A Quantitative Structural Study of Late Pan-African Compressional Deformation in the Central Eastern Desert (Egypt) During Gondwana Assembly

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Abstract

The Arabian-Nubian-Shield (ANS) is composed of a number of island arcs together with fragments of oceanic lithosphere and minor continental terranes. The terranes collided with each other until c. 600 Ma ago. Subsequently, they were accreted onto West Gondwana, west of the present River Nile. Apart from widespread ophiolite nappe emplacement, collisional deformation and related lithospheric thickening appear to be relatively weak. Early post-collisional structures comprise not only extensional features such as fault-bounded (molasse) basins and metamorphic core complexes, but also major wrench fault systems, and thrusts and folds. The Hammamat Group was deposited in fault-bounded basins, which formed due to N-S to NW-SE directed extension. Hammamat Group sediments were intruded by late orogenic granites, dated as c. 595 Ma old. A NNW-SSE-oriented compression prevailed after the deposition of the Hammamat Sediments. This is documented by the presence of NW-verging folds and SE-dipping thrusts that were refolded and thrusted in the same direction. Restoration of a NNW-SSE-oriented balanced section across Wadi Queih indicates more than 25% of shortening. Transpressional wrenching related to the Najd Fault System followed this stage. The wrenching produced NW-SE sinistral faults associated with positive flower structures that comprise NE-verging folds and SW-dipping thrusts. Section restoration across these late structures indicates 15–17% shortening in the NE-SW direction. At a regional scale, the two post-Hammamat compressional phases produced an interference pattern with domes and basins. It can be shown that the Najd Fault System splays into a horsetail structure in the Wadi Queih area and loses displacement towards N and NW. The present study shows a distinct space and time relationship between deposition of Hammamat Group/late-Pan-African clastic sediments and late stages of Najd Fault transpression. Therefore, the Hammamat sediments do not represent the latest tectonic feature of the Pan-African orogeny in the ANS. The latest orogenic episodes were the two successive phases of compression and transpression, respectively. It is speculated that extension during (Hammamat) basin formation was sufficiently effective to reduce the thickness of the orogenic lithosphere until it became gravitationally stable, and incapable of further gravitational deformation.

Key words: Pan-African, Arabian-Nubian Shield, section restoration, late-orogenic structure, transpression.

Introduction

Whereas the Arabian-Nubian Shield is generally accepted as an example of an accretionary orogen, which developed from an assemblage of mostly intra-oceanic magmatic arc terranes with subordinate continental terranes (e.g., Gass, 1981; Kröner, 1985; Stern, 1994), there is still no general consensus on the evolution from the accretion to the subsequent cratonization during the final collision between East and West Gondwana. An early review by Stern (1985) stressed the extensional component of transform faulting at this stage, whereas later models (O’Connor, 1996; Fritz et al., 1996; Smith et al., 1999) viewed the orogeny as being dominated by transform or transpressional processes. This is in contrast to other models of early convergence and collision, followed by late orogenic extension or escape (Burke and Sengör, 1986; Stern, 1994; Blasband et al., 2000). Recently, Fowler and El Kalioubi (2004) developed a further model that stresses nappe transport during gravitational collapse accompanied by tectonic squeezing as the dominant process to explain the observed deformational sequence.
In general, the processes involved in convergence include components of pure shear compression and simple shear wrenching, i.e., transpression, which can lead to lithospheric thickening and subsequent re-adjustment of lithospheric thickness to normal and potentially stable conditions. Apart from erosion and associated isostatic re-equilibration, such re-adjustment may be achieved by tectonic processes, in particular extensional collapse (e.g., Dewey, 1988). This late orogenic stage of gravitational collapse is generally regarded as the final episode of orogenic deformation (Dewey, 1988; Blasband et al., 2000). However, during the last decade, there is growing evidence from the northwestern part of the Arabian-Nubian Shield, along the suture between East and West Gondwana, that gravitational collapse is followed by further orogenic deformation, which is mostly compressional or transpressional. This late-orogenic deformational sequence has become well-established qualitatively (e.g., references in Table 1). However, the bulk strains associated with these deformation events has not yet been properly quantified. Therefore, the present work first establishes the late orogenic structural evolution of a key region in detail and then estimates the bulk strains. The example presented here is from a Hammamat Basin near Wadi Queih, near the termination of a major, regional transform zone in Egypt, the Najd Fault System (Stern, 1985; see Fig. 1).

Regional Geology

The Arabian-Nubian-Shield (ANS) is composed of a number of island-arc terranes together with fragments of oceanic lithosphere and minor continental terranes. Accretion and collision established two tiers of orogenic rocks (Bennett and Mosley, 1987). The upper tier is characterized by sequences of low metamorphic grade with their primary textures still discernible. The lower tier is composed of gneissic rocks with relatively higher metamorphic grade but with similar geochemical characteristics to those of the upper tier. Primary contact relationships within and between the tiers are rarely preserved due to intense faulting and shearing. Hermina et al. (1989) and Said (1990) provided comprehensive descriptions and references, which are briefly summarized here.

The ANS and the Eastern Desert in particular are known for numerous well-preserved ophiolite fragments with sequences from layered gabbros, sheeted dykes, pillow lavas, to black cherts (Shackleton et al., 1980; Kröner, 1985; Kröner et al., 1987; Johnson and Woldehaimot, 2003). Even more ubiquitous are bodies of ultramafic rocks. These ophiolite fragments represent remnants of oceanic lithosphere, which are around 800 Ma old. They are presently preserved as parts of tectonic mélanges or as kilometre-scale nappes. Stratigraphically above these ophiolites occur andesitic volcanic sequences, often as pillow lavas, and related volcaniclastic rocks. Eventually, the volcanic rocks evolve with time towards more felsic, sometimes even rhyolitic compositions. Sedimentary rocks are subordinate, with mostly clastic sequences and rare BIF, and carbonates. All of these upper tier rocks were weakly metamorphosed (greenschist, locally amphibolite grade), prior to the deposition of a further volcanic sequence, the Dokhan volcanics of mostly andesitic and rhyolitic composition. The Dokhan volcanics are overlain by molasse-type clastic sedimentary sequences of the Hammamat Group and felsic volcanic rocks, which may be both extrusive (ignimbrites) or intrusive at a shallow level. The post-ophiolite evolution of volcanic sequences is accompanied by compositionally related plutonic rocks, which evolved from calc-alkaline compositions (gabbro, diorite, granitoids) to alkaline granites. Frequent post-tectonic, alkaline granites and dyke swarms, which intruded c. 600 to 550 Ma ago, represent the latest rocks of the orogen.

Although the plutonic rocks are relatively more frequent in the lower tier, other rock types like ophiolitic gabbro and ultramafic rocks, calc-alkaline gabros, granitoids, and psammitic sedimentary rocks have also been identified as protoliths within the gneissic sequence. Since these rock types are similar in composition to the upper tier rocks, it has been argued that they are time-equivalent with the upper tier sequences. Recent radiometric work provided evidence for such a view in some places (e.g., Gabal Silbai, Bregar et al., 2002; location 7 on Fig. 2). However, in other places, gneisses contain fragments of a pre-ophiolite (continental) crust, for example at the Meatiq dome (Loizenbauer et al., 2001, location 5 on Fig. 2).

Tectonic Evolution

The terranes collided with each other and were subsequently accreted onto West Gondwana, or the East Sahara Craton, west of the present River Nile, until c. 600 Ma ago (see Stern, 1994; Unrug, 1997; Johnson and Woldehaimot, 2003, and references therein). Apart from widespread ophiolite nappe emplacement (e.g., Shackleton et al., 1980), collisional deformation and related lithospheric thickening appear to be rather weak (e.g., Shackleton, 1986; Loizenbauer et al., 1999; Fritz et al., 2002). For example, in the whole of the northern part of the ANS no traces of high-pressure metamorphic assemblages have yet been found (e.g., Stern, 1994). Early post-collisional structures comprise extensional features such as fault-bounded (molasse) basins.
(Grothaus et al., 1979; Osman et al., 1993; Rice et al., 1993; Warr et al., 1999) and metamorphic core complexes (Sturchio et al., 1983; Fritz et al., 1996; Blasband et al., 2000), but also major wrench fault systems (Stern, 1985; Sultan et al., 1988; O’Connor, 1996; Abdelsalam et al., 1998) and thrusts and folds (Greiling et al., 1994; Fowler and El Kalioubi, 2004). Hammamat Group sediments are intruded by late orogenic granites, dated as c. 595 Ma old (e.g., Ries et al., 1983; Willis et al., 1988). Figure 1 shows the regional tectonic features of the ANS as the northern part of the East African Orogen between East and West Gondwana, respectively. It also includes some of the important structures of the ANS, which are relevant for the understanding of the late Pan-African orogenic history. In particular, the complex Najd Fault System of NW-SE-trending, sinistral wrench faults dominates the northern ANS (Stern 1985). Detailed studies at the NW tip of this wrench system in Egypt showed considerable NE-SW compression and NW-SE extension after the deposition of terrestrial, coarse- to fine-grained clastic sequences, resembling molasse-type deposits (see Table 1).

The territory from Quseir in the east to Wadi Hammamat in the west (see Fig. 2) has been the topic of numerous studies and is recognized as a classic section through the Pan-African basement (e.g., Hume 1934, 1937; Ries et al., 1983; Sturchio et al., 1983; Stern, 1985; El-Gaby et al., 1988; Sultan et al., 1988; Fritz et al., 1996). While Stern (1985) pointed out interrelationships of transform faulting and extension, Fritz et al. (1996) and Fritz and Messner (1999) interpreted the structures to have originated during orogenic compression or convergence. Detailed structural studies in the Wadi Queih Basin (Abdeen and Warr, 1998) demonstrated a time sequence from basin formation by extension to (orthogonal) NNW-SSE compression and subsequent transpression. Based on these qualitative and directional data, detailed cross-sections parallel with the principal compression directions have been constructed and are graphically restored here in order to help quantify the deformation. The results, together with published and unpublished information from the adjacent areas are then used to discuss the late Pan-African tectonic evolution in the wider context of orogenic evolution and Gondwana.
assembly. Accordingly, the geology of the Wadi Queih area is presented first and then the evolution of the surrounding basins of comparable tectonic setting is discussed.

**The Wadi Queih Area**

*Geology and structural evolution*

The structural geological map (Fig. 3) shows the exposed part of the Hammamat Group in the Wadi Queih area to be juxtaposed to the NE and SW against Cainozoic sedimentary successions along normal faults (Fig. 3). It is only the northern basin margin, where a primary, unconformable contact between the underlying Dokhan volcanics and the Hammamat sequence is preserved. The basal part of the Hammamat sedimentary succession consists of several tens of metres of a coarse, pebble to cobble basal conglomerate, which contains fragments of Pan-African rocks such as metavolcanic, related metasedimentary, and plutonic rocks, including undeformed, pink, younger granites, which are regarded as belonging to the early post-collisional, alkaline granites (e.g., Hassan and Hashad, 1990). The basal conglomerate is overlain by a sequence, which generally fines upwards and contains major depositional cycles in the order of a hundred metres thick and subcycles with several metres in thickness (El-Taky, 1988). The finer-grained parts of these cycles contain rain-drop prints and mud crack polygons (Abdeen et al., 1997), which indicate subaerial conditions during deposition. Also the upper, primary contact against “felsite” may suggest subaerial deposition.

<table>
<thead>
<tr>
<th>Area (see Fig. 2)</th>
<th>Extension direction during basin formation</th>
<th>Early shortening</th>
<th>Strike-slip (sinistral) and late shortening (transpression)</th>
<th>References</th>
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<tr>
<td>Wadi Meesar</td>
<td>NNW-SSE</td>
<td>-</td>
<td>-</td>
<td>Osman (1996)</td>
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<tr>
<td>Wadi Zeidun</td>
<td>NNW-SSE</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Wadi Hammamat</td>
<td>NNW-SSE</td>
<td>subordinate</td>
<td>NE-SW (SW, NE-thrusts)</td>
<td>de Wall et al. (1998), Fowler and Osman (2001), our data</td>
</tr>
<tr>
<td>Um Had</td>
<td>unknown</td>
<td>NNW-SSE (NW-thrusts)</td>
<td>NE-SW (NNW-SSE folds)</td>
<td>Fowler and Osman (2001)</td>
</tr>
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<td>Um Effein</td>
<td>?</td>
<td>subordinate</td>
<td>NE-SW</td>
<td>de Wall et al. (1998)</td>
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<tr>
<td>Um Esh</td>
<td>NW-SE</td>
<td>NNW-SSE</td>
<td>NE-SW</td>
<td>Fowler (2001), Loizenbauer et al. (2001)</td>
</tr>
<tr>
<td>Um Seleimat Fawakhir</td>
<td>NW-SE</td>
<td>NNW-SSE</td>
<td>NE-SW</td>
<td>Fowler and El Kalioubi (2004)</td>
</tr>
<tr>
<td>Gabal Meatiq</td>
<td>NW-SE</td>
<td>NNW-SSE</td>
<td>ENE-WSW (NNW-SSE folds)</td>
<td>Sturchio et al. (1983)</td>
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<td>Wadi Kareim</td>
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<td>NW-SE</td>
<td>NE-SW</td>
<td>Fritz and Messner (1999)</td>
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<td>Gabal El Sibai</td>
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<td>NW-SE</td>
<td>NE-SW</td>
<td>Fritz and Messner (1999)</td>
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<tr>
<td>El Shush-Umm Gheig</td>
<td>NW-SE</td>
<td>NW-SE</td>
<td>NW-SE</td>
<td>Kamal El Din et al. (1992)</td>
</tr>
</tbody>
</table>

*Table 1. Compilation of late Pan-African structural episodes, starting from syn-Hammamat Group extension and basin formation to subsequent compressional and transpressional episodes. The time sequence is from left to right (latest). Location numbers are also shown on the geological map of figure 2.*
Late Pan-African compressional deformation during Gondwana assembly, Egypt

Table 2. Numerical values on the section restorations of figures 5 and 8.

<table>
<thead>
<tr>
<th></th>
<th>Late-stage transpression</th>
<th>Early shortening, NNW-SSE (Fig. 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NE-SW shortening (Fig. 8)</td>
<td>section A - A’</td>
</tr>
<tr>
<td></td>
<td>section B - B’</td>
<td>section C - C’</td>
</tr>
<tr>
<td>Deformed length</td>
<td>4.25 km</td>
<td>5.95 km</td>
</tr>
<tr>
<td>Restored length</td>
<td>5.10 km</td>
<td>7.00 km</td>
</tr>
<tr>
<td>Shortening</td>
<td>17%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Of an ignimbrite, which contains fragments of Hammamat sediments at its base (Abdeen et al., 1991). The structural geological map also shows the trend of (early) folds, as E-W to ENE-WSW (Fig. 3). These folds are associated with early thrusts (Abdeen et al., 1992; Abdeen and Warr, 1998), and both these elements represent the effects of a common, compressive stress field (Fig. 4) that acted after basin formation and deposition of Hammamat Group sediments (see Abdeen and Warr, 1998, for further details).

The section subparallel with the major principal stress direction (Fig. 5a) shows the geometry of the thrusts and their relation with the early folds. The highest thrust (no. 1 on Fig. 5) represents also the oldest thrust, assuming a forward-propagating (towards NNW) thrust system. At a later stage, this thrust system also developed an out-of-sequence thrust (no. 3 on Fig. 5) in the SE of the area. This out-of-sequence thrust cut across the hangingwall of thrust number 1 and transported the Hammamat Group sequence over the pre-Hammamat metamorphic sequence, thus creating a window of Hammamat rocks. The primary contact, at the top of the Hammamat sequence is preserved as a weak erosional unconformity in the eastern part of the area (Fig. 3). There, thrust (no. 1) which bounds the Wadi Queih Basin sequence at its top is cutting across the felsite, up to 300 m stratigraphically above the base of the felsite. As can be seen from the section and the map (Figs. 3, 5), the thickness of the preserved felsite is decreasing towards south so that no felsite is preserved in the very south of the section, at the Hammamat window. As a consequence, thrust number 1 is drawn as a flat in the south, where it is probably following the top surface of the Hammamat sequence. This is consistent with the observation that the thrust is generally subparallel with the...
bedding in the Hammamat sediments. Towards the north, however, the thrust is ramping up into the felsite.

The early structures are overprinted by sinistral strike-slip faults (e.g., Um Kujura Wrench Fault, UKWF, Fig. 3) and related folds in NW-SE direction. The system of strike-slip faults in the western part of the area is clearly the NW tip of the UKWF, where displacement is distributed between minor faults (Fig. 3), similar to a horse-tail structure (e.g., Woodcock and Schubert, 1994). Together with the Eastern Wrench Fault (EWF, Fig. 3), the UKWF represents part of the NW tip of the orogen scale Najd Fault System (Stern, 1985; Sultan et al., 1988). The UKWF and EWF together with the associated folds indicate a transpressional stress field which is distinctly different from the earlier, NW-ward thrust-related stresses (Fig. 4). Fault data on the strike-slip faults may not be sufficient to determine the stress field related to this episode of deformation, since a reactivation of the strike-slip faults during extension cannot be excluded. As can be seen on the map (Fig. 3), some of the strike-slip faults, for example the EWF, are subparallel with younger normal faults (e.g., EQBBF on Fig. 3), and, therefore, likely to show both traces of strike-slip and normal faulting. As a consequence, additional information on the associated folds is used here. These folds show a consistent NW-SE trend on the map (Fig. 3), parallel with the folds and related linear data (fold axes, bedding-axial surface cleavage intersections) documented in the field (Fig. 6). In combination with fault data published by Abdeen and Warr (1998), the folds indicate a stress field with the major principal axis in a NE direction (Fig. 7). This direction, approximately normal to the fold axis and fault trends, is then used for the structural cross sections (Fig. 8).

Subsequent overprint by normal faults (e.g., faults nos. 4, 5 on Fig. 5a) can be related to Cainozoic extension. Although their displacement has been restored (see below), they are not considered or quantified further here.

Section balancing and restoration

The detailed sections on the thrust units of Wadi Queih Hammamat sediments and the surrounding rock units by Abdeen and Warr (1998) provide an opportunity to

Fig. 3. Structural geological map of the Wadi Queih area, redrawn from Abdeen and Warr (1998). For location see figure 2. Sections A–A’ and B–B’ are shown on figure 8, section C–C’ on figure 5.
quantify the deformation in this area (Figs. 5a, and 8 unrestored). Together with the data on strain/stress geometry discussed above and compiled in figures 4 and 7, they form the basis for the section balancing and restoration presented here. Original sections and restorations were drawn at a scale of 1:25,000. Figures 5 and 8 show a reduced, slightly simplified version. Since the topographic relief is low, mostly less than a hundred metres, the surface is drawn as flat. Earlier strain determinations by Abdeen and Warr (1998) showed considerable values of internal strain. However, they determined strain only from rare, fine-grained, incompetent beds (mudstones), which are not representative of the Hammamat sequence as a whole. Even in these incompetent beds a pervasive foliation is developed only at the axial surfaces of some tight folds. Pebble strains in coarse clastic, competent rocks are restricted to the vicinity of faults, where pebbles are faulted. Elsewhere, for example in the basal conglomerate at the northern margin of the Wadi Queih Basin and away from the faults, pebbles do not show any strain effects at all (our observation). Therefore, the strain data of Abdeen and Warr (1998) are taken as local, small-scale features, which are not representative of the Hammamat sequence as a whole. Even in these incompetent beds a pervasive foliation is developed only at the axial surfaces of some tight folds. Pebble strains in coarse clastic, competent rocks are restricted to the vicinity of faults, where pebbles are faulted. Elsewhere, for example in the basal conglomerate at the northern margin of the Wadi Queih Basin and away from the faults, pebbles do not show any strain effects at all (our observation). Therefore, the strain data of Abdeen and Warr (1998) are taken as local, small-scale features, which are not relevant at the map and section scales considered here. Following the general procedures outlined by Woodward et al. (1989), the youngest structural elements were restored first, which are the Cainozoic normal faults in figures 5 and 8. Subsequently, the elements of transpressional deformation were restored (Fig. 8) and, finally, those of the first, thrust-and-fold episode (Fig. 5).

Sections A–A’ and B–B’ (Fig. 5) were selected in order to restore the transpressional deformation, since they are approximately normal to the major principal stress direction (compare Fig. 7). In the first step, the reverse fault elements in ENE-WSW section, together with related folds, (which are associated with later wrench faulting), were restored. Late normal faults are related to Red Sea rifting (e.g., Khalil and McClay, 2002) and are not important here. The EWF, however, is related to the Pan-African wrenching. Since no compression effects across this fault have been observed in the field, no restoration was necessary. The restoration, therefore, represents exclusively the shortening across what is interpreted as a positive (half-)flower structure, which branches from the UKWF. For the fault block between the UKWF and the EWF a shortening of 17% and 15% can be shown for sections A–A’ and B–B’, respectively, using the line length at the base of the Hammamat Group sediments (Fig. 8, Table 2). The eroded and buried parts, respectively, can be reliably reconstructed by down-plunge projection, which is possible due to the gentle plunge of the structures towards the SE (Figs. 3, 5a).

Finally, section C–C’ (Fig. 5) was used to restore the earlier compressional strain. In order to exclude the effects of strike-slip deformation, without deviating too much from the principal strain direction, the section was drawn in between the EWF and the UKWF, respectively. The section is the most complete one for the thrusts in the area, since it includes the fault-bounded window of Hammamat Sediments in the SE of the area and a felsite inlier farther NW. In addition, it is only mildly overprinted by subsequent transpression and extension, respectively. For the restoration the primary, unconformable contact between the Dokhan volcanics and the overlying Hammamat Sediments at the NNW end of the section (C–C’, Fig. 5a) provided a reference, and the thrust contact between Hammamat Sediments and the overlying metavolcanics a datum. The results are shown in figure 5 with sequential restorations, starting from the present section (C–C’, Fig. 5a). The faults are numbered according to their relative age with 1 oldest and 5 youngest. The youngest faults (4, 5) are extensional and oblique to the section line (see map, Fig. 3). They are probably related to Cainozoic, Red Sea extension and their displacement is limited to a few tens of metres. Therefore, these faults are simply restored within the section line (Fig. 5b).

Shortening is restored, starting with the out-of-sequence thrust number 3 (Fig. 5c). Restoration of the folds proceeds along the sole thrust number 2 between the Dokhan Volcanics and the overlying Hammamat Sediments (Fig. 5d). The folds have earlier been mapped in detail and
documented in a number of field photographs, sketches, and cross-sections (Abdeen and Warr, 1998). Therefore, their geometry can be reliably reconstructed, as shown by a form line in the sections in figure 5 (a–c). Similar to the procedure used in restoring the sections on figure 8 (above), the length of the form line at or closest to the bottom of the Hammamat sequence was determined. However, the felsite within the Hammamat Sediments has not been restored since the displacement along its boundaries cannot be quantified reliably. The contact may be a thrust as is shown on the map (Fig. 3), but it may also be an intrusive contact, which is only slightly overprinted. Since the lateral extent of the fault-bounded felsite body is limited, the displacement distance is regarded here as small. As the last step, the thrust fault number 1 between the Hammamat Sediments and the overlying metavolcanic rocks is restored (Fig. 5e). The section restoration indicates 25% of shortening in the NNW-SSE direction (Fig. 5, Table 2). It should be noted, however, that this value is only a minimum figure. As is pointed out on the restored section (Fig. 5e), there are two areas, where section is missing. One area is that of the Hammamat window, where material was removed by erosion in the hangingwall of the out-of-sequence thrust number 3. The other area at the SSE margin of the section is unexposed so that the primary basin margin is buried and the primary basin width is unknown. Therefore, the transport distance of the metavolcanic thrust unit over the Hammamat Group sediments cannot be quantified any further. However, considering the difference in metamorphic grade from greenschist grade in the metavolcanic rocks to sub-greenschist-grade in the Hammamat Sediments (Abdeen and Warr, 1998), the displacement along the low angle thrust would be substantial.

Other Hammamat Group Basins and Regional Structure

Following up on the fundamental studies by Akaad and El Ramly (1958), Akaad and Noweir (1969), and Grothaus et al. (1979) on the distribution and sedimentary
environment of the Hammamat Group basins, modern studies cover now many of the late-orogenic sedimentary deposits (see reviews by Garfunkel, 1999; Blasband et al., 2000, and references in Table 1). Although most of these studies discuss some regional aspects, there is not yet any comprehensive study on the late Pan-African deformational pattern at the scale of the orogen. Therefore, it is attempted here to relate the structural results of the Wadi Queih area to the adjacent areas of the Eastern Desert, the Central Eastern Desert (CED) in order to investigate the regional-scale structural pattern and to test whether the post-Hammamat structural evolution seen at Wadi Queih is representative at the regional scale.

Regional post-Hammamat structures

As a first step, the structures are summarized in this chapter, whilst their genetic implications and tectonic significance are discussed in the following chapters. Table 1 gives a compilation of the most important post-depositional structural events and related features affecting the Hammamat Basins in the region. The basins and their structures are broadly grouped from west to east (Fig. 2). Although younger structures overprinted the regional pattern, careful inspection shows that the general strike of the Hammamat Group sequences in the Queieh-Hammamat region is broadly ENE-WSW. This is clear from Wadi Queih, which was discussed above, and is also clear from the maps of Wadi Kareim by Fritz and Messner (1999). Towards W, at Wadi Zeidoun and Wadi Meesar, the beds are, in general, gently dipping towards northerly directions (Osman, 1996). The situation in Wadi Hammamat is more complex, due to local, NW-SE trending folds and late tectonic granite intrusions (Fowler, 2001; Fowler and Osman, 2001, and references therein). However, at a regional scale, the strike of the northern margin of the Hammamat Group sediments is broadly E-W, with minor fold structures plunging SE (Fowler and Osman, 2001). As a consequence, the major Hammamat exposures can be seen as representing the cores of a set of broadly ENE-WSW oriented synclinal structures separated by anticlinal areas. This set of folds was subsequently overprinted by NW-SE trending strike-slip faults and associated transpression that produced some NW-SE to NNW-SE oriented folds (Fig. 2). The resulting interference pattern can be traced across the whole area between Wadi Hammamat in the west and Quseir in the east. Although there are minor differences in the orientation of the relevant structures, all the published data and the new data presented here are consistent and point to a regional significance of these structures. Based on these spatial correlations of structural elements, it is now possible to relate the structural evolution of the different areas with some confidence.

Regional structural evolution

Extension during basin formation is not well constrained but appears to have been in a general N-S to NW-SE direction (see Table 1). Subsequently, there is a compressional structural event with $\sigma_1$ broadly NNW-SSE, similar to the situation in Wadi Queih (Fig. 4). Thrusts and folds of this early compressional stage are overprinted by complex structural systems associated with a second compressional event. These second generation structures include large-scale wrench faults (broadly NW-SE) with associated positive (half-)flower structures, and folds with NW-SE to NNW-SSE-oriented fold traces. As in the Wadi Queih area a change in the direction of compression from NNW-SSE (Fig. 4) to NE-SW (Fig. 7) can be interpreted. This change in $\sigma_1$ direction may also be accompanied by a change in $\sigma_3$, direction from subvertical to subhorizontal, with a NNW-SSE direction, on the basis of the formation of strike slip faults ($\sigma_3$ vertical; compare Fig. 7). This $\sigma_3$ direction is broadly parallel with the late extension direction as observed, for example, at Um Esh (Fowler and El Kalioubi, 2004), the Meatiq and El Sibai domes, and the Fawakhir granite (Loizenbauer and Neumayr, 1996). As a whole, the local structural studies across the CED show a remarkably consistent orientation of early
post-Hammamat folds and thrusts indicating NNW-SSE compression, and subsequent folds oriented NNW-SSE, which are associated with extension parallel to their fold axial direction and with NW-SE-oriented sinistral wrench faults (Table 1). However, whilst the geometry of these structures and their relative time-sequence appears to be very similar, their absolute timing may be less consistent, as is discussed below.

Discussion

The Wadi Queih area

The Hammamat Group sediments exposed in the Wadi Queih area were deposited in a basin with a broadly E-W-trending northern margin. Basal conglomerates occur only in the NE part of the basin, along the exposed primary margin. This supports the model of NE-SW to E-W elongation directions of the Hammamat Basins proposed by Stern et al. (1988). The sediments, together with the other rock units in the Wadi Queih area were subjected to late Pan-African folding and thrusting processes as indicated by the presence of S and SE dipping low angle thrusts and NNW verging folds (Abdeen et al., 1992; Abdeen and Warr, 1998; Greiling et al., 1994). Subsequently, both the Hammamat sediments and the Pan-African thrust units were deformed by NW-SE oriented sinistral strike-slip faults that belong to the Najd Fault System in the CED (Stern, 1985). These faults are associated with sub-parallel high angle reverse faults that form a positive (half-)flower structure. They are interpreted to be a result of transpression following the Pan-African thrusting (Abdeen et al., 1992; Abdeen and Warr, 1998). Both of these structural episodes clearly post-date basin formation of Hammamat Group sediments, which until recently were presumed to represent the latest features of Pan-African orogeny. Section restorations show a modest amount of compression during both the first and second post-Hammamat deformation phases of >25% and 15–17%, respectively (Table 2, Figs. 5, 8). The restorations quantify the latest stages of a shortening deformation and do not take into consideration any earlier extension, which may have been associated with basin formation. However, they confirm that the Pan-African orogeny at Wadi Queih did not end with late-tectonic extension and collapse but with overall shortening.

Late orogenic basin formation and deformation in the Central Eastern Desert (CED)

The molasse type, Hammamat Group sediments comprise thick, epiclastic successions deposited by alluvial fan-braided stream systems in intermontane basins (Grothaus et al., 1979), and in down-faulted grabens that were trending NE-SW to E-W (Stern et al., 1988). Tectonic overprint of the basins started with granite intrusions at c. 595 Ma ago (Ries et al., 1983) and lasted until c. 580 Ma ago (Loizenbauer et al., 2001, and references therein). As is evident from the traces of major structures, broadly E-W-trending, post Hammamat folds cover the whole of the area, albeit with varying intensity (Fig. 2). This is also the case for NW-SE-trending folds and spatially related strike-slip faults. In addition, a number of studies showed that the time sequence may also be the same over the region (Table 2). In particular, the structural sequence in the Wadi Hammamat type area and adjacent areas (Fig. 2, locations 1–4) has been worked out by several independent groups, which all agree on a post-Hammamat-sediment structural sequence of ENE-WSW folds and thrusts overprinted by NNW-SSE-oriented folds, which are mostly associated with sinistral strike-slip faults in NW-SE direction (e.g., Mostafa and Bakhit, 1988; de Wall et al., 1998; Fowler and Osman, 2001; Fowler and El Kalioubi, 2004). However, there may also be local examples of a more complex or a diachronous evolution. A deformation phase with NW-SE extension at Fawakhir (Loizenbauer and Neumayr, 1996) may be related with the early extension during basin formation or, alternatively, with the late phase of NE-SW compression. The recorded extensional joints strike ENE-WSW. This strike direction is consistent with the regional $\sigma_1$ direction interpreted here (Fig. 7). Therefore, these extensional joints do not necessarily indicate a dominant
component of gravitational deformation, i.e., vertical $\sigma_1$, as envisaged by Loizenbauer and Neumayr (1996), but are interpreted here as related to the late stage of compression with a subhorizontal $\sigma_3$. This late phase of compression has been shown to be associated with NW-SE extension, normal to the shortening direction, by Fowler and El Kalioubi (2004).

In the Um Esh area (location 4, Fig. 2), subhorizontal folds with NW-SE stretching lineations (Fowler and El Kalioubi, 2004) have been correlated here with the late shortening episode (Table 1). However, this is in contrast with the interpretation of Fowler and El Kalioubi (2004) that this episode is associated with gravitational collapse. Further work will have to show, whether the simple correlation in table 1 is correct, or whether an additional episode of post-Hammamat deformation can be verified. This may also be true for the adjacent Gabal Meatiq area (location 5), where Loizenbauer et al. (2001) documented a tectonic history lasting for more than 200 Ma. These authors show only two deformational events after 620 Ma ago. Whilst the early one of N-S extension may be correlated with the basin formation, the second one is similar to the late stage of transpression. However, there appears to be no trace of post 620 Ma (post-Hammamat?) age NNW-SSE compression. Furthermore, there is not yet conclusive evidence, whether the Meatiq dome originated exclusively by gravitative rise of buoyant gneissic material as suggested by Fritz et al. (1996) and Loizenbauer et al. (2001), or exclusively as a dome in a compressional structural interference pattern (Fig. 2). Since these two extremes are not mutually exclusive, it may well be that these two mechanisms acted together.

In the area towards south, Fritz and Messner (1999) argued that the Wadi Kareim Basin (location 6, Fig. 2, Table 1) evolved in two steps. The early step was basin subsidence that was magmatically-induced when extraction of magmas from the lower crust led to compensating downward movement of cold, dense material. The second step was the modification of the basin geometry by strike-slip deformation (belonging to the Najd Fault System). The structural overprint appears to be more complex, when maps and sections from the Wadi Kareim Basin of Fritz and Messner (1999) are considered. There, an approximately E-W oriented syncline is obvious. This syncline is interpreted here as belonging to the system of early post-Hammamat folds which developed mainly after deposition by horizontal compressional forces, and prior to the strike-slip Najd Fault-related deformation.

A comparable structural sequence has also been observed SE of Wadi Kareim in the Sibai Gneissic Complex and at Umm Gheig (locations 7; 8; Ibrahim and Cosgrove, 2001). However, there, the directions of thrusts (WNW strike) and refolding folds (WNW-ESE) are 20° different, appearing to be rotated from the normal NW-SE directions in the other areas by anti-clockwise rotation. Such a rotation is consistent with the sinistral movement along the Najd Fault System (Stern, 1985). Therefore, the difference in the orientation of the structures in the Um Gheig area is interpreted here to be an effect of a latest increment of strike-slip along the Najd Faults. In that case, the wrench faulting has been substantial, in contrast to areas in the north, where the tips of wrench faults can be observed (Wadi Queih), or no wrenching at all (Wadi Hammamat, Atalla Zone). As a consequence, the strike-slip component appears to be subordinate in the NW (e.g., Wadi Hammamat, Atalla zone, de Wall et al., 1998), and more prominent towards SE (e.g., Um Esh, Fawakhir, Fowler and El Kalioubi, 2004; Loizenbauer and Neumayr 1996), and increasing even more farther towards SE, at El Sibai and Um Gheig (Kamal El Din, 1993; Ibrahim and Cosgrove, 2001; Bregar et al., 2002). A variation in strain intensity is also supported by the available quantitative data. 15–17% NE-SW directed shortening are documented in the Wadi Queih area as accompanying the transpression (Fig. 5, Table 2). A section across the Meatiq-Um Esh area shows c. 20% of shortening in the same direction (Fowler and El Kalioubi, 2004; Fowler, pers. comm. 2005).

Such strain variations and apparent disagreement as to the importance of strike-slip faulting can be resolved by the observation that the CED as a whole covers the NW-tip of the regional scale strike-slip faults (see Fig. 2). This information also solves the volume problem at the northern end of the Najd Fault System as discussed by Stern (1985). Displacement is simply dying out northwards with the large-scale faults fanning out into minor faults and associated folds. Together with the earlier compressional event, the Najd Fault episode represents the latest stages of Pan-African orogenic deformation. At a regional scale (Fig. 2), these two post-Hammamat compressional events produced an interference pattern with domes and basins. The structural basins are invariably cored by Hammamat sediments. It has to be noted that some of the basinal sediments are eroded and the basins described here may once have been contiguous, for example the Wadi Hammamat and Wadi Zeidun and Wadi Meesar Basins (see Fig. 2).

Late orogenic structural evolution at a regional scale

Earlier, Greiling et al. (1994) and Blasband et al. (2000) referred the basin formation to the phase 4 of the 5 phase tectonic evolution of mountain belts proposed by Dewey (1988). This phase comprises orogenic collapse and formation of extensional basins within the orogen and along its margins and leads to cooling and a stabilization of the newly formed lithosphere (see discussion by
In spite of wide-spread magmatism, the illite crystallinity data from the Hammamat Basins show that there was no pervasive heating throughout the crust. As can be seen from the available P and T data (Osman et al., 1993; Warr et al., 1999; Abdeen and Warr, 1998; Loizenbauer et al., 2001), subsequent erosion of the orogen prior to early Palaeozoic cover sedimentation was limited to a few kilometers. Apparently, earlier thinning, which ended with the formation of the Hammamat Basins had produced a crust of approximately “normal” continental thickness, which was relatively stable gravitationally, cooled relatively quickly and became strong. However, until the crust was completely consolidated, it suffered at least two episodes of (limited) compressional deformation with \( \sigma_1 \) in (sub-) horizontal orientations.

**Conclusions**

The Hammamat Group was deposited in intramontane basins formed due to N-S to NW-SE directed extension, differential uplift, and erosion of the Pan-African orogen, which provided clastic sediments to the basins. A comparison of post-Hammamat Group structural features in the basement areas west of Quseir and including the type area at Wadi Hammamat, shows a number of similarities. A NNW-SSE-oriented compression prevailed after the deposition of the Hammamat sediments. This is documented by the presence of NW-verging folds and SE-dipping thrusts that were refolded and thrusted in the same direction. Restoration of a NNW-SSE oriented balanced section across Wadi Queih indicates more than 25% shortening. Transpressional wrenching related to the Najd Fault System followed this stage. The wrenching produced NW-SE sinistral faults associated with positive (half-)flower structures that comprise NE verging folds and SW-dipping thrusts. Section restoration across these late structures in the Wadi Queih area indicates 15–17% shortening in the NE-SW direction. The Najd Fault System splays into a horsetail structure in the Wadi Queih area and loses displacement towards N and NW. At the Wadi Hammamat type area and at the Atalla Zone, wrench deformation becomes insignificant and shows that the Najd Fault System dies out also towards west. These strain variations are also supported by the available quantitative data. At a regional scale, the two post-Hammamat compressional phases produced an interference pattern with domes and basins.

The present study shows a distinct space and time relationship between deposition of Hammamat Group late-Pan-African clastic sediments and late stages of Najd System wrench faulting: Hammamat deposition is followed by two episodes of compression, the later of the two being related to Najd Fault transpression. Therefore,
the Hammamat Sediments do not represent the latest tectonic feature of the Pan-African orogeny in the ANS. It is speculated that extension and (Hammamat) basin formation was sufficiently effective so that it reduced the thickness of the orogenic lithosphere until it became gravitationally stable. Instead of further gravitational deformation, the latest orogenic episodes were the two successive phases of compression and transpression, respectively.

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