Strain analysis and deformation history of Zalm area, Arabian shield, Saudi Arabia

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Abstract

The present work deals with the strain analysis and deformation of the Zalm area which is located in the central part of the central Nabitah suture belt, which separates the continental Afif terrane from the ensimatic arc terranes of the western Arabian Shield. This study carried out through field investigation, strain parameters, and microscopic examination for understanding the nature of deformation in the Zalm area. On the basis of the field investigation and the geometry of the contact, it is more likely that the contact between ultramafic rocks and gabbroic rock complex is low-angle thrust faulting. The granitoid rocks are divided into the quartz monzodiorite, monzogranite, alkali-feldspar granite and leucocratic-granodiorite. The Rf/ϕ and Fry techniques on feldspar and mafic grains from 53 samples representative of each rock type were collected in the field. Strain data show that the deformation of the granitic, metavolcanic and amphibole schists samples range from high to moderate. The axial ratios (XZ section) range from 1.60 to 4.10 for the Rf/ϕ method and 2.80 to 4.90 for the Fry method. Furthermore, the finite strain data does not display any significant difference in the deformation behavior between Rf/ϕ and Fry methods. We concluded that the strain magnitude has the same order of deformation in the deformed granitoid and amphibole schists rocks. The majority of samples are in a zone of flattening symmetry, while a few samples are showing constrictional symmetry. In addition, it is noted that the short axes (Z) are sub- perpendicular related with a sub-parallel foliation. Furthermore, the nappe contact are designed during the intrusion of plutons associated with faults in the Zalm regions under brittle to semi-ductile deformation conditions.

1. Introduction

The Arabian Shield displays amalgamated tectonostratigraphic (e.g. Midyan, Hijaz, Asir, Afif, and Ar Rayn) terranes of Tornian (1000–850 Ma) and Cryogenian (850–650 Ma) volcanic and plutonic rocks (Johnson et al., 2003, 2011; Johnson and Kattan, 2012). This led to the formation of a 40–100 km thick lithosphere of the Arabian Shield (Mooney et al., 1985; Alherr et al., 1990; Camp and Roobol, 1992; Sandvol et al., 1998; Hansen et al., 2007). The terranes are separated by four orogenic (e.g. Yanbu, Bir Umq, Nabitah, and Al Amar) suture zones. North and northeast trending of the sutures are assumed between the distinct terranes on the basis of ophiolite- and serpentinite-decorated shear zones (Al-Shanti and Mitchell, 1976; Johnson et al., 2004). NE-oriented Yanbu suture is situated between the Midyan and Hijaz terranes in the northwestern side of the Arabian Shield (Fig. 1). The ophiolites of the Arabian Shield range in age from 690 to 870 Ma, and have a mean age of ~780 Ma that may approximate the onset of terrane accretion (Stern et al., 2004).

The Zalm area is situated between Lat. 22° 30′ and 23° 00′ N and Long. 42° 00′ and 42° 30′ E (Fig. 1). It is located in the Nabitah suture zone, which separates Afif terrane from the ensimatic arc terranes of the western Arabian Shield. Also, the Zalm area is located in the central part of the central Nabitah suture belt, which is characterized by the predominance of the N–S and NW-SE structural trends. The major NW-oriented faults are related to the Najd Fault System, which represents the latest tectonic event that affected the Arabian Shield during the Pan-African tectono-thermal orogeny. The study area is generally of low relief. The mountainous area is isolated in the northern part, and the highest relief is Jabal Zalm which rises about 300 m above the surrounding plains and 1150 m above the sea level. Wadis generally run from south to north. The drainage pattern system is dendritic particularly around Jabal Zalm.
The finite strain analysis investigate the natural of shear zones which display oblate geometries (Coward, 1976; O’Hara and Blockburn, 1989; Ring, 1999; Kassem and Ring, 2004; Kassem, 2012 & 2015). Many authors suggested that the oblate fabrics formed during the volume loss in simple shear zones or during shearing in pure shear with or without volume loss (Simpson and De Poar, 1993; Mukul and Mitra, 1998; Kassemand AbdElRahim, 2010; Kassemetal., 2012). It is important to quantify the strain analysis and the degree of non-coaxiality. Furthermore, the evaluation of strain shapes and the relation of the flattening foliations are characteristic of nappes in the internides of many regions. The contacts are shown major lithological boundaries in the Arabian shield and the occurrence of granitic, metavolcanic and amphibole schist rocks are used to show nappe boundaries (Fritz et al., 1996; Neumayr et al., 1996, 1998). In the Zalm area, it is necessary to investigate the contact between the different units such as granitic, metavolcanic and amphibole schist rocks. In addition, a major lithological margin display the trace of a low angle thrust fault (Stern, 1985).

This study was realized through field observation, finite strain and microscopic study to quantify the tectonic evaluation in the Zalm area. The microstructural and petrological investigations are important to display the characterization of the nappe contacts suggesting that deformation history was applied to the existing nappe structure. Furthermore, the present work will depend on our structural data to explain strain symmetry in the Zalm area (Kassem, 2011 & 2014; Kassem et al., 2016).

2. Geological setting

The Zalm area is mostly made up of Neoproterozoic ultramafic-mafic rock complexes intruded by granitoid plutons. It displays older Cryogenian layered rocks (Tamran Formation and Siham Group) and younger Cryogenian intrusive plutons (Jidh Suite and Humaymh Suite) (Fig. 2). Tamran formation covers the northwestern part of the study area, and is made up of metamorphosed pyroclastic and volcanoclastic rocks and bounded to the east by ultramafic rocks and intruded by monzogranite.

The volcano-sedimentary sequence of the Siham Group is made up of basalt, rhyolite, andesite, shale, lithic sandstone, conglomerate, marble and quartzite. The variation in amounts and thicknesses of these rocks is interpreted in the cross-section and reflected from deep water in the west to a shallow continental margin in the east. The Siham Group is considered as a volcanoclastic rocks in the east dipping associated with subduction zone in the eastward shallowing basin. It grades from oceanic and volcanic to continental-margin and sedimentary from west to the east. The Siham Group in the study area is observed around Zalm village and mainly consists of mafic to intermediate flows, marble,
and subordinate silicic pyroclastic rocks (Fig. 2). The different lithology of Siham Group are mostly weakly to moderately deformed, however they are locally schistose faces and caught up in thrusting. The Neo-proterozoic ultramafic units contain serpentinite and gabbro which represented the ophiolites of the Zalm area. They are also well-preserved as slices of mafic-ultramafic rock along shear zones, and gneiss and schist rocks created from protoliths along shear zones. The Zalm ultramafic complex is exposed as a 20 km long and about 7 km wide belt trending northern east. The Zalm area is bounded by layered gabbro to the south and by post-orogenic granite intrusions to the southeast, east, and northeast. It forms a segment of the larger Ad-Dafinah belt which is considerable a part of the Nabitah suture zone. The ultramafic rocks form both Jabal Zalm and also exposed as scattered bodies in the eastern reaches of the study area. On the basis of the field investigation and the geometry of the contact, it is more likely that the contact between ultramafic rocks and gabbroic rock complex are low-angle thrust faults. The ultramafic rocks are intensively affected by a NE-oriented shear zone in the northeastern part of the area, where they are altered to talc carbonate, leaving nuclei of peridotite serpentinite relics. Gold-bearing quartz veins crosscut the serpentinites along N40 to 60° trends. These veins have been mined by ancient workings.

Gabbroic rock complex (Humaymah suite) occurs as flat or low-lying hills with a distinctive blocky and massive appearance in the central part of the study area (Fig. 2). They are dark-green to greenish-black in color. The gabbroic rocks have been identified by two types within the study area: the first type is an uralite meta-gabbro, and the second type is a hornblende gabbro. In some locations, these gabbroic rocks are strongly sheared with the development of foliation trending N45°E and dipping 70° southeast. The gabbroic rocks are dissected by veinlet-developed microfractures filled by carbonates, quartz, and epidote, where minor-scale faults dislocate these veinlets. The gabbro, close to the contact with the ultramafic rocks, is characterized by rhythmic layering.

The Jidh suite is represented by calc-alkalic intrusive rocks emplaced in the Siham group in the west-central part of the Ajif terrane. The age dating of rocks are not measured, on the other hand, in the Siham group, the main deformation event are predated as structural

![Geologic map of the Zalm area and samples locations.](image)
relationships and considerable as a part of calc-alkalic magmatic core to the Siham volcanic arc. Quartz veins and aplite dikes and veins of different trends dissect all the rock units in the study area. They are discontinuous and trend northeast, dip 80–90° southeast and cover an area of about 1.5 by 4 km.

3. Methodology
In the present work, granitic, metavolcanic rocks and amphibole schist samples are used for finite strain measurements in Zalm area. Using felsic minerals (feldspar, quartz and plagioclase) and mafic...
minerals (hornblende, biotite and chlorite) are measured by the Rf/ϕ and Fry methods (Fry, 1979; Ramsay, 1967; Ramsay and Huber, 1983). In order to estimate the three dimensional strain geometry (X ≥ Y ≥ Z, finite strain axes), we analyzed the two-dimensional strain which performed on XY, XZ and YZ sections. Two techniques in the present study (such as the Rf/ϕ and Fry methods) were used to check and estimate the finite strain data. The strain analysis which used fry technique represent the matrix strain, whereas the Rf/ϕ strains describe the clast strain (Ramsay and Huber, 1983; Ring, 1998). For Rf/ϕ analysis, the mean aspect ratio for each section was measured felsic minerals (feldspar, quartz and plagioclase) with some mafic minerals (hornblende, biotite and chlorite) through calculated the long and short axes per section. The measurement of the Rf/ϕ and fry methods should be cut the sample as thin sections along the XY, YZ and XZ sections and marked the felsic and mafic minerals. The traced outlines were then digitised. A least squares best-fit ellipse was calculated for each marker outline as well as its relative position and orientation. Peach and Lisle (1979) described that the chi-squared minima of the Rf/ϕ analyses were used to determine the tectonic strains. For fry analysis, the central points for feldspar, quartz and plagioclase grains per section (more than 100 grains) were used to calculate the strain analysis. We are used the modified least-square technique which are created by Owens (1984).

The magnitude of the Nadai strain is an important parameter, which is represented by an orthogonal coordinate system. It measured the natural principal strains E_x, E_y and E_z. Brandon, M. (1995) suggested that the distance from the origin provides an invariant measure of the total strain magnitude (E_t), that represented two orthogonal components: volume (E_v) and deviatoric (E_d) strain. E_v and E_d are independent of the rotational component of deformation.

\[ E_t = (E_v^2 + E_d^2)^{1/2} \]

Twenty one (21) samples representative of each rock type were collected in the field work and about 40 thin sections were cut. Samples were cut and prepared in the King AbdulAziz University, Earth Science laboratory, Jidda, Saudi Arabia (Fig. 2). Thin sections of representative samples from the Zalm area were examined using polarized microscope to find out the mineral composition and textures, and to clarify effects of deformation, alteration and metamorphic grade of these rocks. The collected samples include 6 granitoid, 4 gabbro, 4 serpentinite, 2 metagranite and 5 schists samples. The Rf/ϕ and fry methods were used the quartz, feldspar and mafic grains to determine the strain in the deformed granitoid, metavolcanics and amphibole schist samples.
The granitoid rocks in the Zalm area, are divided into Quartz Monzodiorite, Alkali-feldspar, and Monzogranite. Granitoid rocks show elongated few quartz, feldspars grains and plagioclase weakly deformed. The Quartz Monzodiorite contains of quartz, plagioclase, alkali-feldspar minerals (such as orthoclase, perthite, and microcline), quartz, muscovite and biotite. The Monzogranite consists of alkali-feldspar minerals (such as orthoclase, perthite and microcline) and some mafic minerals (such as biotite and hornblende). Alkali-feldspar and Monzogranite. Granitoid rocks show elongated few quartz, feldspars grains and plagioclase weakly deformed. The Quartz Monzodiorite contains of quartz, plagioclase, alkali-feldspar minerals (such as orthoclase, perthite, and microcline), quartz, muscovite and biotite (Fig. 5a and b). Monzogranite contains quartz, alkali-feldspar minerals (such as orthoclase, perthite and biotite), hornblende and biotite (Fig. 4a and b). Gabbro does not shown deformation. Gabbro rocks consist of plagioclase and mafic minerals such as clinopyroxene, orthopyroxene and olivine (Fig. 4c and d). The gabbroic rock complex of the study area can be distinguish petrographically into two main types. The first type is hornblende gabbro consisting of plagioclase, clinopyroxene, orthopyroxene, and hornblende amphibole (Fig. 4c), and the second is Olivine gabbro consisting mainly of plagioclase, clinopyroxene, orthopyroxene (hypersthene) and olivine (Fig. 4d).

Serpentinites samples in the Zalm area consist of serpentine, talc and carbonite. The vertical foliation defined by low to moderate deformation has been observed in the serpentinite with well oriented clasts of serpentine, talc and carbonate grains (Fig. 4a and b). Gabbro does not shown deformation. Gabbro rocks consist of plagioclase and mafic minerals such as clinopyroxene, orthopyroxene and olivine (Fig. 4c and d). The gabbroic rock complex of the study area can be distinguish petrographically into two main types. The first type is hornblende gabbro consisting of plagioclase, clinopyroxene, orthopyroxene, and hornblende amphibole (Fig. 4c), and the second is Olivine gabbro consisting mainly of plagioclase, clinopyroxene, orthopyroxene (hypersthene) and olivine (Fig. 4d).

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deformation and elongated quartz grains have also been observed in the Zalm area (Fig. 5e). It is absorbed that the metavolcanic samples are weakly deformed (Fig. 5f) with elongated feldspars and quartz grains. In some places, the metavolcanic rocks display an elongated texture. The schists samples are moderate to highly deformed (Fig. 5g and h). The vertical foliation defined by high to moderate deformation has been observed in the amphibole schist with well oriented clasts of hornblende grains (Fig. 5g and h). Schist samples consist of hornblende and quartz in the Zalm area. In other case, some grains of quartz are elongated and rotated. In addition, the Zalm area is characterized by the occurrence of gold and chromite mineralization. The chromite exists in the ultramafic rocks, whereas the gold is associated with quartz veins intruding along shear zones.

5. Strain measurements

The strain data are summarized in Table 1 and Figs. 5–9. The axial ratios of the Rf/ϕ and Fry methods in the XZ sections range from 1.65 to 3.37 and 1.26 to 2.56 respectively for the Schist, metavolcanics and deformed granitiods rocks (see Table 1). The axial ratios in the YZ sections range from 1.57 to 3.01 for the Rf/ϕ method and 1.14 to 2.11 for Fry method for the Schist, metavolcanics and deformed granitiods rocks (Table 1). The axial ratios of the Rf/ϕ method in the XY sections range from 1.57 to 3.01. Furthermore, the axial ratios of the Fry method in the XY sections range from 1.14 to 2.11 for the Schist, metavolcanics and granitiods rocks (Table 1).

Finite stretches indicate a narrow range of deformation of the different type of rocks. In addition, the stretches in the X direction (Sx) range from 1.18 to 1.56 for the Rf/ϕ technique and from 1.09 to 1.53 for the Fry technique. The strain in the Y direction (Sy) ranges from 1.11 to 1.39 for the Rf/ϕ method and from 0.88 to 1.28 for the Fry method that show both contraction and extension deformation. In the Z direction, the stretches (Sz) range from 0.46 to 0.72 that indicate vertical shortening of 28%–54% for the Rf/ϕ technique. In Fry technique, Sz ranges from 0.59 to 0.87, that display vertical shortening of 13%–41% (Table 1). The data show no significant difference in the deformation behavior between Rf/ϕ and Fry techniques. In other word, the deformation have same order in all studied rock types, which apparent in the field (Figs. 6–10).

The axial ratios of the Rf/ϕ and Fry techniques in the K sections range from 0.01 to 0.28 and 0.01 to 5.08 respectivity for the Schist, metavolcanics and granitiods rocks (Table 1). The axial ratios of the Rf/ϕ method in the Nadi strain sections range from 0.406 to 0.950 and 0.175 to 0.676 for fry method in the different type of rocks (Table 1). The axial ratios of the Rf/ϕ method in the Lode’s sections range from 0.505 to 0.976 for the Schist, metavolcanics and granitiods rocks and variety from 0.032 to 0.984 for fry method in the same type of rocks (Table 1).

The related strain data are summarized in Table 1 and given in a Flinn diagram (Fig. 6), which divided into prolate and oblate shapes for the strain ellipsoids. Hossack (1968) classified the strain symmetry into constrictional vs flattening, which shows information on volumetric strain. However, we are expected minor or no volume changes, due to the porosities during deformation very slight, specially in the basement rocks (Kasse and Ring, 2004).

As shown in Figure (5), the Rf/ϕ strains display flattening and constrictional symmetry. In general, the majority of samples are in a zone of flattening symmetry, while a few samples are showing constrictional symmetry. The Fry strains reveal 19 samples with flattening symmetry and 3 samples fall constrictional symmetry. Hence, the Rf/ϕ values derived from the analysis of quartz, alkali-feldspar, plagioclase and some mafic minerals represent regional strains (Fig. 6).

The studied samples display that no major difference in deformation behavior for the feldspar, amphibole minerals, and the quartz-mica matrix are observed. In addition, the similar deformation for investigated samples was shown during the metamorphic conditions and characterized of the same magnitude. Thus, the main phase of foliation is comparable in Schist, metavolcanics, amphibolites and deformed granitiods samples, showing similar deformation behavior in all different types of rocks (Figs. 7 and 8).
The data shows relationship between the finite strain and strain axes in the Zalm area. The axial ratio between XZ vs YZ showing pronounced positive correlation (Fig. 9a). The axial ratio between XY vs XZ shows pronounced positive correlation (Fig. 9b). These characteristics indicate the prolate nature of the strain symmetry. The relationship between principal strain Ratios (K) vs Strain magnitude (ET) shows data for $R_f/\phi$ less than Fry method, also the axial ratio between K vs (ET) displays pronounced more or less constant correlation (Fig. 10a). In addition, the relationship between Principal strain Ratios (K) vs Lode’s parameter (LP) indicates that the data shows for $R_f/\phi$ less than Fry method, also the axial ratio between K vs (LP) shows pronounced negative correlation (Fig. 10b). The relationship between strain magnitude (ET) vs Lode’s parameter (LP) showing the data for $R_f/\phi$ and Fry method mainly constant (Fig. 10c). The axial ratio between (ET) vs (LP) also shows pronounced random correlation for $R_f/\phi$ method, while the axial ratio between (ET) vs (LP) shows pronounced wide distribution correlation for Fry method (Fig. 10c).

6. Discussion

The Zalm ultramafic complex forms a segment of the Ad-Dafinah belt, which represented as part of the Nabitalh suture zone (Stoeser and Camp, 1985). These ultramafic rocks display as scattered bodies near the Zalm area. It was intruded as a thick sill between the Lamisah shale and rhyolite member of the Bahjah Formation and now occupies the core of a northeast-trending downward facing antiform. It comprises talc schist and listwanite with many magnesite veins and a core of massive serpentine that appears to be layered. The layering cannot directly be confirmed at the outcrop, although a base gabbronrorite preserves primary igneous layering which is parallel to that inferred in the serpentine and the bedding of the envelope. The gabbronrorite is rhythmically layered with clinopyroxene at the base and labradorite/biotonite at the top. Original petrographic features of the serpentine are difficult to recognize but Sustrac (1980) reported the presence of dunite and pyroxene peridotite within the complex.

The tectonic evolution of the Zalm area seems to have undergone three main stages, namely Subduction, Nabitalh orogeny and Najd orogeny. It is suggested that the Tamran Formation represents a part of the Jiddah terrane before the beginning of the Jiddah-Afif convergence. Shallow-marine continental-shelf sediments of the Siham Group have been deposited on the western margin of the Afif terrane during subduction. The Jidh calc-alkaline rocks are the product of subduction-related magmatism. The collision of Afif and Jiddah terranes coincided with the Nabitalh orogeny, which was associated with folding and easterly directed overthrusting of the Siham Group, as well as syntectonic plutonism along the suture itself. The Najd orogeny began between about 640 and 630 Ma ago, following decline of the Nabitalh orogeny. The unmetamorphosed volcanic and sedimentary rocks of the

Fig. 8. a) Finite strain graph of YZ plane for Z8d sample, b) showing center to center graph, c) showing $R_f/\phi$ graph, d) showing polar graph.

Fig. 9. The axial ratio showing the strain symmetry for the $R_f/\phi$ method (grey triangle) and Fry method (grey square). (a) The relation between YZ vs XZ (b) The relation between XY vs XZ.
Bani Ghayy Group, exposed to the east of study area, were deposited in north-trending grabens that resulted from the transtension of the Najd strike-slip faulting. The structural framework created by the Najd orogeny has controlled the deposition of the Bani Ghayy Group and the early Phanerozoic rocks. However, Age dating for the different types of granitoid rocks is recommended to reveal their sequence of occurrence. Also detailed investigation of the unassigned ultramafic rocks will help for an adequate evaluation of the gold mineralization in the Zalm area.

The Zalm area exhibits Neoproterozoic ultramafic-mafic rock complexes intruded by granitoid plutons. It contains; based on Johnson (2006); older Cryogenian layered rocks (Tamran Formation and Siham Group) and younger Cryogenian intrusive plutons (Jidh Suite and Huaymh Suite).

Our finite strain data shows that oblate strain symmetry (flattening strain) are observed in the Schist, metavolcanics, amphibolites and granitoids rocks of the Zalm area. The different lithology in the present area are displayed as flattening strain that indicate a general process causing flat-lying foliations. Our field work explain that granitoids rocks intruded the Schist and metavolcanics rocks. The strain magnitude are characterized by a wide-ranging and a heterogeneous deformation. On other word, the relationship between the strain magnitude and contacts does not detect (see Table 1). In addition, our strain magnitude data show the same order in the different lithology in the Zalm area. Therefore, we suggested that the Schist, metavolcanics and granitoids rocks have the similar deformation events at the same time approximately.

In the present work, the Rf/ϕ related strains created from ductile-deformed feldspar could be attributed to thrusting inspired deformation. Also, our data suggested that the deformation time for the accumulation of finite strain represents brittle to semi-ductile deformation during thrusting and intrusions of the deformed granitoids. It suggested that the structure and tectonic of the Zalm area is dominantly considered by pervasive and sub-horizontal foliations from the main metamorphic phase, which are almost sub parallel to the fault contacts in the Zalm area.

7. Conclusion

The investigations of strain and deformation data for the Zalm area are concluded as the following remarks:

- The strain data are characterized by both oblate strain and prolate strain symmetry in the Zalm area.
- This explains that the time of deformation is the accumulation of brittle to semi-ductile deformation during thrusting and intrusions.
- The accumulated of finite strain created during superimposed deformation. It explained that the contacts formed during the accumulation of finite strain.
- During thrusting the accumulation of brittle-semi-ductile deformation was not formed by simple shearing but the pure shearing is also important played due to a vertical shortening. It is concluded that the vertical shortening was effected by the sub-horizontal foliation in the studied area.
- It is suggested that the tectonic contacts were created during deformation and metamorphism with progressive over thrusting under brittle-semi-ductile conditions. In addition, the main-phase foliation is the same for Schist, metavolcanics, amphibolites and granitoids rocks, which also displays similar of deformation behavior in the different lithology.

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