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STRUCTURAL EVOLUTION OF EL-ATAWI AREA, CENTRAL EASTERN DESERT, EGYPT

AHMED M. HEGAZI

Geology Department, Suez Canal University*

ABSTRACT

El-Atawi area is covered mainly be metasediments, metavolcanics serpentinites, cataclastic granodiorites, El-Atawi alkali granite, which are intruded in many places by post-granite dykes and late volcanics (mainly trachites).

The geometric analysis and the cross-cutting and overprinting relationships of the mesoscopic structural elements reveals that the metasediments and metavolcanics have been subjected to three folding phases. The F1-fold generation is the oldest one and was refolded by a widely distributed system of isoclinal overturned F2-folds. The F3 isoclinal, reclined folding system represents the youngest folding phase which are recorded at the study area.

The folding pattern of El-Atawi area could be evolved through the superimposing of three successive folding phases. The geometry of the interference pattern produced by the superimposing of two folding generations depends on the values taken by angles α and β. At El-Atawi area the superimposing of F1 and F2 has α and β angles which are compatible with that of the condition suitable to produce type-2 interference pattern of RAMSAY (1967). The overprinting of F3-folding has resulted in the formation of type-1 interference pattern. Due to this superimposing process, El-Atawi area was folded into a series of sharply elongated domes and basins which is well-developed in the metasediments exposed at the area.

INTRODUCTION

El-Atawi area is a part of the Precambrian basement complex exposed in the Central Eastern Desert, and it is bounded by latitudes 25°35' and 25°40' N and longitudes 34°07' and 34°15' E. It is a mountainous terrane characterized by high peaks such as G. El Sibai, G. Um-Luseifa, and G. Andia. The highest two triangulation points in the area occur in the granite mass of G. El-Atawi (1062 m), at the southeastern part, and in the metavolcanics of G. El-Hameir (829 m), at the southwestern corner. The area is traversed by two main wadis, namely Abu-Garadi and El-Atawi. The southern parts are drained by W. E-Miyah and W. Sitra.

El-Atawi area has been the subject of many studies, particularly as being a part of G. El-Sibai area. Most of the studies are mainly concerned with metamorphism, geochemistry, and regional tectonic setting. Structurally, El-Atawi area belongs to the major upper tectonic units (Suprastructure), which include serpentinites, metavolcanics and their equivalent volcaniclastics (SABER, 1993). The present work aims at analyzing the mesoscopic fabrics and structures, and describing their geometric style, orientation, ad overprinting relationships. Resolving the spatial and the temporal relationships of the mesoscopic structures helps deciphering the tectonic history of the deformed rocks. Eventually, the structural evolution of the study area, based on the geometric and kinematic analyses, it also simulated.

* Ismailia 41522, Egypt

GEOLOGIC SETTING

The metamorphic belt of El-Atawi area is bounded at the north and easy by the red and pink alkali granite masses of G. El-Sibai and G. Um-Luseifa, and at the south by the red, coarse- to medium-grained, alkali granite of G. El-Atawi. The granite-gneiss and the other metamorphic rocks are the oldest rock units, whereas the alkali granites are the youngest ones. The metamorphic rocks of El-Atawi area are intensively folded and regionally metamorphosed assemblage of volcanics and volcaniclastic sediments that range in metamorphism from green schist to amphibolite facies. Furthermore, the volcaniclastic sediments contain dismembered ophiolitic masses of serpentinite and related rocks, together with spilitic pillow lava (EL-SHAZLY and SABET, 1955, and EL-BAHARIYA, 1988).

The metasediments include meta-mudstones, meta-greywakes, schists, phyllites, and hornselfes, (Plate Ia). The main metavolcanics are represented by fine- and coarse-grained meta-basalts, meta-andesites, meta-dacites and rhyodacites, (Plate Ib). Other rock units exposed in the study area are serpentinites, cataclastic granodiorites, diorites, Hammamat metasediments, El-Atawi alkali granite, (Plate Ic), post-granite dykes, and late volcanics (trachytes), (SABET, 1961, RAGAB, 1971 and EL-GHAWABY, 1973).

Three main alkali granites outcrop in El-Atawi area; namely, G. El-Atawi, Abu-Garadi and the northern gneissose granite. Many apophyses are intruded from the first two granite bodies into the older metamorphic rocks. Moreover, G. El-Atawi is a part of a granite batholith which is located at the southeastern part of the area (KHAWASIK, 1968).

SABER (1993) revealed that G. El-Sibai area is characterized by the presence of two major structural units separated by a shear zone. The lower tectonic unit is referred to as the infrastructure, whereas the upper tectonic unit is defined as the suprastructure. The infrastructural rocks are differentiated into amphibolite-migmatite association, quartz-feldspar gneiss, and gneissic granites. The suprastucture is exposed in two belts overlaying the infrastructure, and is made up of weakly metamorphosed basic to intermediate volcanics and their equivalent volcaniclastics.

Accordingly, the El-Atawi metasediments and metavolcanics belong to the Pan-African suprastructure island-arc volcanics and volcaniclastics which are thrusted over the infrastructural units located to the north.

The areal distribution of different lithologic units exposed in El-Atawi area, as verified during the field work, is shown in *Fig. 1.* Their relative ages are arranged from the oldest to the youngest as follows: metasediments, metavolcanics, serpentinites, cataclastic granitoids, El-Atawi alkali granite, and post-granite dykes.

MESOSCOPIC STRUCTURES AND FABRICS

Conventionally, the simple mesoscopic structures and fabrics are treated geometrically as planes or lines. Hence, the field orientation data, i.e., the mesoscopic structures which have been measured and recorded in the field will be treated under the following topics:

1. Planar structures

These structures include the bedding planes and the cross- and graded-bedding in the metasediments, the relic banding in metavolcanics, as well as the foliation and fracture cleavage in both rock units (Plate Id).

Linear structures:

These structures encompass minor fold hinges, intersection lineations, and pencil and rod structures in both metasediments and metavolcanics (Plate Ie).

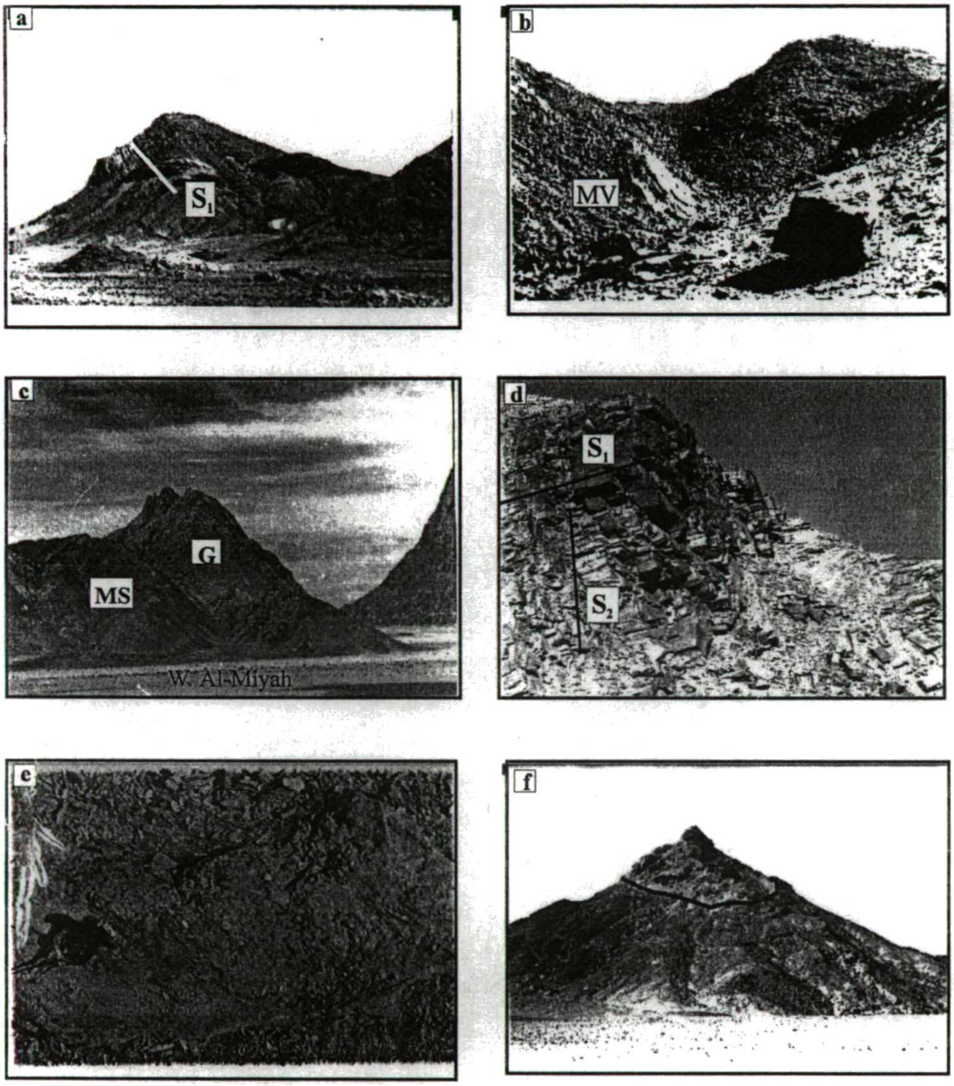

Plate I.

(a): Isoclinally F2-folds in Metasediments, El-Atawi area, looking SE
(b): Metavolcanics of G. Al-Hameir.
(c): G. El-Atawi alkali granite (G) intruding Hammamat metasediments (MS), W. Al-Miyah, looking north.
(d): S1-foliation and S2-fracture cleavage in metasediments, W. Abu-Garadi, looking NW.
(e): Pencil structure in metasediments, El-Atawi area.
(f): Elongated basin-pattern which is a part of type-I interference pattern in metasediments, El-Atawi area (looking NW).

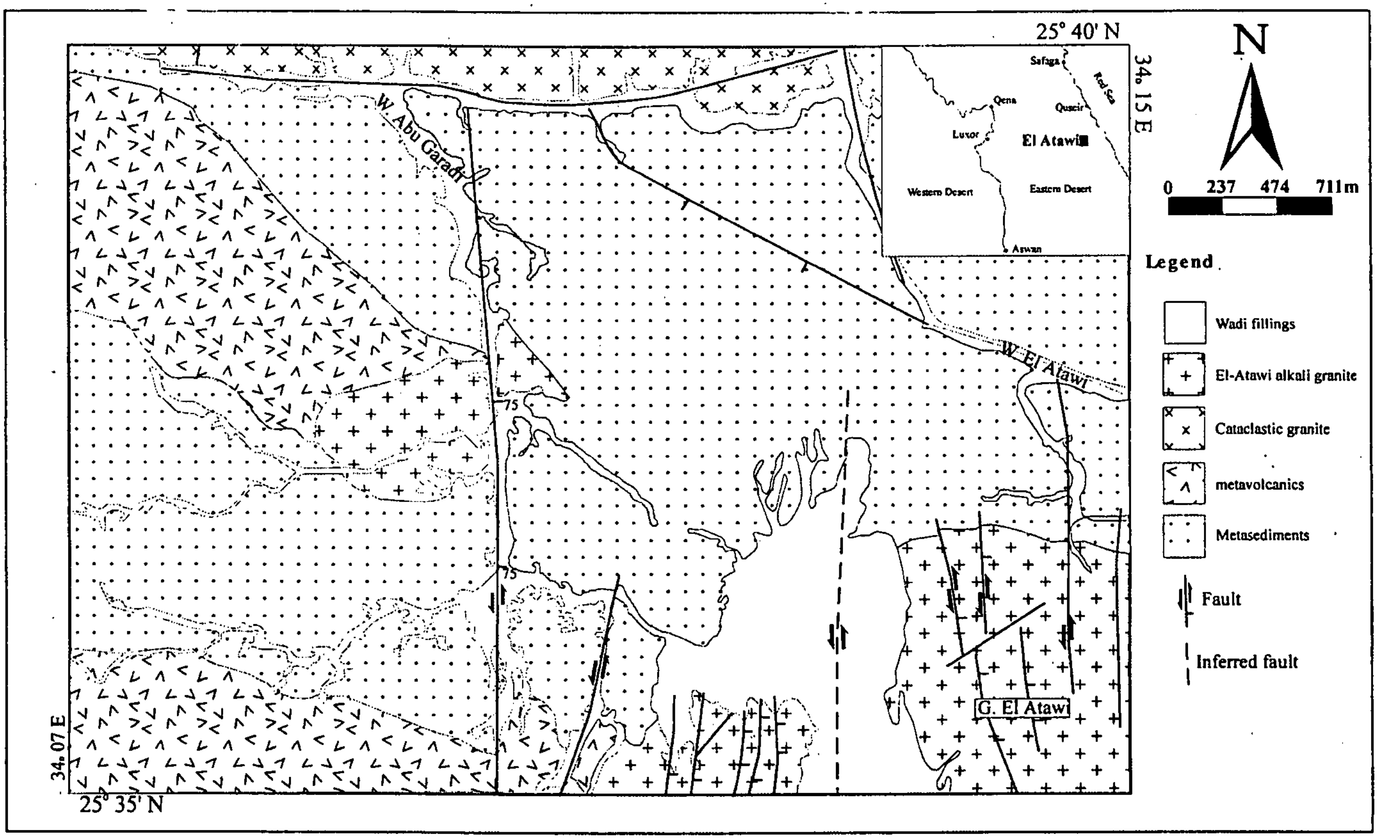

Fig. 1. Geological map of El-Atawi area, Central Eastern Desert

The mesoscopic structures which are measured and recorded in El-Atawi area are plotted on the structural map (*Fig. 2*) and their geometrical and genetical relationships are exhibited in Table 1.

TABLE 1

The genetic relation of the mesoscopic structures in El-Atawi area

Relative age	Symbol	Type of structure	Mesoscopic structures in the field
Primary structures	S_0	Primary S-surfaces	- Bedding, cross-, graded-bedding in metasediments - Banding in metavolcanics.
Secondary structures associated with the first folding phase (F1)	S_1	Axial planes of F1	- Foliations. - Fracture cleavage.
	B_1	Axes of F1 in S_0 with S_1 as axial plane	Hinges of minor folds belong to F1
	L_1	Lineations parallel to the S_0-S_1 intersections	- Cleavage-bedding intersection - Pencil and rod structures
Secondary structures associated with the second folding phase (F2)	S_2	Axial plane of F2	- Foliations. - Stay cleavage - Fracture cleavage.
	B_2	Axes of F2 in S_0 & S_1 with S_2 as axial plane	Hinges of minor folds belong to F2
	L_2	Lineations associated with F2	S_0-S_2 & S_1-S_2 intersection lineatons
Secondary structures associated with the third folding phase (F3)	S_3	Axial plane of F3	- Slaty cleavage
	B_3	Axes of F3 in S-surfaces with S_3 as axial plane	Hinges of minor folds belong to F3
	L_3	Lineations associated with F3	Intersection lineations of S3 with different S-surfaces

GEOMETRICAL ANALYSIS

The conventional geometrical analysis is carried out by plotting the poles to a given structural planar element or the plunge of a linear element on an equal area net, then the geometrical interpretation of these data can often be done by inspection, assisted by contouring methods.

In the present work the mesoscopic structural elements are plotted and contoured using "SPHERISTAT", an orientation analysis and plotting program for MSDOS Computers, Version 1.1.

1. Planar elements:

The contour diagram of poles to S0-surfaces represented by bedding planes in metasediments and banding in metavolcanics is shown in *Fig. 3*. This diagram shows that the poles are distributed along a girdle and they posses a bimodal distribution. The attitude of the axial plane is predicted to be S55°W/50°, and the axis is plunging 36° towards N70°W. Although the poles to the bedding are generally configurated into a great circle (*Fig. 3*), it is evident that these poles attend to arrange along another girdle whose

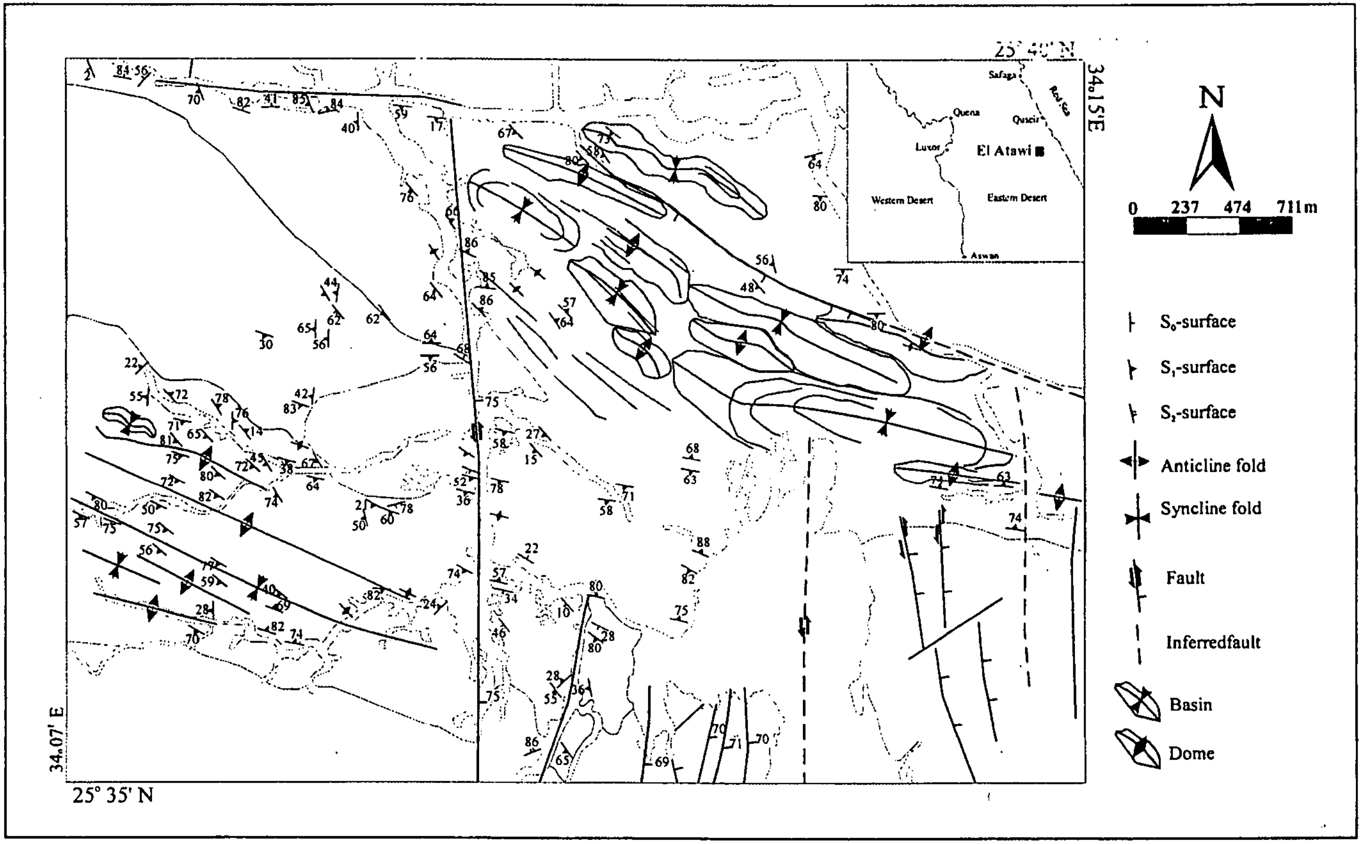

Fig. 2. Structural map of El-Atawi area, Central Eastern Desert, showing the predicted closed elongated interference patterns Resulted by the superimposing of the folding phases.

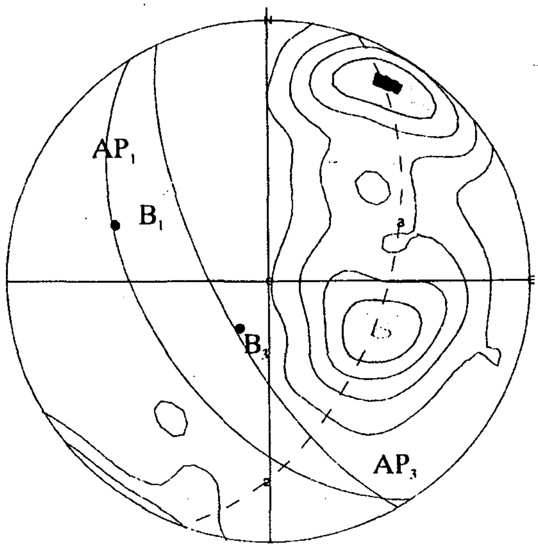

Fig. 3. Stereogram of poles to bedding and banding in metasediments and meta volcanics, El-Atawi area.
AP_1: Axial plane and B_1: geometric axis of the first phase of folding.
AP_3: Axial plane and B_3: geometric axis of the third phase of folding.

geometric axis plunging 70° due S36° W and the attitude of its axial plane is S58°W/74°. WOODCOCK (1977) introduced K- and C-ratios as useful indicators of the fabric shapes of folding. The K-ratio is an estimate of both girdle and cluster tendencies of the directional data, whereas, the C-ratio is a measure of their strength of preferred orientation. The K- and C-ratios of the plottered S0-surfaces are estimated 0.76 and 1.2, respectively, indicating a weakly developed girdle and cluster pattern of folding which also has a weak preferred orientation.

The poles to foliations also suggest a girdle distribution whose axis is horizontally trending in N55°W direction, whereas the attitude of the axial plane is S35°W/70° (Fig. 4). The K- and C-ratios of the plotted foliation surfaces are respectively estimated 0.95 and 1.38, indicating a weakly-developed girdle and cluster pattern of folding which is characterized by a weak preferred orientation. The folding in foliations surfaces seems to have an isoclinal overturned style. Furthermore, the diagram shows that the poles tend to spread along another great circle whose geometric axis plunges 70° to S36°W, and the attitude of its axial plane is S58°W/74°.

The geometric analysis clearly indicates that there are three generations of folding. The first one has a geometric axis plunging 36° to N70°W and an axial surface (S55°W/50°). The second generation of folding has a horizontal geometric axis trending N55°W-S55°E and an axial surface (S35°W/70°). The third one has a geometric axis that plunges 70°, S36°W, and an axial surface (S58°W/74°).

FLEUTY (1964) suggested a useful geometrical classification scheme for folds based on the relative orientation and the absolute inclinations of hinge lines and axial surfaces. According to this classification, the three folding phases that affected El-Atawi area are listed in Table 2.

TABLE 2

Geometrical classification of folds (FLEUTY 1964)

Generation	Axial surface	Hinge	Type of fold
1st	moderately inclined	moderately plunging	moderately inclined, moderately plunging
2nd	steeply inclined	horizontal	horizontal, steeply inclined
3rd	steeply inclined	steeply plunging	steeply plunging, steeply plunging

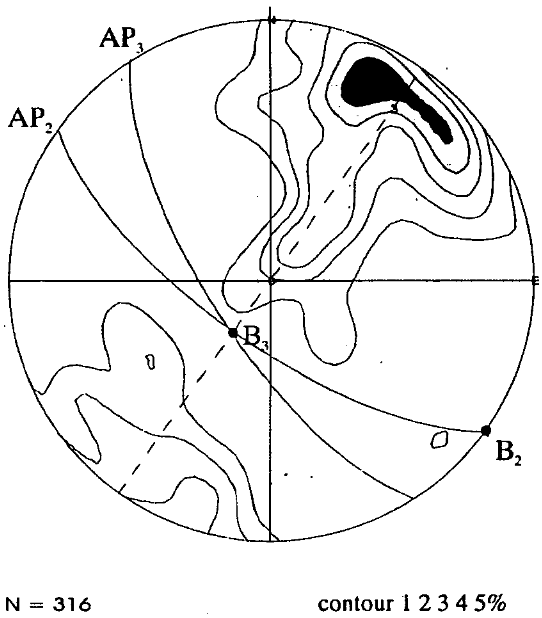

Fig. 4. Stereogram of poles to foliations in metasediments and meta volcanics, El-Atawi area.
AP_2: Axial plane and B_2: geometric axis of the second phase of folding.
AP_3: Axial plane and B_3: geometric axis of the third phase of folding.

2. Linear structures:

a) L_{1-a}-intersection lineations:

These lineations are represented by the intersection of the bedding S_0-surfaces and the first foliation S_1-surfaces. The intersections are plotted on stereogram (*Fig. 5a*), which exhibits that the measurements are hovering around the B1-geometric axis, i.e., they are more or less parallel to it, with a tendency to spread along a small circle due to the effect of subsequent refolding.

b) L_{1-b} pencil structure:

The pencil structure is a very distinctive linear structure associated with folded and cleaved mudstones and siltstones which are widely exposed at El-Atawi area, (Plate Ie). It is formed by the intersection of bedding fissility surfaces (S_0) and cleavage surfaces (S_1). It is predicted from the stereogram of the pencil structures (*Fig. 5b*) that these linears are distributed in a bimodal pattern, and they hover around an average attitude with maximum plunging 16° to N86°W. Moreover, the plot shows a tendency to spread along a small circle whose center is found to be concomitant with the B3-geometric axis.

c) L3-intersection lineations:

The linear structures produced by the intersection of the S_3-foliations with the previously formed S-foliations. These linear structures are projected on a stereogram (*Fig. 5c*). The distribution of data on the stereogram suggests a unique average plunging 68°, S26°E, which is more or less parallel to B3-geometric axis.

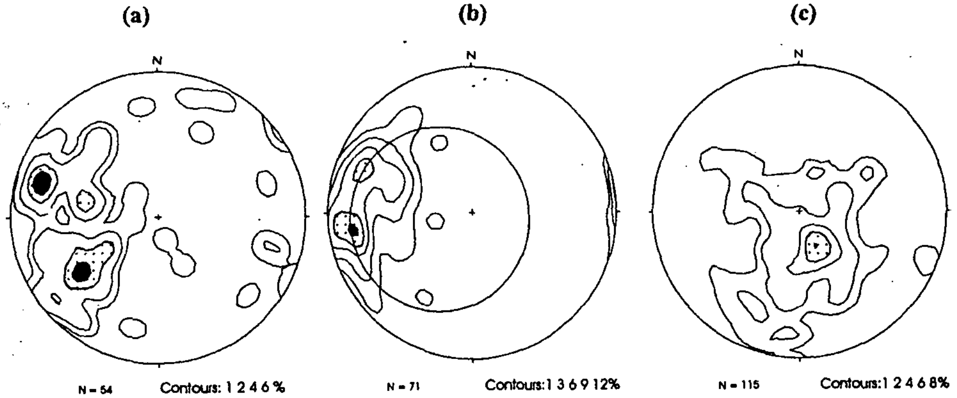

Fig. 5. Stereogram of L1-a intersection lineations (a), L1-b pencil structures (b), and L3 intersection lineations (c) in metasediments and metavolcanics, El-Atawi area.

d) Fold hinges:

The hinges of the different fold generations are plotted on a stereogram (*Fig. 6*), that shows distinctive maxima which could be related to the three folding phases. Two maxima; 1a and 1b, whose attitudes are 24° due West and 32° to N26°W respectively, re-

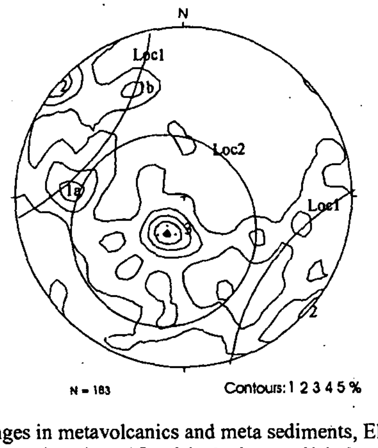

Fig. 6. Stereogram of fold hinges in metavolcanics and meta sediments, El-Atawi aea. (Loc1: is the locus of B1 about B2-geometric axis and Loc2 is the locus of b1 about B3-geometric axis)

present the locus of rotation of B1-geometric axis through a small circle about B2-geometric axis. The stereogram also shows another maximum, denoted as "2" in *Fig. 6*, coinciding with B2-geometric axis. This maximum is horizontal and trends to N46°W-S46°E. Moreover, the B3-fold hinges are represented by a pronounced maximum designated as "3" plunging 68° to S18°W. This maximum have the highest contour value (5%) indicating that the F3-fold hinges are more or less coaxial. This means that F3-hinges have not been subjected to subsequent refolding events. In addition to that, the stereogram exhibits a subordinate clustering of fold hinges that could be interpreted in terms of the locus of rotation of different geometric axes about a subsequent refolding axis.

STUCTURAL EVOLUTION

The structural evolution of El-Atawi area, based on the foregoing geometric and kinematic analyses, could be simulated in terms of the superimposing of three successive folding phases. The geometric analysis of the preserved bedding planes (S0) and the different foliation surfaces (S_1, S_2 & S_2) reveals that the metasediments and metavolcanics have been subjected to three folding phase. The cross-cutting and overprinting relationships of the mesoscopic structural elements have verified that F1-fold generation is the oldest one and are refolded by a widely distributed system of isoclinal overturned F2-folds. Representative measurements of S1-foliations (*Fig. 7a*) are distributed along a girdle whose geometric axis plunges 18° towards S39°E. The axial plane, which is measured directly in the field, has an attitude S27°W/70°. Also, representative measurements F2-fold hinges (*Fig. 7b*). show bimodal distribution, which is a clue for refolding process. The F3-folding system represents the youngest folding phase recorded at the area. This is confirmed by selective measurements reveals that the F3-folding is isoclinal and having axial plane whose attitude is S58°W/77°, whereas the geometric axis plunges 74° to S23°W. The characteristic feature of F3-fold hinges, is its clustering in the SW quadrant of the plot (*Fig. 8b*), indicating their tendency to be coaxial. This means that they are more or less parallel and show no signs of refolding process.

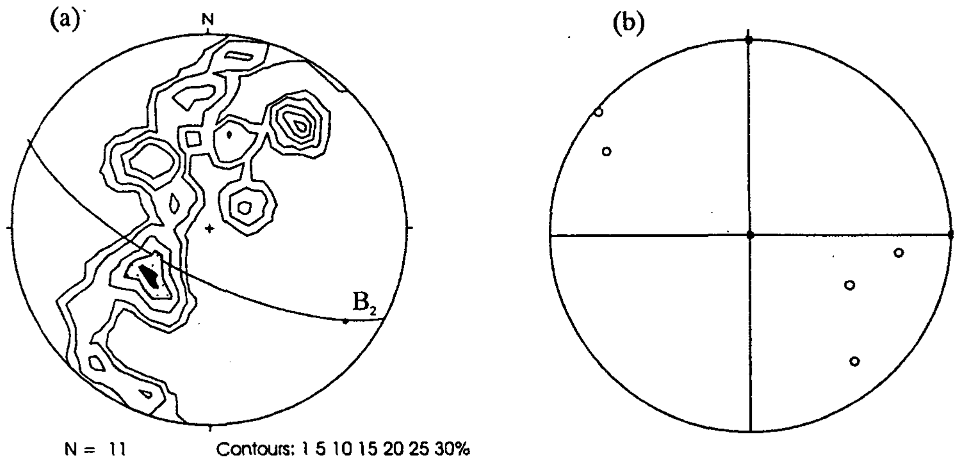

Fig. 7. Stereogram of poles to S1-foliations (a), and the F2 hinges (b)

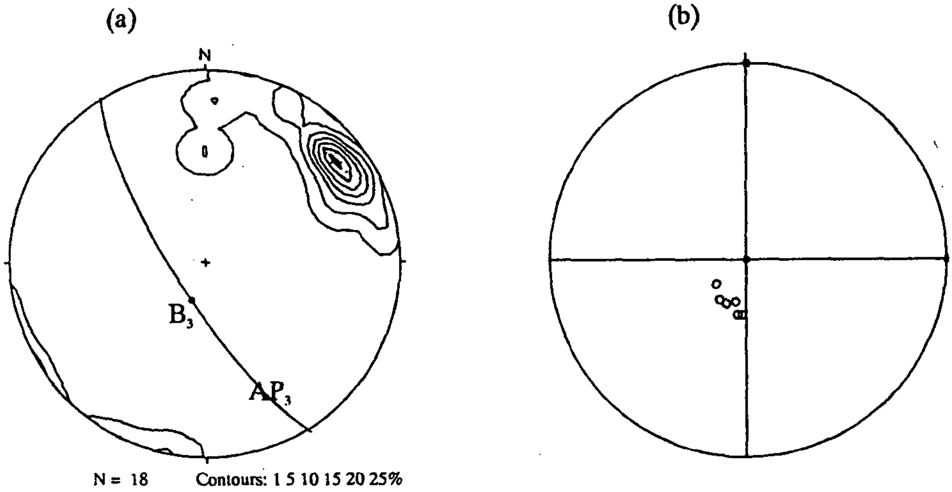

Fig. 8. Stereogram of poles to S2-foliations (a), and the F3 hinges (b)

The folding pattern of El-Atawi area (*Fig. 2*), could be evolved through different successive steps which began with original S0-surfaces represented by the bedding surface in the metasediments and banding in metavolcanics. These surfaces were initially horizontal and later on, they were tilted and their attitude became N70°W/36° (*Fig. 9a*). The original layered materials were subjected to an inhomogenous strain due to a compressive stress regime whose maximum principal axis plunged 44°, N66°E. This compressive stress resulted in the formation of the first folding phase F1, whose geometric axis plunges 36° to N70°W direction and the S1-axial surface (S55°W/50°), (*Fig. 9b*). If the nature and orientation of strain increments change, any previously folded rock layers may be subjected to refolding about different axial directions, and the axial surfaces of the original folds may take up some folded forms (RAMSAY, 1967). This is clearly exhibited at the study area, where the first folding generation F1 is superimposed by a second phase of folding F2, which related to subhorizontal compressive stress trending N35°E. F2-folds are generally isoclinal overturned folds and its B_2-geometric axis is horizontal one trending N55°W, whereas the attitude of S_2-axial surface is S35°W/70° (*Fig. 9c*). The geometry of the three-dimensional form produced by the superimposing of the first and second folding generation depends on the values taken by angles α and β. Where α is the angle between the two axes of successive folding, and β is the angle between the pole to the first axial plane and the direction of flow (a_2) of the second fold generation (RAMSAY, 1967). At El-Atawi area the superimposing of F1 and F2 has α and β equal to 36° and 69° respectively. These values are found to be compatible with that of the condition suitable to produce type-2 interference pattern of RAMSAY (1967) (*Fig. 9d*). The F3-folds are isoclinal, reclined fold (*Fig. 9e*) which took place by the influence of NW-SE-oriented horizontal compressive stress axis. The overprinting of F3-folding on the widely distributed F2-folds resulted in the formation of type-1 interference pattern (*Fig. 9f*) and the values of angles α and β are 77° and 75° respectively. Due to this superimposing process, El-Atawi area is folded into a series of elongated domes and basins, (Plate If), which is well-developed in the metasediments exposed at the area (*Fig. 2*). The sharply inflected and elongated domes and basins could be attributed to the very tightly nature of the interfering folds (TURNER and WEISS, 1963).

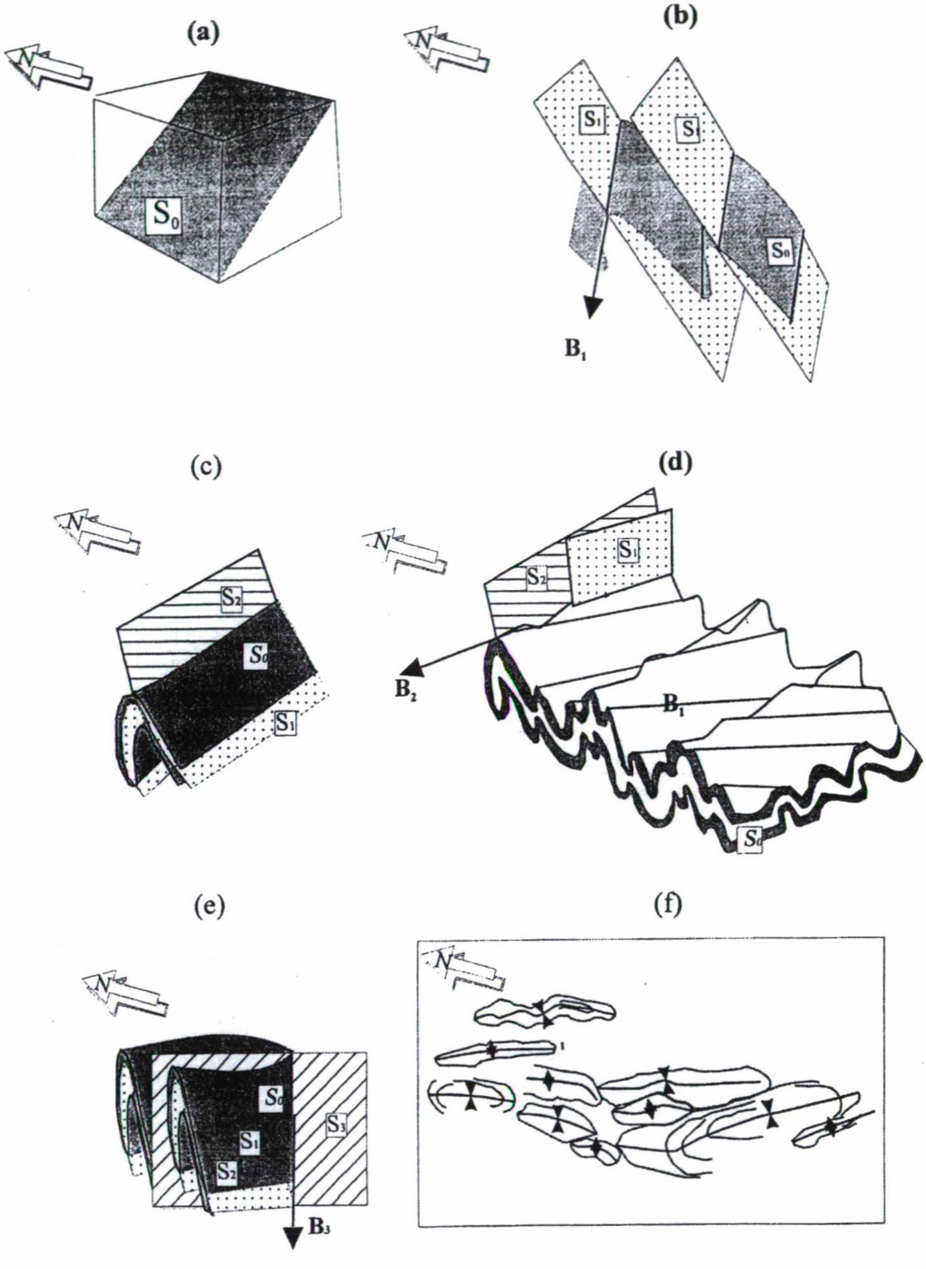

Fig. 9. A proposed structural evolution model of El-Atawi area, Central Eastern Desert. (S_0: bedding and banding, S_1, S_2 & S_3: first, second and third axial surfaces. B_1, B_2 and B_3: first, second and third geometric axes.)

SUMMARY AND CONCLUSIONS

The metasediments and metavolcanics of El-Atawi area are intensively folded and regionally metamorphosed assemblage of volcanics and volcaniclastic sediments of green schist and amphibolite facies. They belong to the Pan-African suprastructure island-arc volcanics and volcaniclastics thrusted over the infrastructural units located to the north.

The metasediments include meta-mudstones, meta-greywakes, schists, phyllites, and hornfelses. The main metavolcanics are represented by fine- and coarse-grained meta-basalts, meta-andesites, meta-dacites and rhyodacites. Other rock units exposed in the study ara are serpentinites, cataclastic granodiorites, diorites, Hammamat metasediments, El-Atawi alkali granite, post-granite dykes, and late volcanics (trachytes). Futhermore, the volcanoclastic sediments contain dismembered ophiolitic masses of serpentinite and related rocks, together with spilitic pillow lava.

The geometric analysis and the cross-cutting and overprinting relationships of the mesoscopic structural elements reveals that the metasediments and metavolcanics have been subjected to three folding phases. The F1-fold generation is the oldest one whose geometric axis plunges 36° to N70°W direction and the S_1-axial surface (S55°W/50°). They are refolded by a widely distributed system of F2-folds. F2-folds are generally isoclinal overturned folds and its B2-geometric axis is horizontal one trending N55°W, whereas the attitude of S2-axial surface is S35°W/70°. The F3-folding system represents the youngest folding phase recorded at the area. These F3-folds are isoclinal and having axial plane whose attitude is S58°W/77°, whereas the geometric axis plunges 74° to S23°W.

The folding pattern of El-Atawi area could be evolved through different successive steps which began with original S0-surfaces represented by the bedding surfaces in the metasediments and banding in metavolcanics. These surfaces were subjected to a compressive stress regime whose maximum principal axis plunged 44°, N66°E which resulted in the formation of the first folding phase F1. The previously folded rock layers may be subjected to refolding about different axial directions, and the axial surfaces of the original fold may take up some folded forms. This is exhibited at the study area, where the first folding generation F1 is superimposed by a second phase of folding F2, which related to subhorizontal compressive stress trending N35°E. The geometry of the interference pattern produced by this superimposing depends on the values taken by angles α and β. At El-Atawi area the superimposing of F1 and F2 has α and β angles which are compatible with that of the condition suitable to produce type-2 interference pattern of RAMSAY (1967). The F3-folds took place by the influence of NW-SE-oriented horizontal compressive stress axis. The overprinting of F3-folding has resulted in the formation of type-1 interference pattern. Due to this superimposing process, El-Atawi area is folded into a series of elongated domes and basins which is well-developed in the metasediments exposed at the area.

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