Post-collisional shortening in the late Pan-African Hamisana high strain zone, SE Egypt: field and magnetic fabric evidence

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Received 7 April 2000; accepted 8 September 2000

Abstract

The Hamisana zone (HZ) is one of the major high strain zones of the Pan-African (Neoproterozoic) Arabian–Nubian shield (ANS). It trends broadly N–S from northern Sudan into southeastern Egypt and meets the present Red Sea coast at ≈ 23°N. The HZ has been the subject of controversy with regard to its importance for the Pan-African structural evolution. Interpretations range from a suture zone, a regional shear zone, or a large-scale transpressional wrench fault system. In this study, we characterize the nature of the high strain deformation by applying the anisotropy of magnetic susceptibility method along with field and microstructural investigations. These investigations demonstrate that deformation in the HZ is dominated by pure shear under upper greenschist/amphibolite grade metamorphic conditions, producing E–W shortening, but with a strong N–S-extensional component. This deformation also led to folding of regional-scale thrusts (including the base of ophiolite nappes such as Gabal Gerf and Onib). Consequently, the high strain deformation is younger than ophiolite emplacement and suturing of terranes. A weak subsequent overprint was mostly non-coaxial. It took place under considerably lower temperature and led to a minor NE–SW-trending, dextral wrench fault. Although it is of only local importance this fault may be itself a conjugate relative to the prominent NW–SE-trending sinistral Najd faults in the northern ANS. Therefore, the HZ is dominated by late orogenic compressional deformation and cannot be related to either large-scale transpressional orogeny or major escape tectonics. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Hamisana zone; Arabian–Nubian shield; Late-orogenic compression; Magnetic susceptibility

1. Introduction

The Pan-African orogenic cycle has long been recognized as a period of major crustal accretion, where continental, island-arc, and oceanic terranes were brought together to form the crystalline basement of the African continent as part of a late Neoproterozoic supercontinent (Unrug, 1997, for review). Whereas some parts of the Pan-African orogen are characterized by continental collisional tectonics (Burke and Sengör,
During the last two decades, the Arabian–Nubian shield (ANS), the northeastern part of Africa–Arabia, has been established as a typical example of an accretionary orogen with lateral accretion and suturing (Gass, 1981; Kröner, 1985; Kröner et al., 1987; Stern, 1994). In the course of orogenic activity, numerous sutures and other major deformational zones originated all across this shield. Subsequent to the assembly of terranes, late deformation zones developed as the expression of lateral escape tectonics or other transtensional or transpressional episodes during the final stages of continental crust formation (Burke and Şengör, 1986; Stern, 1985, 1994; Johnson and Kattan, 1999). Contrasting models of transpressional orogeny (Sanderson and Marchini, 1984) have been proposed for the ANS (O’Connor et al., 1994; Abdelsalam et al., 1998), some of which relate terrane assembly to a single, major event of transpression.

In order to distinguish between these models, it is essential to re-examine the evolution of the orogenic structures in the ANS. Towards that aim, the present authors studied a major Pan-African deformational zone, the Hamisana zone (HZ), which is exposed in the Red Sea Hills of southeastern Egypt and northeastern Sudan (Fig. 1). The N–S-trending HZ is spectacularly visible on satellite images, where it can be traced for more than 300 km (Miller and Dixon, 1992). It is parallel with a zone of similar size on the Sudan–Ethiopia border, the Baraka zone (Dixon et al., 1987) and the less prominent Oko zone, which is located 100 km to the east/southeast of the HZ (Abdelsalam, 1994, Fig. 1).

Well-defined ophiolites and ophiolite belts have been mapped on both sides of the HZ and interpreted as a suture zone between major Pan-African terranes. East of the HZ this belt was called the Onib-Sol Hamed suture (Fitches et al., 1983; Dixon et al., 1987; Kröner et al., 1987; Stern et al., 1989, 1990, Fig. 1). The HZ, cuts the Onib-Sol Hamed suture and is, consequently, younger. Although this structural relationship has been well documented (Stern et al., 1990; Miller and Dixon, 1992), a contrasting model of the HZ as a major transpressional zone during terrane accretion has been proposed recently, comprising...
a relatively simple evolution from oblique convergence and suturing towards transpressional shear zones as a final stage of orogeny (O’Connor et al., 1994; Nasr et al., 1998; Smith et al., 1999).

As it is clear from this controversy, the time sequence and the general tectonic significance of these structures at a regional scale are not yet fully known. Based on recent mapping by the Egyptian Geological Survey, a part of the HZ (Figs. 1 and 2) was studied in the field and sampled for detailed structural studies. In addition to the usual structural geological investigations, the anisotropy of magnetic susceptibility (AMS) of the rocks in the HZ was studied. This latter method has been shown to be most sensitive to document the type and style of deformation even in places where no or hardly any deformation is visible macroscopically (Tarling and Hrouda, 1993). In that way, it is possible not only to characterize the deformation within the HZ but also to determine a subsequent overprint, which may escape detection by other methods. This application of the AMS method is the first major study of this kind in the ANS, apart from minor pilot studies (Greiling, 1997; de Wall et al., 1998, 1999; El Eraki and Greiling, 1998).

2. Evolution of the Arabian–Nubian shield and the Hamisana zone

2.1. Arabian–Nubian shield

The ANS evolved during the Neoproterozoic, Pan-African episode from a number of island-arc and minor continental terranes. They were accreted onto an East Sahara craton, which was previously affected in the Neoproterozoic and is now mostly covered by Phanerozoic sediments and is presumed to extend westwards from the Keraf suture (Abdelsalam et al., 1998). Lithologically, this tectonic evolution from oceanic lithosphere to island-arcs and continental lithosphere is well documented by the rock sequences building up the ANS: ophiolite suites, ocean floor (cherts) and passive margin (quartzofeldspathic and carbonated) sedimentary sequences, island arc, calc-alkaline igneous rocks, both intrusive and supracrustal, together with “syn-orogenic” sediments derived from these igneous rocks. Finally, syn-collisional and late- to post-tectonic magmatic activity produced some gabbroic but mostly granitoid intrusives and related volcanics. Late-orogenic, molasse-type sediments are only found in some intramontane basins, mostly in the NW of the ANS (Akaad and El Ramly, 1958; Osman et al., 1993). Structurally, at least parts of the tectonic evolution are also documented, for example subduction-related tectonic mélangé or fossil accretionary prism – (Wadi Ghadir; El Sharkawy and El Bayoumi, 1979; Shackleton et al., 1980) or early, ‘syn-island-arc’ deformation (Wadi Hafafit; El Ramly et al., 1984; Rashwan, 1991). Subsequent structures comprise both extensional features such as fault-bounded (molasse) basins (Rice et al., 1993) and metamorphic core complexes (Sturchio, et al., 1983; Fritz et al., 1996), large-scale thrusts (Ries et al., 1983; El Ramly et al., 1984), and major wrench fault systems (Stern, 1985; Sultan et al., 1988; Shimron, 1990; O’Connor et al., 1994; Abdelsalam et al., 1998; Greiling et al., 1998). Apparently, both extensional and compressional deformation, as they are documented in the ANS, represent post-collisional structures and are succeeded by and associated with wrench faulting (Abdeen et al., 1992; Greiling et al., 1994; Johnson and Kattan, 1999).
The most important of such faults in the north-western ANS are the NW–SE-oriented Najd system, including Wadi Kharit-Wadi Hodein fault zones, the broadly N–S-oriented HZ and the Oko Shear zone (Abdelsalam, 1994; Kröner et al., 1987; Stern, 1985, 1994; Greiling et al., 1994; Fig. 1).

2.2. The Hamisana zone

The northern part of the HZ cuts across sequences of gneisses, which are structurally overlain by ophiolitic nappes and intruded by a number of granitoids (EGSMA, 1999, Fig. 2). The probably oldest rocks exposed are a sequence of variegated gneisses, containing both metasedimentary and igneous components. The latter comprise both mafic, amphibolitic layers as well as felsic, fine-grained and coarse-grained para- and ortho-gneisses and, locally, close to younger intrusives, also migmatites. The gneissic sequences form a basal tier (tier 1, Bennet and Mosley, 1987; Greiling et al., 1994) and are structurally overlain by a number of major nappe units, which are dominated by ophiolite fragments (Gerf nappe, Kröner et al., 1987) and form a second tier (tier 2). Both these major units are folded and intruded by a number of syn- to late-tectonic granitoid plutons as well as some dyke swarms (Stern et al., 1990; Miller and Dixon, 1992).

The ophiolites are c. 730 Ma old (Zimmer et al., 1995) and the tier 1 gneisses originated about c. 660 Ma ago, during and after the formation and collision of island-arcs (Stern et al., 1989). Activity along the HZ may have begun as early as 660 Ma ago, culminating in intense thermal activity 550–580 Ma ago (Stern et al., 1989). undeformed, post-tectonic granites dated at 510 Ma ago define an upper age limit of the deformation (Stern et al., 1989). Whereas tiers 1 and 2 are generally flat-lying at a regional scale, they are overprinted by the N–S-trending HZ, up to a few tens of km wide, where foliations are generally steep (Fig. 3) and strain appears to be higher and deformation more complex than in the surrounding domains (Stern et al., 1990; Miller and Dixon, 1992).

An apparent offset of the Onib-Sol Hamed suture zone to the east of the HZ against the Allaqi suture zone to the west led earlier authors to presume a horizontal, strike-slip movement along the HZ (Kröner et al., 1987; Stern et al., 1989). However, recent results from the Allaqi suture zone (Sadek, 1995; EGSMA, 1996; our observations) show that this suture is curving from the Wadi Allaqi towards the southeast and that related ophiolite fragments occur to the south of the Allaqi-Heiani Belt of ophiolite nappes, which was earlier thought to represent the suture zone. Therefore, an alternative location for the Allaqi suture is tentatively shown on Fig. 1.

3. Field observations

The gneissic rocks of the HZ and the surrounding area are characterized by a distinct metamorphic banding (s1), which is particularly clear between felsic or intermediate layers intercalated with amphibolite (Fig. 9(A)–(C)). On both sides of the HZ this banding is flat-lying at a regional scale with gentle folds at km-scale wavelengths (EGSMA, 1999).

Towards the HZ, the N–S-trending folds become tighter, so that the metamorphic banding

![Fig. 3. Schematic section across the HZ (a) and structural field data from the study area, (b) orientation of foliation showing a girdle distribution. The best-fit great circle and its pole (p-pole) are shown, (c) orientation of mineral and stretching lineations. Diagrams (b) and (c) are equal area lower hemisphere stereonets.](image-url)
dips more steeply (Fig. 9(A)–(B)). At the western margin of the HZ, the orientation of the metamorphic banding rotates successively from moderate to steep westerly dips to almost vertical at the HZ itself. There, a zone c. 5–10 km wide is characterized by steep to vertical dips, striking broadly N–S (Figs. 2 and 3(b)), with subhorizontal mineral and stretching lineations in N–S directions (Fig. 3(c)). At lithologic contacts in the HZ, a penetrative foliation (s2) can be observed, which cuts the metamorphic banding at a low angle. Towards east, the dip shallows again and shows a transition to flat-lying ophiolite nappes, including the Wadi Onib ophiolite fragment (Fitches et al., 1983), overlying granitoid and other gneissic sequences.

Consequently, the HZ appears as a major N–S-trending, upright antiformal structure, with a high strain zone broadly along and parallel with its axial surface. In some parts, minor folds with amplitudes and wavelengths in a cm-scale around N–S-trending axes can be recognized (El Kady, unpublished Diploma thesis, and own observations). Apparently, the foliation (s2) is the axial surface cleavage of these folds.

Locally, a subhorizontal to moderately plunging N–S lineation is well developed, marked by stretched plagioclase and a hornblende mineral lineation in the amphibolites (Fig. 9(D)) and metavolcanic rocks and by a quartz and feldspar stretching lineation in the orthogneisses. The lineation orientation forms a well-defined cluster on the stereonet with a mean of 354°05 (Fig. 3(c)). Its significance is discussed in the context of the microstructural observations.

4. Magnetic fabric analyses

4.1. Anisotropy of magnetic susceptibility (AMS) methods

Anisotropic magnetic behaviour of low field susceptibility has been established as a method for the detection of fabric anisotropies (Tarling and Hrouda, 1993; Borradaile and Henry, 1997). The advantage of this method, compared to conventional macroscopic and microscopic and X-ray diffraction techniques, is its high sensitivity to weak differences in the crystallographic orientation of paramagnetic minerals (such as phyllosilicates and amphiboles) and in the grain shape and distribution of ferrimagnetic minerals (magnetite). AMS studies have been found to be particularly useful in constraining very low strains both related to regional deformation events (Borradaile, 1988) and pluton emplacements (Bouchez et al., 1990, 1997). In deformation fabrics there is a correlation between the rock foliation and the magnetic foliation and rock lineation and magnetic lineation, respectively (Tarling and Hrouda, 1993; Siegesmund et al., 1995).

For detailed magnetic fabric analyses by the AMS method (Tarling and Hrouda, 1993) various rock types from 35 sites distributed over an area of approximately 500 km² were sampled (Fig. 2). Handspecimens were oriented in the field and from every sample up to 6 AMS standard cylinders (1 in. in diameter, 0.8 in. in height) were drilled in the laboratory. A total of 109 specimens were investigated. The measurements were performed in low fields (300 A/m) with a Kapppabridge (KLY-2) manufactured by AGICO (Jelinek, 1980). Thermomagnetic investigations for magneto-mineralogy used a CS-2 furnace apparatus of AGICO (Hrouda, 1994).

The magnetic susceptibility (κ) is a material property which describes the ability to acquire a magnetization (M) in an applied field (H). As both M and H expressed in SI units (Système Internationale), are measured in A/m, the constant κ is dimensionless. The AMS is a second rank tensor which is expressed by the AMS-ellipsoid with principal axes κₘₐₓ, κₐₘᵢₙ, κᵢₙₜ. The volume susceptibility (κ = (κₘₐₓ + κᵢₙₜ + κₐₘᵢₙ)/3), shape and anisotropy factors are calculated from directional measurements taken in different sample positions using the standard software for the KLY-2 equipment (Hrouda et al., 1990). The shape of the AMS-ellipsoid is described by the parameter T: (2(ln κₐₘᵢₙ − ln κₘₐₓ)/(ln κₘₐₓ − ln κₐₘᵢₙ − 1) which is >0 to +1 for oblate, 0 for neutral and <0 to −1 for prolate geometry (Jelinek, 1981). The anisotropy of the ellipsoid is expressed by the P' value, the so-called corrected anisotropy factor: exp (2(ln κₘₐₓ − ln κ)² + 2(ln
Table 1
Magnetic data for the individual samples

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<th>$\alpha_{95}^c$</th>
<th>Fol$^c$</th>
<th>$\alpha_{95}^c$</th>
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<td>298/61</td>
<td>–</td>
<td>0.83</td>
<td>1.15</td>
</tr>
<tr>
<td>P 40</td>
<td>paragneiss</td>
<td>4</td>
<td>82</td>
<td>171/10</td>
<td>1.9</td>
<td>221/17</td>
<td>2.2</td>
<td>0.69</td>
<td>1.10</td>
</tr>
</tbody>
</table>

$\kappa_{ln} = \ln \kappa^2 + 2(\ln \kappa_{min} - \ln \kappa^2)^{1/2}$ (Jelinek, 1981). From the determined geographic orientation for the principal axes of the susceptibility ellipsoids, the mean values for the magnetic lineation and the magnetic foliation are calculated based on Fisher distribution analyses. The magnetic lineation refers to the direction of maximum susceptibility ($\kappa_{max}$), the direction of minimum susceptibility ($\kappa_{min}$) is the pole to the magnetic foliation plane. Directional data are presented in stereonets (Figs. 5 and 6(a) and (b)). All results of the AMS analyses are compiled in Table 1.

*a* $\kappa$ = volume susceptibility in $10^{-6}$ SI.

*b* Lin = trend and plunge of the magnetic lineation and $\alpha_{95}$ confidence angle.

*c* Fol = dip direction and angle of dip of the magnetic foliation and $\alpha_{95}$ confidence angle.

*d* $T$ = mean shape factor of the AMS-ellipsoid.

*e* $P$ = mean corrected anisotropy factor for the AMS-ellipsoid.
4.2. Volume susceptibility

In polycrystalline rocks as they are characteristic for the HZ the volume susceptibility is the sum of susceptibility and volume content of the various mineralogical components. Since different rock types occur in the HZ a strong variation in volume susceptibility due to their variations in mineral composition is observed. Lowest values are in the order of $10^{-5}$ SI for leucogranites, the highest susceptibilities exceed $5 \times 10^{-2}$ SI in magnetite-bearing amphibolites (Table 1). In the samples with low susceptibility, paramagnetic minerals such as biotite in the paragneisses and biotite schists and hornblende in the amphibolites are dominating the magnetic fabric. In the samples with higher susceptibilities ($\kappa > 10^{-3}$) the magnetic behaviour is determined by the ferrimagnetic mineral fabric. Thermomagnetic curves reveal a strong decrease in susceptibility at temperatures of 590°C indicating that the ferrimagnetic fabric is represented by pure magnetite (Fig. 4).

4.3. Orientation and interpretation of the AMS directional data

A compilation of the orientation of the AMS data from all samples measured is given in the stereographic projection in Fig. 5. The magnetic foliation poles ($\kappa_{\min}$) are distributed along a great circle, documenting a rotation of the foliation surfaces around a horizontal N–S trending axis ($\pi$-pole). This geometry is in agreement with the geometry of a regional-scale concentric fold structure with a horizontal, N–S trending $\beta$-axis (Fig. 3). The $\pi$-pole (002°/08°) constructed from the magnetic foliation poles is subparallel with the magnetic lineation (Fig. 5(b)) with a mean orientation of 179°/01°.

The general pattern of magnetic fabric correlates well with the field-measured foliation and lineation data, as presented in Fig. 3(b) and (c). However, whilst the lineations measured in the field appear to have a clear unimodal distribution with a single maximum around a horizontal mean, the magnetic lineations tend to scatter towards moderate to steep inclinations. The stronger scatter in the magnetic lineation data relative to the field data reveals that the fabric in the HZ is more complex than expected from the analysis of the field data alone. Therefore, we analyzed the AMS data in more detail: the directional data are presented in foliation and lineation maps, respectively, with added stereographic projections of the structural elements (Fig. 6(A) and (B)). In both maps, a subdivision into two structural domains is evident. In domain I, the magnetic foliation trends generally N–S. However, dip angles vary between 10° and 89°. The stereo
graphic projection exhibits a distribution of the magnetic foliation poles along a great circle with a nearly horizontal π-pole, which is trending N–S, and subparallel with the strike of the HZ. This pattern reflects the general geometry in the HZ and corresponds to the field observations (Fig. 3(b)). The magnetic lineations trend N–S with gentle to moderate plunges towards the S and N, respectively, but the lineations are generally steeper in the western part of the HZ. This orientation accords with the field data presented in Fig. 3(c), where the magnetic lineation is parallel with the best-fit π-pole for the magnetic foliation. So, generally, the magnetic fabric in structural domain I is symmetrical with a girdle distribution of the magnetic foliation around a N–S-trending axis, which is parallel with the observed lineation.

A second structural domain (domain II) forms a SW–NE trending sigmoidal trace across the HZ where the magnetic foliations and lineations are reoriented towards a NE–SW direction. The angle of plunge for the magnetic lineations is variable and ranges from low (03°) to high (70°) values.

4.4. Shape of AMS-ellipsoids

The AMS measurements provide detailed information on fabric anisotropies and give strain and mineralogical information in addition to conventional structural data (Borradaile and Henry, 1997). However, for a reliable interpretation of the magnetic fabric a detailed knowledge of the components of the rock fabric and their respective contributions to the final AMS values is necessary (Borradaile, 1988; Rochette, 1987). In the present study various rock types were investigated. As a consequence, a strong variation in shape (T) ranging between +0.88 and −0.56, and anisotropy (P') reaching from 1.02 up to 1.60 (Table 1) is observed. In the Jelinek-diagram (P' vs. T) (Jelinek, 1981) this variation is obvious for both structural domains (Fig. 7(a)). This may indicate a general fabric inhomogeneity for the samples from the HZ with both prolate (stretched: \( k_{\text{max}} > k_{\text{int}} > k_{\text{min}} \)) and oblate (flattened: \( k_{\text{max}} = k_{\text{int}} > k_{\text{min}} \)) subfabrics. However, it could also be a consequence of single crystal magnetic anisotropy of the paramagnetic mineral components. AMS in

![Fig. 6. (A) Magnetic foliation map and (B) magnetic lineation map, covering the same area as Fig. 2. Inset stereonets show the orientation means as calculated for each sampling site (data in Table 1). Note two domains (I and II, respectively), which are distinct by their fabric orientation.](image)
5. Microstructures

Rocks in the HZ are characterized by a metamorphic fabric developed under amphibolite facies conditions. Amphibolites and hornblende-bearing gneisses, derived from volcanic rocks and gabbros contain coarse-grained green hornblende, biotite, feldspar and quartz. In the amphibolites, pronounced linear as well as distinct planar fabrics occur, which are defined by elongated feldspar aggregates and the preferred orientation of hornblende (Fig. 9(D)). Aspect ratios for prolate feldspar porphyroclasts in amphibolite, with a well-developed linear fabric, reach up to 4.

Coarse-grained biotite and muscovite produce the metamorphic foliation in the orthogneisses and metagranitoids. Occasionally, a stretching lineation is marked by elongated quartz grains and ribbon quartz. Inclusions of a continuous mica foliation within large anhedral quartz grains and paramagnetic minerals is a function of single crystal anisotropy and degree of preferred orientation (Siegesmund et al., 1995; Hrouda et al., 1997). However, from Fig. 7 it is obvious that scattering of the shape factor values is indicated both in samples with low (mainly paramagnetic minerals) and with high (ferrimagnetic minerals) susceptibilities. Therefore, we conclude that beside mineralogical influences the observed variations in ellipsoid shape are related to differences in fabric geometry across the HZ. However, a significant relationship of the shape factors to a particular structural domain or a systematic variation in the shape along and across the HZ was not detected. In general, the AMS results agree with the field observations, where also variations in the rock fabrics have been detected.
irregular phase boundaries between quartz and feldspar indicate secondary grain growth (Fig. 9(E)). The quartz grains are overprinted by a subsequent deformation, which produced undulatory extinction and deformation bands.

In samples displaying a gneissic fabric, S–C geometries are observed, which are defined by elongated grains of quartz, mica or hornblende. In structural domain I, this fabric is not very pronounced and only occasionally a shear sense determination is possible. The angle between the oblique fabric (S) and the shear foliation (C) ranges between 30 and 45° and indicates a component of left-lateral shear for the ductile deformation (Fig. 9(E)).

In structural domain II the strain is concentrated within discrete micro-shear zones that can be observed locally between quartz and feldspar phase boundaries. In these zones, quartz grains show dynamic recrystallisation and anisometric subgrains with long axes oriented oblique (40°) to the shear zone boundaries (Fig. 9(F)). In the feldspar, sets of intracrystalline microfractures were observed and deformation twinning and discontinuous undulatory extinction is abundant. Occasionally, subgrain development and recrystallisation is also observed within narrow zones in the feldspar grains. Biotite recrystallized during this deformation episode. Apart from the distinct shear zones, the fabric was only weakly affected by deformation, resulting in undulatory extinction in quartz and twinning in feldspar. These observations indicate that in the domain II deformation was distinctly localized. The high temperature deformation fabric observed in structural domain I was overprinted by lower temperature deformation in structural domain II. The microstructures in samples P 23 (Fig. 9(F)) and P 6 from this domain indicate a dextral movement for this low temperature shear deformation under amphibolite facies metamorphic conditions at the HZ as a whole (Fig. 8). A strong indication of this deformation episode is also observed in the samples P 9, P 11 and P 12 at the western part of the study area, where the magnetic lineations are rotated from N–S (structural domain I) towards NW–SE (structural domain II). Here, quartz is strongly affected by undulosity and subgrain development and in feldspar densely spaced deformation twinning and fracturing is observed.

Almost all samples experienced a minor overprint under lower greenschist facies metamorphic conditions. This caused fracturing of feldspar and hornblende and, occasionally, was accompanied by retrograde mineral reactions such as formation of chlorite along fractures in hornblende, as well as the sericitization of feldspar.

6. Interpretation of AMS data and microstructures

The axes of the AMS-ellipsoids are generally subparallel with the fabric axes with \( \kappa_{\text{max}} \) parallel to the mineral or stretching lineation and \( \kappa_{\text{min}} \) normal to the metamorphic foliation (Figs. 3 and 5). In samples with high susceptibility this anisotropy is due to anisometric magnetite grains elongated in the direction of lineation (Grégoire et al., 1995), and to an anisotropy in distribution of magnetite (Hargraves et al., 1991). In samples dominated by a paramagnetic fabric the coincidence is caused by the preferred orientation of biotite and hornblende, which are minerals with high single crystal susceptibility anisotropies (Friedrich, 1995; Siegesmund et al., 1995; Hrouda et al., 1997). The magnetic fabric, therefore, can provide information about the orientation of the finite strain in the HZ. However, it has to be taken into account, that the AMS method integrates across the whole fabric and, therefore, may reflect resultants of interfering subfabrics (Rochette and Vialon, 1984; Hrouda and Potfaj, 1993). For example in a S–C geometry (sensu Berthé et al., 1979), deflections between the magnetic foliation (S) and the shear foliation (C-plane) may occur (Aranguren et al., 1995). However, in the samples investigated here, such a shear fabric is only weakly developed and the resulting deflections are considered to be negligible. Another problem interpreting AMS data can be caused by mineralogical components that produce an inverse magnetic fabric as it is occasionally observed for hornblende with \( \kappa_{\text{max}} \) per-
Fig. 9. Structural features of the HZ: A, B Field photographs from the western margin of the HZ, looking S (A) and SW (B), respectively, from a point at the southern end of Gabal Um Rasein (Fig. 2 for location). The photographs are arranged so as to show the steep dip of the foliation within the HZ (cliffs in A) and the shallowing dips away from the HZ (towards W, B). The central part of the slope in B is build up of the lbib gneiss, the top of the Gabal Gerf ophiolite nappe (compare map, Fig. 2). C Example of banded gneiss with amphibolite layers (black), showing (broadly symmetric) boudinage, which indicates N–S extension and E–W shortening. East side of Um Rasein, Fig. 2 for location; hammer for scale (above central boudin). D Handspecimen of amphibolite from the HZ (P 26) cut parallel with a mineral lineation marked by elongated feldspar porphyroclasts (structural X direction; XY section) and normal to the mineral lineation (YZ section), respectively. The amphibolite shows a pronounced stretching fabric. E, F Photomicrographs of orthogneisses from the HZ, showing examples from domain I (E) and II (F), respectively: (E) coarse-grained, elongated quartz with lobate boundaries but little internal deformation defines an early foliation (S). Younger foliation surfaces (C), defined by mica minerals, cut the early foliation and are interpreted here as shear surfaces. This S–C fabric indicates a sinistral sense of shear (sample P 21, X polarizers). (F) Dynamically recrystallized quartz. Quartz grains and subgrains are oriented oblique to the earlier foliation and indicate a dextral shear deformation (sample P 23, X polarizers).

Microstructural analyses and AMS-directional data and shape parameters indicate a variation in deformation fabric along the HZ ranging from strongly oblate to strongly prolate geometries. Simple shear deformation is concentrated in discrete zones. Between these zones the fabric shows mostly a pronounced stretching lineation but locally also flattening fabrics with no macroscopically visible mineral lineations.
As a consequence of strong simple shear deformation a divergence between the high strain and low strain geometries should be expected, since the angle between the shear zone boundary and the X-axis of the strain ellipsoid decreases from 45° towards a subparallel orientation with progressive simple shear deformation. Such oblique magnetic fabrics have been observed in regions where granite emplacement is related to strike-slip fault zones (Djouadi et al., 1997) or to transform geometry (Bouillin et al., 1993).

However, in the present study, the lineations in high strain and low strain areas are parallel, for example 352°6° for the nearly undeformed meta-granitoid (P 10) and 359°2° for a strongly deformed orthogneiss (P 21). This supports the results of microstructural observations that non-coaxial deformation is a minor component of the bulk deformation in the HZ.

The pronounced sigmoidal deflection of the magnetic lineation in structural domain II (Fig. 6) is clear on the map in Fig. 9, where the trend of the traces of the magnetic lineation trajectories is presented. This deflection and progressive rotation of the magnetic lineation in the SW-part of the study area are accompanied by low temperature deformation as described in the chapter above (fractures in feldspar, strong undulose extinction and localized recrystallization in quartz). For some samples a sense of shear could be determined and is indicated on the map (Fig. 9).

7. Discussion

From the regional tectonic context and from geologic maps, a strike-slip movement along the HZ has been inferred (Vail, 1985, 1988; Kröner et al., 1987; Greiling et al., 1994; Nasr et al., 1998). However, at least some field-based structural studies (Stern et al., 1990; Miller and Dixon, 1992) failed to detect traces of such a large-scale deformation and in particular those of a strike-slip episode along the north-central part of the HZ. These latter results are partly in accordance with our observations in the field that the deformation appears to be relatively weak in places. But detailed studies revealed a more complex story: the amount and geometry of strain show strong variations across the HZ.

Macroscopic fabric elements and the magnetic fabric in the study area show a good correlation. For example, magnetic lineations are subparallel with the stretching or mineral lineations and magnetic foliations are subparallel with the metamorphic banding. AMS and field data can thus be combined for an interpretation of the deformation regime in the zone of concentrated deformation. In structural domain I (Figs. 6 and 9), the major part of the HZ, the foliation poles form a girdle distribution around the orientation of a well-defined subhorizontal N–S trending lineation that is developed locally as a stretching lineation. This geometry is attributable to a constrictional regime, in contrast to a flattening regime, where a well-clustered foliation and a more scattered lineation should be expected. These results are in conflict with the interpretation of Miller and Dixon (1992) who described a down dip direction for the lineation and inferred a predominance of crustal shortening by folding and thrusting. However, we agree with these authors that the ductile deformation in the HZ is mainly coaxial and strike slip deformation is limited.

The curvature and bending of pre-existing structural units towards the HZ and into parallelism with the HZ-trend (Fig. 1) may be suggestive of a ‘drag’, as it is produced by (strike-slip) fault movement. However, this ‘drag’ is broadly symmetrical on both sides of the HZ and thus not indicative of any significant relative movement across the HZ. Instead, our data imply that this outcrop pattern is that of an antiform, which becomes progressively tighter at the HZ. Although this antiform is almost horizontal at a local scale (Fig. 3), it plunges gently towards the south at a regional scale, thus producing the observed outcrop pattern of fold limbs bending away from the tight fold closure at the HSZ towards the NW and NE (Fig. 1).

No deviation of magnetic lineation orientations between the different lithologies is observed. This holds also for the deformed granitoids. Therefore, the intrusion of the granitoids is considered to have taken place before or during the deformation along the HZ. Consequently, such high strain
zones as the HZ are not only important late- to post-tectonic elements but may have played a major role also during and after the accretionary orogenic evolution, probably also during the ascent of granitoid plutons (Hutton and Reavy, 1992; D'Lemos et al., 1992; Castro et al., 1999).

The observed lower temperature overprint in the NE–SW-trending structural domain II by dextral shear deformation is geometrically related to the NE–SW-trending dextral shear zone, described by Stern et al. (1990) (Figs. 1 and 9) as late structures truncating the N–S-trending fabric of the HZ. These authors interpreted such structures as shear components of a transpressive deformation with shortening normal to the HZ, which developed contemporaneously or at a late stage of HZ deformation. However, our study shows that the structures in the HZ are related to two different episodes of deformation. An early, mainly coaxial phase, with E–W shortening and pronounced N–S extension under amphibolite facies metamorphic conditions (structural domain I) and a subsequent, mostly non-coaxial overprint under considerably lower temperature, greenschist facies metamorphic conditions (structural domain II).

The late overprint could be related to stress fields active during the break-up of the Red Sea, where continental high strain zones may have been reactivated (Dixon et al., 1987; Talbot and Ghebreab, 1997). However, earlier work on post-Pan-African basement deformation showed a more brittle faulting during Red Sea tectonics (Greiling et al., 1988). Therefore, it appears to be more likely that also the domain II deformation is related to a latest Pan-African deformational episode. Consequently, the NE–SW-trending, dextral strike-slip zone at domain II is interpreted as a conjugate zone relative to the NW–SE-trending, sinistral fault zones of Wadi Hodein or Najd (Stern, 1985, 1994; Greiling et al., 1994). In addition to Stern et al. (1990) our results show that such dextral, conjugate strike-slip zones may be more widespread than it was known previously, although their regional importance is limited.

In conclusion, the present results show the HZ as a zone of high strain but with only minor components of wrench faulting. Deformation is dominated by pure shear producing E–W-shortening, with a strong N–S-extensional component, resulting in constrictional strain. It is only a subsequent overprint, which produced minor dextral wrench movement along a discrete, NE–SW-trending zone (domain II on Fig. 9).

Since these structures overprint the ophiolite nappes of the Allaqi-Sol Hamed suture, it can be inferred that the E–W-shortening which produced the HZ took place after suturing of the Gabgaba terrane with the terrane adjacent towards north.

In a wider regional context, the present results provide an important complement to the tectonic history of the ANS: the Allaqi-Sol Hamed suture, trending broadly E–W, is overprinted by E–W shortening during the formation of the HZ. Such an E–W shortening has been proposed during the suturing of the Gabgaba terrane with older continental crust towards W (Keraf suture, Abdelsalam et al., 1998, Fig. 1). As a consequence, the accretion of the ANS in northern Sudan–southern Egypt, can be confirmed as polyphase or at least a two-phase event with early suturing by N–S convergence (formation of Allaqi-Sol Hamed suture) and a later stage with c. E–W convergence leading to collision of the earlier assembled terranes with a craton towards west and the formation of the Keraf suture (Abdelsalam et al., 1998). These results preclude earlier views of the Pan-African evolution as a broadly continuous episode of transpressional orogeny (O’Connor et al., 1994). Neither are there traces of large-scale escape movements in the present area to the south of the Najd Faults (Stern, 1985, 1994) in a wider sense.

Acknowledgements

This work is a part of a cooperation between the Geologisch-Paläontologisches Institut, Heidelberg, and the Egyptian Geological Survey and Mining Authority (EGSMA), Cairo, supported by the BMBW through the Forschungszentrum Jülich, International Bureau. The financial assistance is gratefully acknowledged. We thank the Chairmen of EGSMA, G.M. Naim and M. El Hinnawy for their generous support. Many
thanks to L. Nano for his assistance in laboratory work and L.N. Warr, A. Kontny and A. Maklouf for helpful discussions. M. El Eraki provided some of the samples. We thank reviewers J. Meert and R.J. Stern for detailed comments and suggestions that considerably improved the quality of the paper.

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