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The Feiran-Solaf metamorphic complex, Sinai, Egypt: Evidence for orthogonal or oblique tectonic convergence?

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ABSTRACT

New structural data collected along five transects across the trend of the Feiran-Solaf metamorphic complex (FSC) in the Sinai, provide a more precise depiction of the macroscopic folds. The two main macrofolds of the complex, the NW-SE trending Feiran and Solaf antiforms, appear to be thrust-related folds with detachments at different stratigraphic levels in the FSC. Contrary to earlier views, there is only one macrofolding event (D2) in the FSC, accompanied by NW-SE trending F2 mesofolds with varying style. While the F2 mesofolds are most commonly open concentric and symmetrical, some of these folds have been modified by inhomogeneous shear strain to become tight “similar” style asymmetric mesofolds in a zone of intense ductile shearing along the SW flank of the Feiran antiform. The recent Najd-related transpression model for FSC D2 deformation is evaluated. An alternative model for D2 as a product of orthogonal convergence is preferred. The D2 event recorded the collision of the FSC with the Sa'al terrane at ~800 Ma. The Kid arc complex collided with the Feiran and Sa'al complexes during subsequent NNW-SSE convergence at about 620-600 Ma.

1. Introduction

The late Proterozoic basement of the Sinai, Egypt represents a part of the Arabian-Nubian Shield (ANS) that evolved between 870 and 550 Ma (Stern, 1994; Stern and Johnson, 2010; Johnson et al., 2011). The history of the ANS began with the Mozambique Ocean (870-800 Ma) (Johnson et al., 2004; Stern and Johnson, 2010). Relics of this ocean crust are represented by obducted ophiolite slices throughout the Eastern Desert of Egypt. Closure of the Mozambique Ocean proceeded through stages of subduction, with the development of island arc terranes (800-680 Ma) (Johnson et al., 2011; Johnson, 2014, followed by middle to late Cryogenian (790-640 Ma) stacking of the arcs and collision of microcontinents (Meert, 2003) to produce an assembly identified as the proto-ANS (Johnson et al., 2011). The final unification of East and West Gondwana in the late Cryogenian – early Ediacaran (650-580 Ma) was achieved by collision of the proto-ANS with the Sahara Metacraton to form the East African Orogen (EAO) (Stern, 1994; Kusky et al., 2003; Stern and Johnson, 2010; Johnson et al., 2011). The ANS was assembled during this event, and was further affected by intensive granitic magmatism, completing the cratonization of the shield (Johnson et al., 2011).

Fragments of pre-ANS basement and accreted island arcs are found in the northern part of the ANS in the Sinai, as four metamorphic massifs, separated by huge volumes of syn-to post-collision granitoids. The four massifs briefly described ahead are 1) the Sa'al-Zaghara, 2) the Taba-Elat, 3) the Kid and 4) the Feiran-Solaf complexes (Fig. 1). The intermediate-silicic **Sa'al-Zaghara Complex** metavolcanics (Shimron et al., 1993) are thought to have erupted during pre-ANS (Stenian) times (Be'eri-Shlevin et al., 2012). These rocks are greenschist facies metamorphosed, though a narrow belt of migmatites exists in the centre of the complex. The main post-foliation deformation is ENE–WSW folding associated with NNW-wards thrust stacking, followed by intrusion of diorites and NW-SE gentler refolding (Fowler et al., 2015). The **Taba-Elat Complex** consists of the 800–820 Ma metapelitic Elat schists

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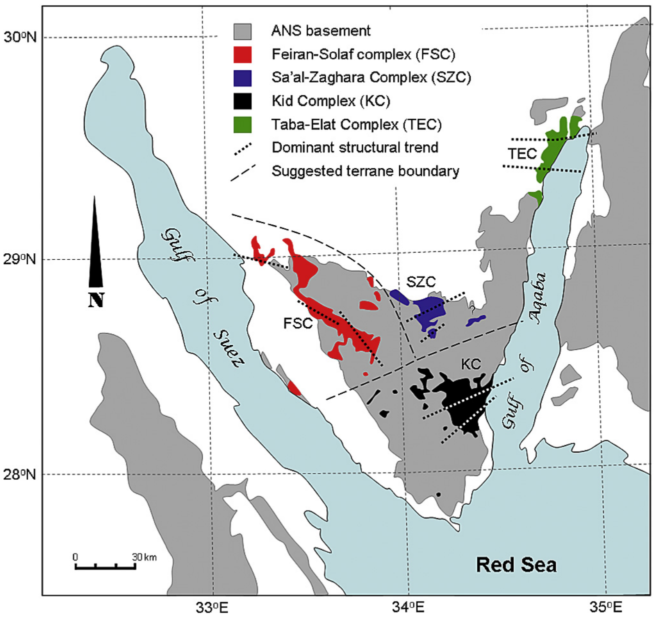

Fig. 1. Geological map of the Sinai Peninsula showing the four metamorphic complexes (Feiran-Solaf (FSC), Sa'al-Zaghara (SZC), Kid (KC) and Taba-Elat (TEC) Complexes). Also shown are the dominant structural trends in the four complexes, and proposed locations of terrane boundaries between the Sa'al-Zaghara, Feiran-Solaf and Kid Complexes (see text 5.9. and Fig. 15 for further explanation).

(Kröner et al., 1990; Eyal et al., 1992; Beyth et al., 2011), deformed and HT-LP metamorphosed during intrusion of the Taba and Fjord gneissic diorites and tonalites (Abu El-Enen et al., 1999, 2004). The foliated rocks were folded about ~E–W trending folds and intruded by the Elat granite gneiss at 740–744 Ma (Eyal, 1980; Cosca et al., 1999). The **Kid Complex** sediments and volcanics were probably deposited around 650 Ma (Bielski, 1982; Reymer, 1984). The metavolcanics in the northern part of the complex were HT metamorphosed and foliated during SSE-ward thrusting (Shimron, 1984; Abu El-Enen et al., 2003; Abu El-Enen, 2008; Fowler et al., 2010) or extension-associated magmatism (Reymer and Oertel, 1985; Brooijmans et al., 2003; Blasband et al., 2000). The southern half of the complex consists of low grade metavolcanics and metasediments (Shimron, 1983). The main structural trend is ENE–WSW. The **Feiran Complex**, which is the focus of this contribution, is dominated by high grade gneisses, migmatites, amphibolites, schists and orthogneisses of probable Cryogenian age (El-Gaby and Ahmed, 1980; Stern and Manton, 1987; El-Shafei and Kusky, 2003), with originally subhorizontal gneissic foliation, later folded about NW-SE trending folds (Abdel-Meguid, 1992; Fowler and Hassan, 2008; Abu-Alam and Stüwe, 2009). These recent works on the four complexes have attempted to lay the foundation of a tectonic model for the northern ANS.

The study area for this contribution, the Feiran-Solaf complex (FSC), has a number of structural aspects that set it apart from the other complexes. These aspects require explanation before a unifying tectonic model for the Sinai can succeed. For example, the stretching and flattening strains associated with the development of the gneissosity are more intense and penetrative in the FSC (Fowler and Hassan, 2008 – see notes below). Another characteristic is the dominant NW-SE structural trend in the FSC, compared to the *E*-W to ENE-WSW structural trends recorded in the other complexes (Fig. 1). This dramatic trend difference has obvious implications for the deformation kinematics and tectonic interpretations of the FSC. Some models have been suggested (El-Shafei and Kusky, 2003; Abu Alam and Stüwe, 2009) though details of the macroscopic structure have been unclear, disputed or ignored.

The aim of this contribution is to provide a clear description of the macroscopic folds and thrusts of the FSC, based on new data from five detailed transects across the complex. The thrust-fold relations are considered, then the relations between the mesoscale and macroscale folds in the area are explained, with the intention of determining which structural event(s) the macrofolds and thrusts belong to. A correlation of the deformation events of the FSC with those of nearby complexes is discussed, followed by an account of the tectonic implications of these conclusions. In the following text the geological characteristics of the FSC are described. The fold and thrust structure of the complex is then presented, followed by a discussion of the significance of the results for the tectonic history of the complex.

2. Geological characteristics

2.1. *The preserved sequence and its thickness*

The succession of lithologies in the Feiran and Solaf zones has been divided into formations by El-Gaby and Ahmed (1980). Their stratigraphy sequence began with the Feiran units, the lowest being the Nidia El-Samra Formation (2000 m), followed by the Aleiyat Formation (3000 m); overlain by the Solaf units, consisting of the El-Khali' Formation (1800 m), followed by the Um Tarr Formation (2000 m), and finally the El-Sheikh Formation (no thickness given). This arrangement gives a succession reaching about 9000 m in thickness. This stratigraphic scheme was revised by Ahmed (1981), who correlated the Feiran and Solaf formations. He correlated the Nidia El-Samra with the El-Khali'; and the Aleiyat with the Um Tarr plus El-Sheikh, resulting in the exposed stratigraphic thickness totalling about 5000 m.

2.2. *The main lithologies and their protoliths*

The most abundant lithologies in the Feiran zone are hornblende-biotite gneiss and biotite gneiss (Fig. 2a), passing downwards into granitic and migmatitic gneiss (Fig. 2b), hosting amphibolite, hornblende gneiss, calc-silicate gneiss and abundant pegmatite (Fig. 2b–d). There are also thick sills of gneissic diorite and granodiorite (Eyal et al., 2015) (Fig. 2e). The main Solaf rock units are gneissic diorite in the lower sections (Fig. 2f and g), overlain by hornblende-biotite gneiss, quartzofeldspathic granulite ('metapsammite') (Fig. 2h), and probable silicic metapyroclastics (Fig. 2i), succeeded by a calc-silicate gneiss/marble sequence (Fig. 2j).

There is disagreement on the protoliths of the FSC lithologies (Table 1). Calcareous sedimentary protoliths have been considered for the hornblende and biotite bearing gneisses, migmatites and calcsilicate rocks (El-Gaby and Ahmed, 1980; Soliman et al., 1988; Belasy, 1991; Kabesh et al., 2013), and sandstones for the quartzofeldspathic granulites. Thin lithological interlayering and the presence of cordierite, sillimanite and almandine garnet (Akaad et al., 1967; El-Shafei and Kusky, 2003; Abu Alam and Stüwe, 2009) support sedimentary origin. However, these characteristic phases are rare and recent workers have proposed a volcanic origin for the hornblende and biotite bearing gneisses, based on geochemical evidence (Stern and Manton, 1987; Abu Anbar and Abd El-Wahed, 2004; Abu El-Enen and Whitehouse, 2013). The amphibolites may have been sedimentary in origin (Akaad et al., 1967; El-Gaby and Ahmed, 1980), or were basaltic sills or flows (El Tokhi, 1992).

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