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Polyphase Folding in Nugrus-Sikeit Area South Eastern Desert, Egypt

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ABSTRACT. The lithological constitution of Nugrus-Sikeit area comprises a sequence of dismembered ophiolites, tectonic mélange association and arc assemblage. These older rocks are intensively deformed and intruded by intracratonic association, which within the mapped area, is represented by gabbros and the associated hornblendite together with younger granites.

Planar and linear mesoscopic structures exhibited by the rocks of Nugrus-Sikeit area indicate that these rocks are involved in superimposed folding events and at least three fold generations (F1, F2 & F3) can be recognized.

The F1 folds resulted in isoclined folding of S0, and other primary structures around WNW-ESE axes. This phase represents the main folding that affected the area. Besides establishing the WNW-ESE pattern of rock units, it was also responsible for the transposition of S0 into penetrative surfaces S1 accompanying low to medium grade regional metamorphism.

The F2 folds refolded the F1 folds into upright to overturned and even recumbent folds about NW-SE axes together with the crenulation of S1 surfaces producing crenulation cleavage S2.

The F3 folds are of mild intensity compared to the F1 and F2 generations. It neither appeared to disturb the orientation of the earlier structures nor accompanied by strong transposition foliation. Associated folds are of the mesodimension and maintain a fairly constant NNE-SSW trend.

Introduction

The studied area is a Precambrian basement terrain that is situated roughly 90 km SW of Mersa Alam on the southern Red Sea coast of Egypt. It covers an area of over 350 km^2 that is constituted of different lithological assemblages of igneous and metamorphic rocks. Such rocks, in terms of metamorphism and deformation, are essentially polycyclic and featured by the frequent presence of multiple mesoscopic structures together with various types of folds with different trends.

Several previous contributions have been made to the tectonic setting of this area and its surroundings. Garson and Krs (1976) considered that Wadi Shait thrust lies within the range of the regional N45º-60ºE block faulting and should be older than the Wadi Nugrus thrust, which lies within the range of deep-seated tectonic zones N 30º-35º W. Abdel Khalek (1979) recorded the possibility that the two thrusts are contemporaneous and represent one thrust line curved in NW direction. Abdel Khalek and Abdel Wahed (1984) recorded three deformational phases d1, d2 and d3. The first deformational phase (d1) is represented by NW-SE axial planes and axes plunging SE and NW respectively. The second (d2) is represented by tight overturned and have SW plunging axes. The third deformational phase (d3) is the weakest in intensity and resulted in open and tight symmetric and asymmetric folds and have NW-SE axial planes.

This paper attempts to highlight the complex folding affecting W. Nugrus-Sikeit area utilizing the analysis of mesoscopic structural elements approach. Over 2000 measurements including both planar and linear structural elements covering all parts of Nugrus-Sikeit area were collected and incorporated in this study.

Geologic Setting

The area of study is constituted of a wide range of lithologies, which on the basis of field observations and structural relations, are grouped and classified into the following major sequences; dismembered ophiolites, tectonic mélange assemblage, arc assemblage and intracratonic rock association (Fig. 1). The rocks are generally intensively deformed and show clear gradual variation from low grade green schist facies at the end of W. Nugrus (epidote and chlorite facies), through the medium grade amphibolite facies (W. Abu Rusheid and W. Nugrus) to high grade tectonic mélange at W. Sikeit (staurolite-kyanite-sillimanite facies) (Surour, 1995; Awad, 1994 and Attawiya *et al.* 1989).

The area comprises two nappes (ophiolite rocks and arc assemblage) separated by tectonic mèlange rocks. These rock associations are intruded by intracratonic gabbroic and granitic rocks.

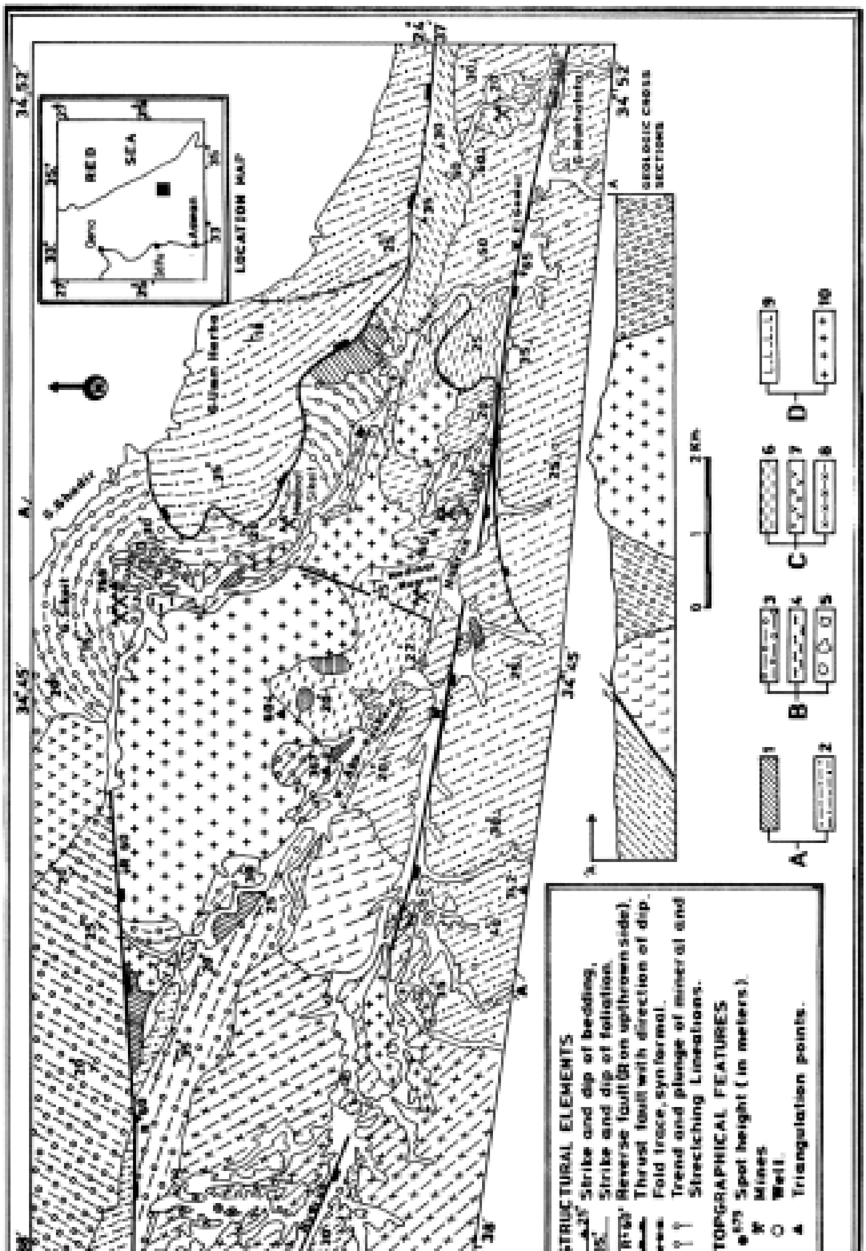

FIG. 1. Geological map of Nugrus-Sikeit area, Southeastern Desert, Egypt. Legend: 1 – Ultramafic rocks, 2 – layered metagabbros, 3 – Schists, 4 – Paragneisses, 5 – Metaconglomerates, 6 – Metasediments, 7 – Metavolcanics, 8 – Diorites, 9 – Younger gabbros, 10 – Younger granites.

The ultramafic rocks are characterized by tholeiitic, high-Ti ophiolite (MORB), equivalent to metamorphic peridotite and ultramafic cumulate of low temperature Alpine type. They have boudinaged lenses of magnesite and chromite pods of 0.5-4.0 m thick and 1-5 m long (Saleh, 1997). The presence of chromite pods classifies the presented ophiolitic rocks with the Harzbargite Ophiolite Types (HOT) of Nicolas (1989) indicating their formation in high temperature, high spreading rate and high degree of mantle partial melting environment. The mafic rocks are tholeiitic, high alumina, high-Ti ophiolite and equivalent to oceanic gabbros (MORB) and back-arc basin (Saleh, 1997).

The gneisses of W. Abu Rusheid are graywackes in composition and were shed into an adjacent basin associated with an active continental margin environment floored by an oceanic crust (ophiolite rocks) (Eid, 1986 and Saleh, 1997). The increase of metamorphism in the ophiolitic matrix (sillimanite- staurolite- kyanite facies) could be interpreted as a result of depressing the deeper parts of the thrust zone under the obducted ophiolite load. This also led to the assumption that the original transport direction was generally from southward as metamorphism increases in the original down dip direction of the thrusted sheet and the southward direction of plunge of the existing stria .

The dismembered ophiolite represents the oldest rocks exposed in the area. It is mainly constituted of meta-peridotites, meta-pyroxinites, layered metagabbros and ortho-amphibolites. These rocks are highly tectonized and form fold thrust sheets around W. Sikeit, W. Nugrus, W. Abu Rusheid as well as fragments in the schists, paragneises and metaconglomerates. The base of the ultramafics is relatively highly foliated and thrusted over the metasediments and arc metavolcanics by southward dipping faults.

The tectonic mélange assemblage is composed mainly of different varieties of schist, paragneiss and metaconglomerate that enclose abundant fragments of meta-peridotite, meta-pyroxenite and ortho-amphibolite of variable sizes and dimensions. These rocks are highly foliated and featured by the frequent presence of folds of mesodimension and boudinaged quartz lenses (up to 10-15 cm long) extending parallel to the foliation planes. The imprints of supperimposed folding of these rocks are manifested by the crenulation of the foliation into minor asymmetric folds.

The arc assemblage is constituted of metasediments (meta-calcpelites and meta-psammopelites), arc metavolcanics (meta-andesites and meta-dacites), and arc plutonites (diorites and quartz diorites). These metamorphic rocks display relics of primary graded bedding, foliations, laminations and are intensively folded. The foliation planes trend N70ºW and N20ºE, with an angle of dip 65º/SW and 40º/SE respectively, showing antiform with fold axis plunging 38º due S52ºE.

The intracratonic association is represented, within the area of study, by younger gabbros and the associated hornblendite, younger granites as well as post granitic dykes and veins.

Structure

Polyphase folding in the studied area is clearly evidenced not only by the frequent presence of mesoscopic structures of different types and attitudes but also by the superimposing and overprinting of these structures (Fig. 2). Among these folds, the plunging asymmetric, concentric recumbent "S"-form, typical "Z"-form, horizontal inclined and gentle isoclinal folds are recognized (Fig. 3 - 7). In addition to bedding (S0), two and other foliation surfaces (S1 & S2) reflecting two fold episodes are recognized. The associated linear structures are numerous and include mineral lineation, long axes of deformed pebbles, boudin axes (Fig. 8) as well as hinges of mesofolds.

In the present work, identification of the different folding phases that affected the area was approached utilizing the stereographic projection method of analysis using a lower-hemisphere equal-area net (Weiss, 1957; Turner and Weiss, 1963; Ramsay, 1967; Billings, 1972; and Davis and Reynolds, 1996) as follow:

S0, is only locally preserved in the metasediments as it is almost transposed into secondary foliation. On a stereoplot (Fig. 9a), these surfaces are distributed in a manner suggesting three probabilities of great circles distribution. The normal to these great circles, geometric fold axes, are of the following attitudes :

The first (B_0^1) plunges 20º due S75ºE.

The second (B_0^2) plunges 5º due S45ºE.

The third (B_0^3) plunges 5º due S15ºW.

S1 is mainly expressed by schistosity in the tectonic mèlange and metasediments as well as by gneissosity and lithologic layering in gneisses and metagabbros respectively. On stereoplot (Fig. 9b), the poles to these surfaces show a great circle distribution which is indicative of being originated during an even older phase of folding (F1) and that they are refolded around gently plunging fold axis in the SE direction (F2).

S2 is a crenulation cleavage that is locally developed due to crinkling the preexisting S1 surfaces into kinks of few centimeters in amplitude. On stereoplot (Fig. 9c), the poles to these surfaces form a tight cluster, which besides revealing a predominance in the N50ºW trend is suggestive of being apparently unaffected by subsequent fold events.

L1 lineation, in the present work, is defined by the preferred orientation of elongate mineral grains, long axes of deformed pebbles as well as the parallel

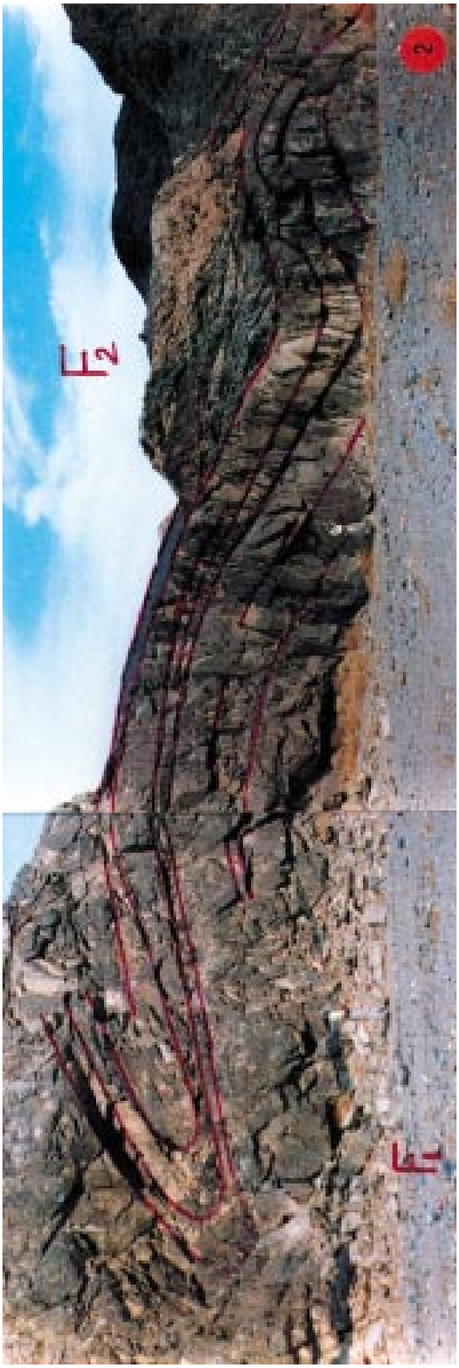

FIG. 2. Panoramaic view showing tight isoclinal (F1) folds refolded about NW-SE trending axial plane (F2), W. Nugrus-Sikeit area.

Fig. 3. Close up view showing plunging asymmetric fold in foliated metasediments, W. Nugrus-Sikeit area.

Fig. 4. Close up view showing concentric recumbent S-form fold in tectonic mélange, W. Sikeit area.

FIG. 5. Close up view showing typical Z-form with sub-horizontal axial plane folds, W. Nugrus area.

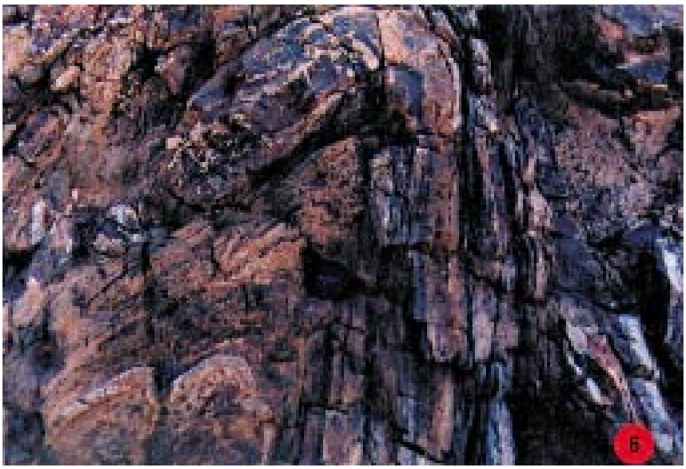

FIG. 6. Close up view showing horizontal inclined fold in metasediments at W. Nugrus area.

Fig. 7. Close up view showing tight isoclinal folding refolded around gently plunging axis in NW-SE direction (F2), in tectonic mélange, W. Sikeit area.

Fig. 8. Close up view showing boundinage structure in paragneiss alternating with meta-psammopelites dislocated by low-angle normal fault, W. Nugrus area, looking SW.

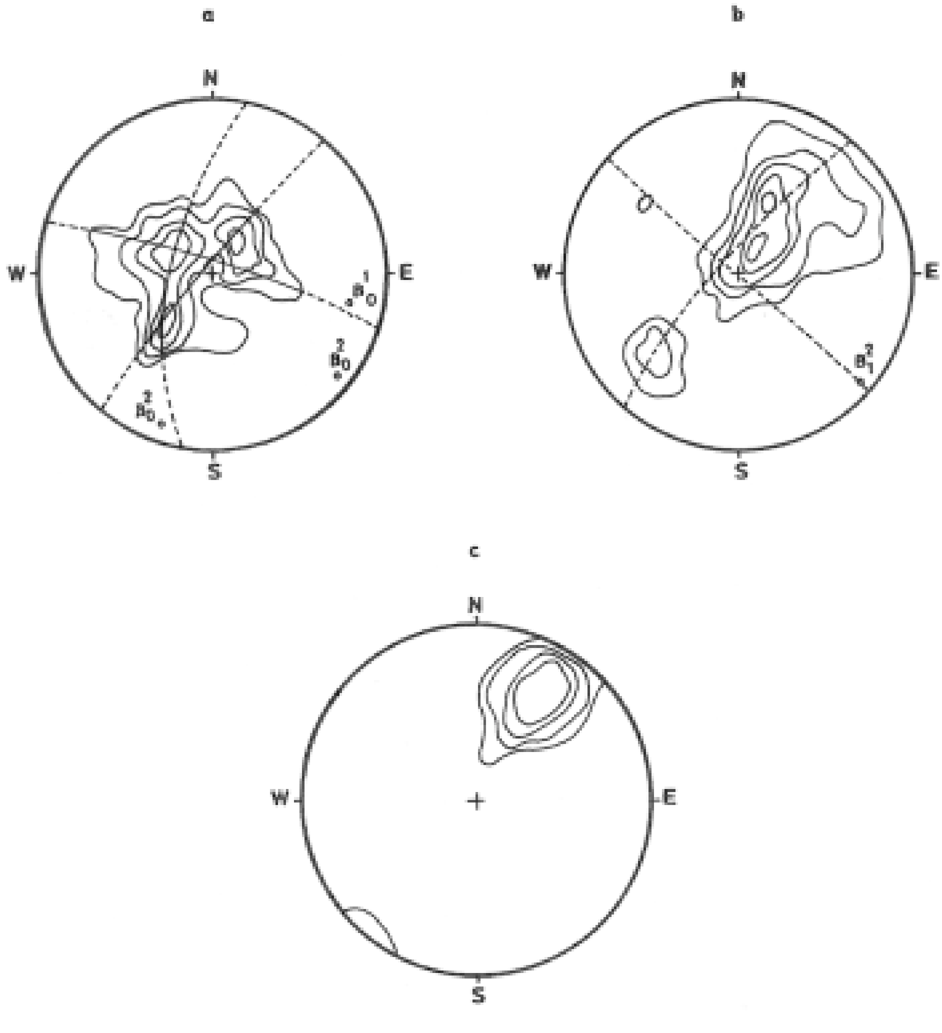

FIG. 9(a). Stereogram of poles to bedding planes (S0) in metasediments, W. Nugrus-Sikeit area(N = 370).

FIG. 9(b). Stereogram of poles to layering, foliation and gneissosity (S1) in layered metagabbros, metasediments and paragneisses, W. Nugrus-Sikeit area. poles to bedding planes (S0) metasediments, W. Nugrus-Sikeit area (N = 750).

FIG. 9(c). Stereogram of crenulation cleavage (S2) in tectonic mélange and metasediments, W. Nugrus-Sikeit area (N = 90).

boudin axes. These different linear structures are grouped together because in any given outcrop they are found aligned parallel to each other and to the S1 foliation surfaces. They, therefore, are ascribed to the first fold episode (F1) and are denoted L1. On stereoplot (Fig. 10a), this lineation form a great circle distribution of general WNW-ESE strike and southward direction of dip. Such a plane, according to Turner and Weiss (1963), reflects the original trend of the projected lineation before their refolding and accordingly is interpretted to represent the trend of the F1 fold episode.

L2 lineation is defined by the hinges of mesofolds that are particularly developed in the area of W. Sikeit-W. El Gemal. On stereoplot (Fig. 10b), the hinges of such folds show a predominance in the NW-SE trend coinciding with the trend revealed from the stereoplots of both S1 and S2. These mesofolds accodingly, are inferred to pertain to the F2 fold episode and are denoted L2.

L3 lineation is defined by the hinges of the mesofolds exposed in the youngest rocks around W. Abu Rusheid-W. Nugrus (Fig. 1). On stereoplot (Fig. 10c) such lineation forms two distinct opposite maxima, which besides revealing a predominance in the NNE-SSW trend are suggestive of being apparently unaffected by subsequent folding events. However, the opposite direction of plunge could be attributed to doming caused by later epirogenic movement rather than to lateral compressional forces resulting in the emplacement of the garnet leucogranites. These mesofolds, therefore, are attributed to the last and youngest fold episode F3.

Discussion and Evolutionary Model

In view of the described mesoscopic structural analysis, three fold episodes (F1, F2 and F3) affected the basement rocks of W. Nugrus-W. Sikeit area. The first two phases are relatively pronounced producing regional folds compared to the third one (F3) which is of less intensity.

F1 Fold Episode (ESE-WNW)

This phase appears to represent the main folding episode that affected the area. It resulted in the isoclined folding of the existing rock units about axes gently plunging to ESE together with their thrusting along WNW-ESE trend. These folds can be seen in mappable units of bedded rocks. Folding during this episode as inferred from the stereoplots of S0, S1 and L1 are related to NNE-SSW shortening direction. Besides establishing the WNW-ESE pattern of older rock units, this folding phase resulted in the transposition of bedding (S0) into penetrative surfaces (S1) accompanying upper green schist-lower amphibolite facies metamorphism. Also the fragments of the pre-existing rocks (quartz &

gabbros) were elongated and the individual brittle layers underwent boudinage. Structures produced during this phase are rarely preserved as they were almost extensively obliterated during subsequent phases and when found they appear folded about NW-SE trending axes (Fig. 10d).

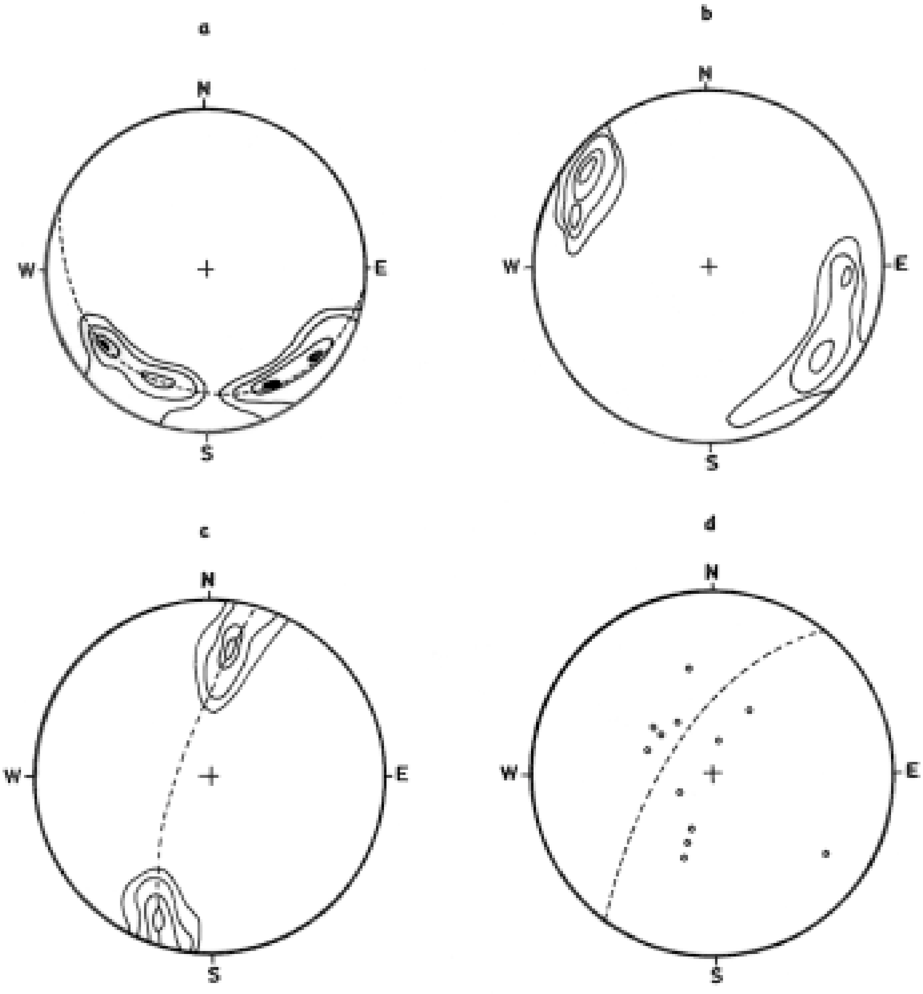

FIG. 10(a). Stereogram of minerals lineation, deformed pebbles and boundin axes (L1) in layered metagabbros and metasediments, W. Nugrus-Sikeit area (N = 360).

FIG. 10(b). Stereogram of the axes of minor fold (L2), W. Sikeit-W. El-Gemal area (N = 76).

FIG. 10(c). Stereogram of the axes of minor folds (L3), W. Abu Rusheid-W. Nugrus area (N=107).

FIG. 10(d). Stereogram of the mesoscopic folds axes (F2), W. Nugrus area.(N=145).Stereogram of the axes of minor fold (L2(, W. Sikeit-W. El-Gemal area (N = 76).

F2 Fold Episode (NW-SE)

Folding during the second episode has a style different from F1 and a characteristic trend of its axial surface (S2). As inferred from the stereoplot of S0, S1 and S2, the F2 folding is related to shortening oriented NE-SW and resulted in folding the earlier structures into normal upright to overturned folds around NW-SE trending axes. This phase does not appear to have been accompanied by strong transposition foliation and the S2 foliation appears as a crenulation cleavage rather than complete transposition. The main effect of F2 fold episode imposed on the earlier structures were folding of F1 fold and S1 foliation around NW-SE axes (Fig. 2 and 7). This is associated with the dispersion of the linear structures produced during F1 episode (L1) along a great circle depicting a locus plane of general WNW-ESE strike (Fig. 10a). Such a plane, according to Turner and Weiss (1963), reflects the original trend of the projected L1 lineation before their refolding and accordingly is interpretated to represent the trend of the F1 folds. Folds of this generation wherever observed are found warped and occasionally folded about NNE-SSW axes.

F3 Fold Episode (NNE-SSW)

This folding phase is evidenced from the stereoplot of hinges of mesofolds originated from shortening directed WNW-ESE. This folding phase is much less intense compared to both F1 and F2, and appeared to be unaccompanied by strong transposition relation. On the macroscale, folds of this generation are only exhibited in the northeastern part of the map (Fig.1), where the tectonic melange are folded around north-northeast plunging axis. These folds are generally of the mesodimension and maintain a fairly constant NNE-SSW trend. Its main effect imposed on the earlier structures is mainly expressed in the partial distribution of hinges of ealier mesofolds along NNE-SSW trending axial planes. Structures produced during this phase are cross cut by the younger garnet leucogranite .

A model for the geological evolution of this part of Nugrus-Sikeit area is presented here, and is based on the arc-continent collision and the observed field relations in the study area (Fig. 11):

1 – The oceanic plate was subducted in a NNE direction under the continental margin. This caused spreading of thinned crust in back-arc basin (marginal basin) formed landward arcs. During the Pan-African time, sediments of the continental arc, outer arc, and/or magmatic arc derivation, were deposited along an active continental margin in a basin floored by oceanic crust.

2 – During continued subduction, these rocks were metamorphosed at low to medium grade of greenschist to lower thrusted amphibolite facies. The continental margin assemblage (schists & paragneisses) was deformed during and after its deposition. It was mixed with the ophiolites forming tectonic mélange

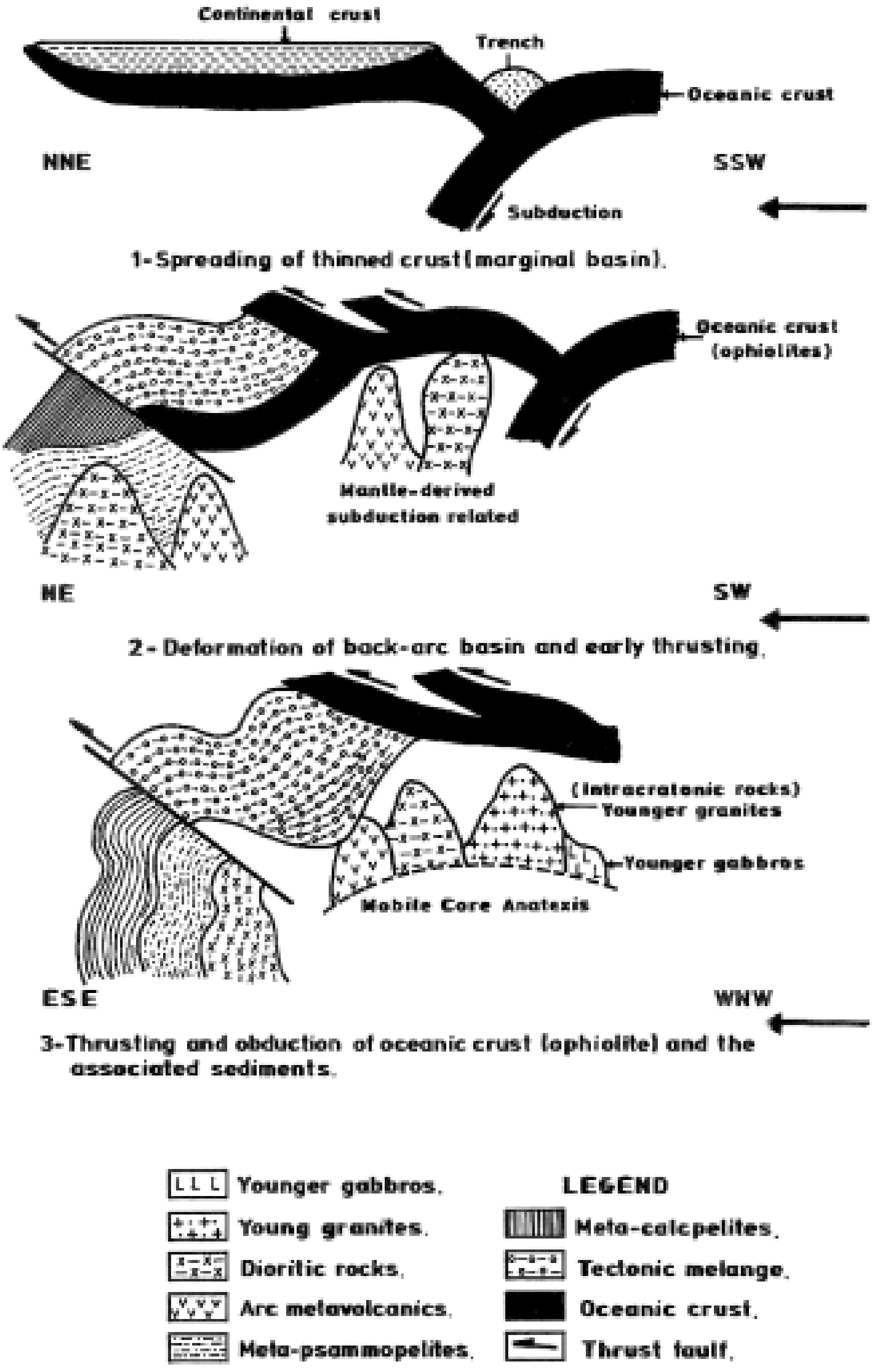

FIG. 11. Evolutionary plate-tectonic model.

assemblage, where it is obducted onto the former margin (F1 episode) forming a consolidated continental lithosphere (Harris, 1983).

3 – The back-arc basin was then subjected to deformation, folding and thrusting of the dismembered ophiolite (F2 episode). During this stage, magmatic arcs of calc-alkaline magmatism were generated comprising andesites, dacites and arrested trapped bodies of dioritic arc plutons intruding Nugrus-Sikeit area, about 800-700 Ma ago (El Gaby *et al.,* 1988).

4 – Finally, at the late to post tectonic stage (F3 episode) Nugrus-Sikeit area was intruded by younger gabbros and associated hornblendites, younger granites and post granite dykes.

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تعدد الطيّ بمنطقة نجرس– سيكيت – جنوب الصحراء الشرقية ، مصر

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المستخلص. تغطى منطقة نجرس– سيكيت أنواع مختلفة من صخور الأوفيوليت وتجمعات الميلانج التكتوني ، وتعلوها صخور القوس البركانية المتحولة ، وهي صخور متشوهة ومقطوعة بواسطة المتداخلات الصخرية (إنتراكراتونيك) ذات العمر الأحدث ، وتشمل صخور الجابرو والهورنبلنديت والجرانيت .

ولقد اتضح من تحليل العناصر التركيبية المختلفة ومن تتابع النشؤ التركيبي أن منطقة نجرس–سيكيت قد تعرضت على الأقل لثلاث مراحل تكتونية من أحداث الطي (ط١ ، ط٢ ، ط٣).

وتشير كل الدلائل إلى أن المنطقة ليست طية بسيطة ، ولكنها منظومات طي ، كل واحدة منها تتكون من عدة طيات مقعرة ومحدبة متعاقبة. حيث نشأ حدث الطي ط١ نتيجة قصور موجهة باتجاه جنوب جنوب غرب – شمال شمال شرق ، وأسفر عن طي الوحدات الصخرية القديمة لحين ما قبل الكمبري إلى طيات متماثلة الميل ، ويبدو أن هذا الحدث كان بمثابة الحدث الفعال الرئيسي في المنطقة ، ومصاحباً لكل من الدثور وعمليات التحول الإقليمي التي تعرضت لها تلك الصخور.

وبالنسبة لحدث الطي ط٢ فعلى الرغم من نشؤه من قصور موجهة في الاتجاه شمال شرق – جنوب غرب ، إلا أنه لم يسفر عن نشوء طيات كبيرة بل أيضاً ينسب فى إخلال بالاتجاه العام لطيات الحدث ط١ . وأخيراً نشأ حدث الطي ط٣ في اتجاه شمال شمال شرق – جنوب جنوب غرب ، أدي الحدث إلى طي الوحدات الصخرية الأحدث عمراً التابعة لأواخر ما قبل الكمبري بطيات مفتوحة كبيرة الحجم.