear features represent linear geomorphologic features (valleys, cliffs, and ridges) and fractures (joints, dykes and faults). The lineaments were statistically analyzed according to their azimuth (relative to the true north), number and length (in kilometers). The azimuth interval size is 10 degrees and within each interval lineament numbers and lengths are cumulated (Table 1). Number and length (in meter) of linear features are displayed in the graphical histograms presented in Fig. 10. Based on the lineaments map and graphical histograms, the area is dominated by two structural tectonic trends. These two tectonic trends are ordered according to their N% and L% as follows: The first prevailing lineaments extend between N30W and N70W (43.23% dominance), which represent later Tertiary normal faults and dykes parallel to the Red Sea. The second predominant lineaments set follows the direction restricted between N30E and N60E (32.5% dominance), which extends nearly parallel to the Tertiary normal faults and dykes parallel to the Gulf of Aden.



Fig, 8: The field photographs displaying: (a) Mesozoic sediments surrounded by Tertiary volcanic rocks; (b) high angle normal fault in Cretaceous sediments; (d) two sets of normal faults ruptured cretaceous sandstone, the first parallel to the bedding plane, where the sandstone beds sliced along normal faults while the other nearly perpendicular to the bedding)white lines are the fault plans, while the red lines are bedding(.

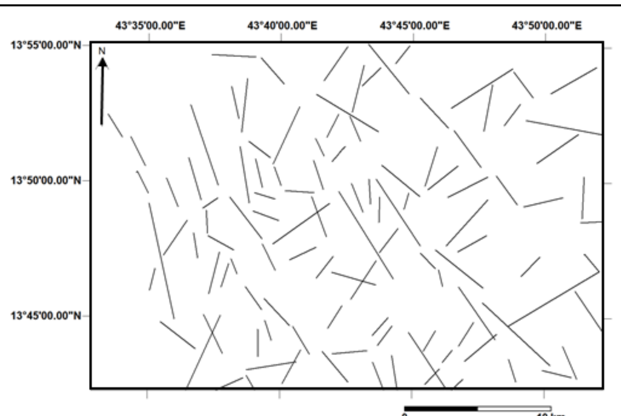


Fig. 9: Lineaments of Sharab area picked from Landsat image scale 1: 50000.

TABLE 1
FREQUENCY DISTRIBUTIONS OF THE LINEAMENTS DATA IN THE STUDY AREA.

Azimuth	Number (N)		Length in km. (L)		N %		L
Intervals	NE/SW	NW/SE	NE/SW	NW/SE	NE/SW	NW/SE	NE/SW
0:10	6	2	2.36	2.58	4.08	1.36	1.50
>10:20	5	1	5.00	1.62	3.40	0.68	3.17
>20:30	10	2	9.37	1.77	6.80	1.36	5.94
>30:40	12	9	15.52	11.58	8.16	6.12	9.84
>40:50	24	20	22.55	19.71	16.33	13.61	14.30
>50:60	12	17	13.18	23.75	8.16	11.56	8.36
>60:70	3	12	7.08	13.12	2.04	8.16	4.49
>70:80	1	4	1.63	3.48	0.68	2.72	1.03
>80:90	4	3	0.75	2.64	2.72	2.04	0.48

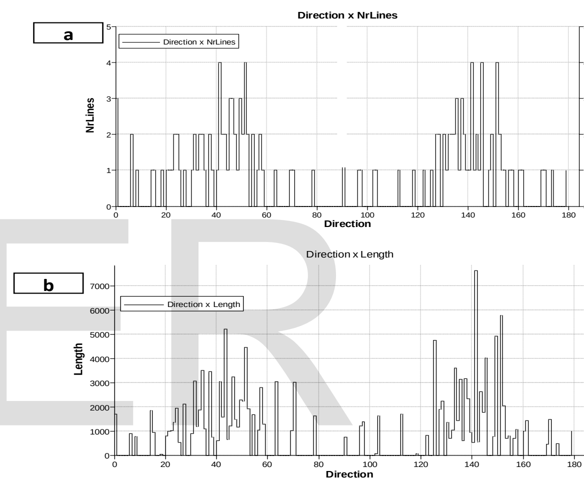


Fig. 10 :Graphical histograms of number of linear features (a) and length (in meter) (b) with respect to the direction in the Sharab area.

7 SUMMARY AND CONCLUSIONS

The outcomes of the geological studies and field observations in the Sharab area, revealed that there are four main lithological units includes: Precambrian basement rocks, Mesozoic sedimentary cover and Tertiary volcanic rocks. The Tertiary volcanic rocks are the dominant, while the other two types found in minor and controlled by regional structures. Other exposures included the quaternary sediments, which restricted in valleys and near the NE corner of the mapped area. The Precambrian basement consists of metamorphosed rocks and intrusions, the metamorphosed rocks include biotite gneisses, quartzofedspathic gneiss, quartzite and migmatites, which undergone metamorphism under conditions of amphibolite facies, while intrusions comprise granite and pegmatite. The Mesozoic sedimentary rocks were formed in two depositional environments. A lower marine environment represented by Jurassic Amran Group (limestone, Shale and evaporates) and upper continental to shallow marine environment known with

Cretaceous Tawilah Group (Sandstone, siltstone, shale and conglomerate). Tertiary volcanic rocks predominantly include basalt with subordinate rhyolite and volcaniclastic deposits.

The structural features configuration observed in the study area is the product of overprinting, superimposed and interference structural elements created through at least six deformation phases (D_1:D_6), documented within the metamorphosed Precambrian basement. The four phases of deformations (D_1-D_4) are believed to represent remnants of the Pan-African orogenic events.

The brittle faults recognized in the area postdate D_4 and have a consistent NE-SW, NW-SE strikes with major faults formed later during Tertiary. It is a well-known that normal faults control lithological unit exposures, certain faults like the NW-SE related with opening of Red Sea. The lineaments are orientated in two main trends, following the direction of the maximum stresses of D6 deformation phase.

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