PERGAMON

Journal of Structural Geology 22 (2000) 1827–1835

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Progressive development of lattice preferred orientations (LPOs) of naturally deformed quartz within a transpressional collision zone (Panafrican Orogen in the Eastern Desert of Egypt)

Wolfgang Unzog*, Walter Kurz

Institut für Geologie und Paläontologie, Karl-Franzens Universität Graz, Heinrichstrasse 26, A-8010 Graz, Austria

Received 30 November 1999; accepted 26 June 2000

Abstract

Lattice preferred orientations (LPOs) of quartz were used to establish differences in deformation geometry, finite strain, and temperature within a transpressional collision zone within the Panafrican Orogen in the Eastern Desert of Egypt. Metamorphic and/or magmatic core complexes in the area are bordered in the NW and SW by ductile sinistral NW-trending strike-slip zones and low angle normal faults (LANFs). Simultaneous activity of both fault systems suggests bulk W–E shortening coeval with orogen-parallel extension. Displacement partitioned into orogen-parallel sinistral strike-slip faults and LANFs. This study compares both quartz-LPOs in shear-zones and normal faults.

From south to north, quartz c-axis data show a continuous evolution along orogen-parallel strike-slip faults from maxima in *Y*, with a slight tendency to oblique single girdles at the margins of the Wadi Beitan and Hafafit complexes, to asymmetric crossed girdles and oblique single girdles along the margins of the Sibai and Meatiq complexes. The NW-directed LANFs to the NW of the Hafafit and the SE-directed LANFs to the SE of the Sibai show maxima in *Y*. The SE-directed LANF at the SE margin of the Meatiq complex shows symmetric crossed girdles, indicating coaxial deformation geometry.

Oblique single girdles and maxima in Y occur in the southern part of the orogen, whereas crossed girdle distributions dominate in the northern part. The variation in quartz c-axis patterns is explained in terms of decreasing metamorphic grade during deformation from the S (medium to high grade) to the N (low grade), and decreasing finite strain. This is in accordance with the general progression of transpressional tectonics and exhumation of core complexes from S to N.

1. Introduction

The analysis of lattice preferred orientation patterns (LPOs or textures) is of considerable interest for the investigation of the structural evolution of tectonic units. LPO development is governed by the following factors: (1) the active deformation mechanism; (2) the shape of the finite strain ellipsoid (plane strain, oblate, prolate) (e.g., Lister, 1978), and the strain magnitude; and (3) the strain path. Especially, the textural evolution within naturally and experimentally deformed quartzites has been extensively investigated for several boundary conditions (e.g., Lister, 1977, 1981; Lister and Paterson, 1979; Lister and Hobbs, 1980; Etchecopar, 1977; Etchecopar and Vasseur, 1987; Jessell, 1988a,b; Jessell and Lister, 1990; Schmid and Casey, 1986, Law, 1987; Law et al., 1990).

Within the Panafrican Orogen in the Eastern Desert of Egypt basement domains are bounded by sets of shear zones and normal faults. Both structural elements define a crustal-scale wrench corridor. Displacement within this corridor partitioned into orogen-parallel sinistral strike-slip faults and low-angle normal faults which form extensional bridges between strike-slip faults (Bregar et al., 1997). Simultaneous activity of both fault systems suggests bulk oblique shortening with consequent orogen-parallel extension.

Transpression in terms of oblique shortening and convergence generally results in partitioning between zones of simple shear and zones of pure shear (Platt, 1993; Ellis et al., 1995; Theyssier et al., 1995). Oblique shortening relative to pre-existing surfaces and structures results in the development of discrete shear zones along the boundaries of upbending domes. Non-coaxial flow is localised within these shear zones and along associated low-angle normal shear zones along the upper margins of such domes. Partitioning of transpressional deformation can occur when stress is applied oblique to pre-existing zones of structural weakness (Jones and Tanner, 1995).

* Corresponding author.

0191-8141/00/$ - see front matter
PII: S0191-8141(00)00087-0

This study focusses on the evolution of quartz LPOs along several strike-slip and low-angle normal faults. The aim is to obtain information on the strain variations along strike, the deformational conditions, and the variation of kinematics at different positions within the orogen.

2. Geological setting

The Panafrican Orogen within the Eastern Desert of Egypt is characterised by a nappe assembly that includes ophiolite nappes and related magmatic and sedimentary assemblages (Panafrican nappes: e.g., Ries et al., 1983; Kröner et al., 1994; Greiling et al., 1994; Fritz et al., 1996), which are thrusted over polymetamorphosed and polydeformed basement units (Neumayr et al., 1996, 1998). Structures related to stacking developed during Neoproterozoic convergence (between ca. 650–580 Ma) and document an anticlockwise composite displacement path (Fritz et al., 1996), with orogen-parallel flow in internal domains and orthogonal, westward-directed thrusting in foreland domains. This situation has been explained by foreland-directed thrust propagation during bulk oblique convergence (Wallbrecher et al., 1993). Shortening resulted in thin-skinned nappe tectonics in the hanging-wall sections, and was associated with a minor amount of crustal thickening in the footwall (Fritz et al., 1996).

The basement domains can be described as core complexes (Bregar et al., 1997), which are arranged subparallel to the strike of the orogen over a distance exceeding 400 km (Fig. 1). They have been exhumed coevally with final nappe stacking in the foreland (Fritz et al., 1996). These crystalline domes form a conspicuous geological feature in the Eastern Desert of Egypt (El Gaby et al., 1990). They are aligned parallel to the strike of the orogen with culminations (from south to north) in the Wadi Beitan, the Hafafit, Sibai, and Meatiq crystalline domes. Basement domains are entirely bound by sets of shear zones and normal faults. Both structural elements define a crustal-scale wrench corridor known as the Najd Fault System (Stern, 1985). Displacement within the Najd wrench corridor partitioned into NW-striking, orogen-parallel sinistral strike-slip faults, which developed along western and eastern margins of the core complexes (domes). North- and south-dipping low-angle normal faults along the northern and southern margins of the domes form extensional bridges between strike-slip faults (Bregar et al., 1997). Simultaneous activity of both fault systems suggests bulk SW–NE shortening coeval with orogen-parallel extension (ca. NW–SE). Structural observations (Bregar et al., 1997; Fritz et al., 1996; Unzog, 1999) document a continuous decrease of shortening from the S to the N, which is indicated by stronger buckling in the Wadi Beitan and weak buckling in the Meatiq core complex. Exhumation of core complexes along normal faults triggered denudation, which is expressed by the formation of molasse basins adjacent to the core complexes (Messner et al., 1996) (Fig. 1). Coeval with exhumation of the metamorphic core complexes, numerous calc-alkaline intrusions have been emplaced along this wrench corridor.

A close relation between exhumation of the core complexes, activity of the composite set of faults (strike-slip and normal faults) and intrusion of the plutons is evident from radiometric age data. U/Pb zircon ages from the Abu Ziran pluton give 614 ± 8 Ma (Stern and Hedge, 1985), whereas activity of the Najd Fault System is revealed by $^{40}Ar/^{39}Ar$ ages of synkinematically grown muscovite within the strike-slip faults, giving 588 ± 0.3 Ma, and normal faults, giving 595 ± 0.5 Ma (Fritz et al., 1996). Regional cooling of the Meatiq Dome (Fig. 1) at about the same time is suggested by $^{40}Ar/^{39}Ar$ ages of hornblende around 585 Ma and muscovite around 580 Ma. Generally, $^{40}Ar/^{39}Ar$ ages decrease along the strike of the orogen from south (ca. 640 Ma) to north (570 Ma) (Neumayr et al., 1998). Closure temperatures of hornblende of ca. 550 ± 25°C and muscovite of 375–400°C (Dodson, 1973) suggest cooling from approximately 550 to 350°C within this time interval during exhumation of the Meatiq metamorphic core complex. Late to post tectonic magmatic activity is constrained by a Rb/Sr isochron at 579 ± 6 Ma (Sturchio et al., 1983) of a circular-shaped discordant granitoid body in the centre of the Meatiq dome (Fig. 1). There are poor age constraints on the deposition ages of intramontane molasse basins but provenance studies from conglomerates (Messner et al., 1996) have shown that clasts within the basins have been derived from the metamorphic core complexes. Although all these data have been obtained from different techniques, they all indicate a coeval activity of sedimentation, magmatic activity, activation of the fault system and exhumation of the Meatiq dome at around 600 Ma.

3. Methods

We discuss the evolution of microstructures and LPOs within rock samples that had been deformed at variable P-T conditions, in order to get information on their deformational properties at both low and high metamorphic grade. X-ray texture analyses of quartz were carried out with a Siemens D500 X-ray goniometer at the University of Graz (Austria) in reflexion mode. The apparative and methodical limitations restrict samples to a size of 2.5×1.5 cm^2. The X-ray beam is reflected from an area of about 5×5 mm^2. Generally we used a 0.6° diaphragm for the detector. This allows the detection of single peaks that are spaced at a 2θ of at least 1.2°. However, for polyphase rock samples, a 0.28° diaphragm has been applied in order to achieve better peak separation and to avoid interaction of diffraction peaks of similar d-spacing. The evaluation of pole figures was done with the program TexAT v. 2.2c/ODF AT v.1.1a provided by Siemens Co., which is based on the Harmonic Method (Bunge, 1981, 1985; Bunge and Esling, 1985), and with the

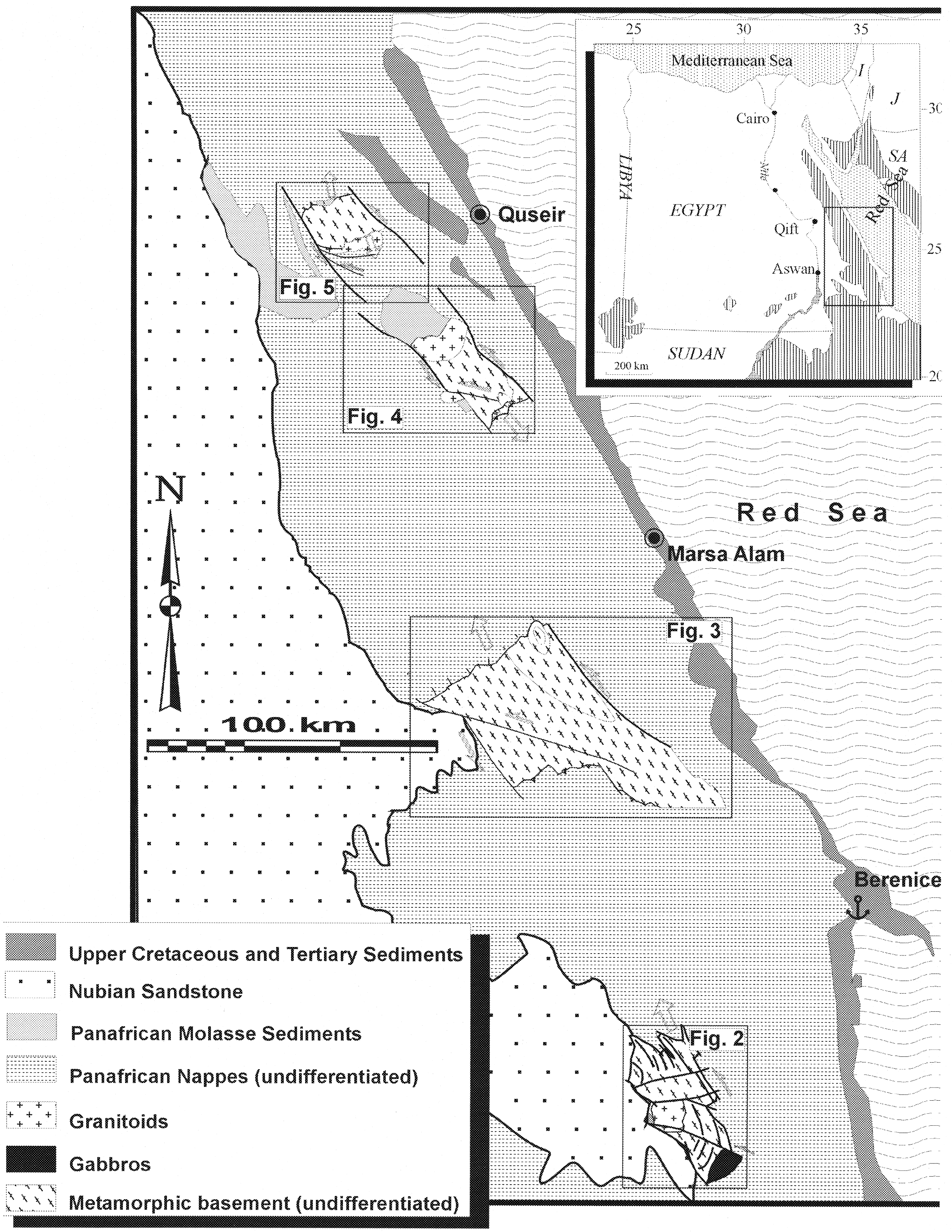

Fig. 1. Tectonic sketch of the Panafrican Orogen in the Eastern Desert of Egypt, and the locations of investigated areas; the insert shows the distribution of the Panafrican Orogen in Egypt and Saudi Arabia.

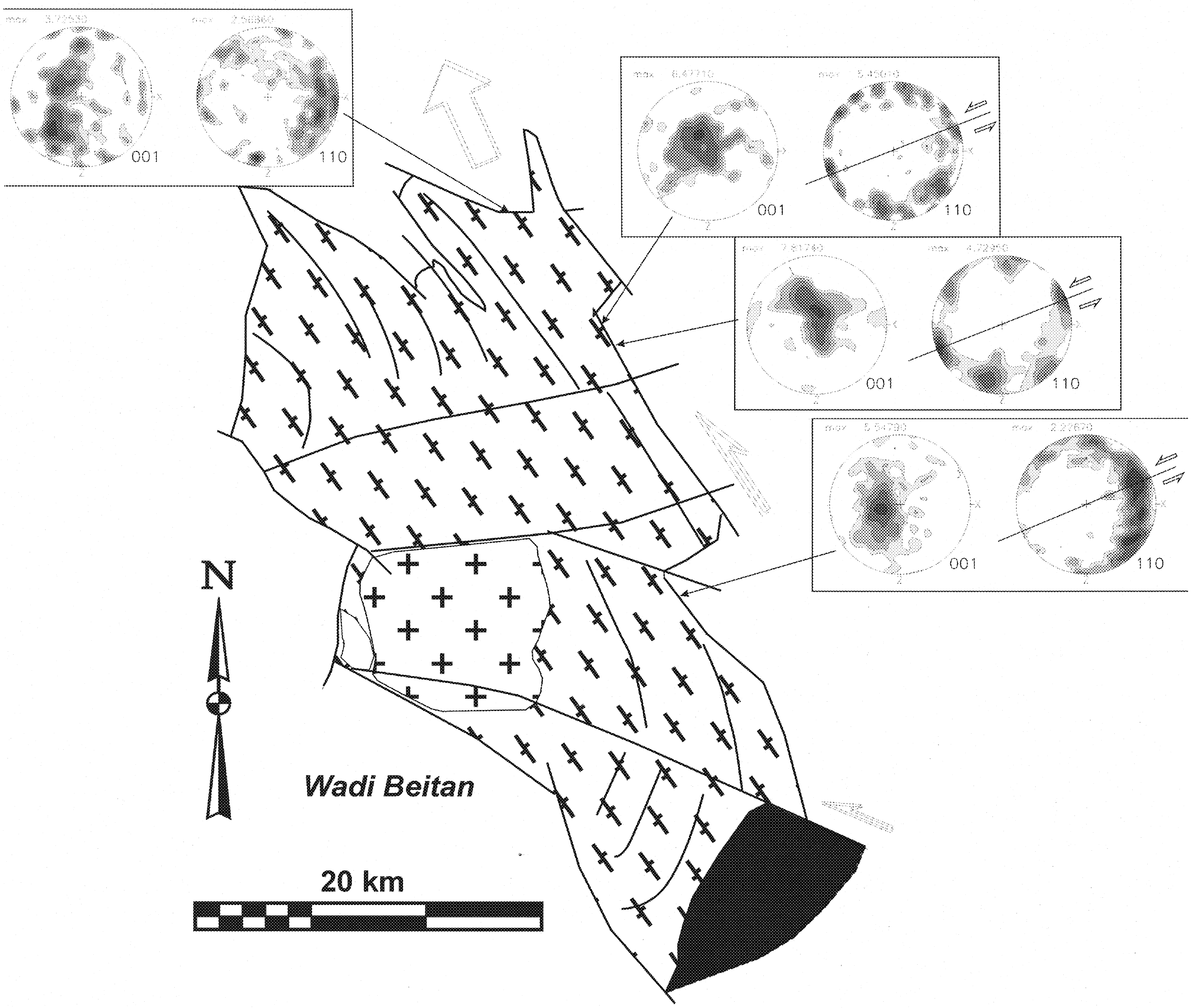

Fig. 2. Tectonic sketch of the Wadi Beitan area, showing the arrangement of confining strike-slip and low-angle normal faults (for legend see Fig. 1), and related quartz LPOs ([001]: *c*-axes; [110]: *a*-axes); Stereographic projections within the kinematic *X–Z* section, lower hemisphere; logarithmic gradation of isolines; first isoline: uniform distribution; fifth isoline: 85% of maximum; *X* marks the direction of the stretching lineation and the strike of the shear zone boundary; line through the dominating *a*-axis maxima and arrows indicate the orientation of the dominant gliding plane for prism-a-slip. Lack of axis symmetry results from cutting slighty oblique to the lineation.

program package MENTEX (Vector Method; Schaeben et al., 1985; Schaeben, 1994). Both program packages include corrections for background and beam defocussing. Several packages use Bravais crystallographic indices for the description of crystallographic directions, omitting the index {i} of the {hkil} notation. Furthermore, comparative neutron texture analyses have been carried out with the goniometer SKAT at the pulsed neutron reactor IBR2 at the Joint Institute for Neutron Research (JINR) in Dubna (Russia), which allows the measurement of samples of about 27 cm^3. These analyses are based on the time of flight (TOF) of neutrons within a neutron beam, which is directly related to their wavelength (Ullemeyer et al., 1998) and, therefore, d-spacing. The optical determination of LPOs has been carried out using a standard universal-stage.

4. Quartz lattice preferred orientation patterns (LPOs)

4.1. Wadi Beitan

Along the strike-slip fault marking the eastern margin of the Wadi Beitan core complex (Fig. 2), quartz *c*-axes [001] form well-defined maxima near the *Y*-axis, with a slight tendency to be distributed along a single girdle within the *YZ*-plane. Accordingly, the *a*-axes [110] form three maxima at the margin of the pole figure, with one well pronounced maximum in the NE/SW sectors of the pole figure, which documents a simple shear component with a left-lateral sense of shear. Low-angle normal faults along the NW margin of the Wadi Betan are characterized by single girdle *c*-axes distributions. However, two maxima between the *Y*- and *Z*-axis are very well pronounced. The *a*-axes form one

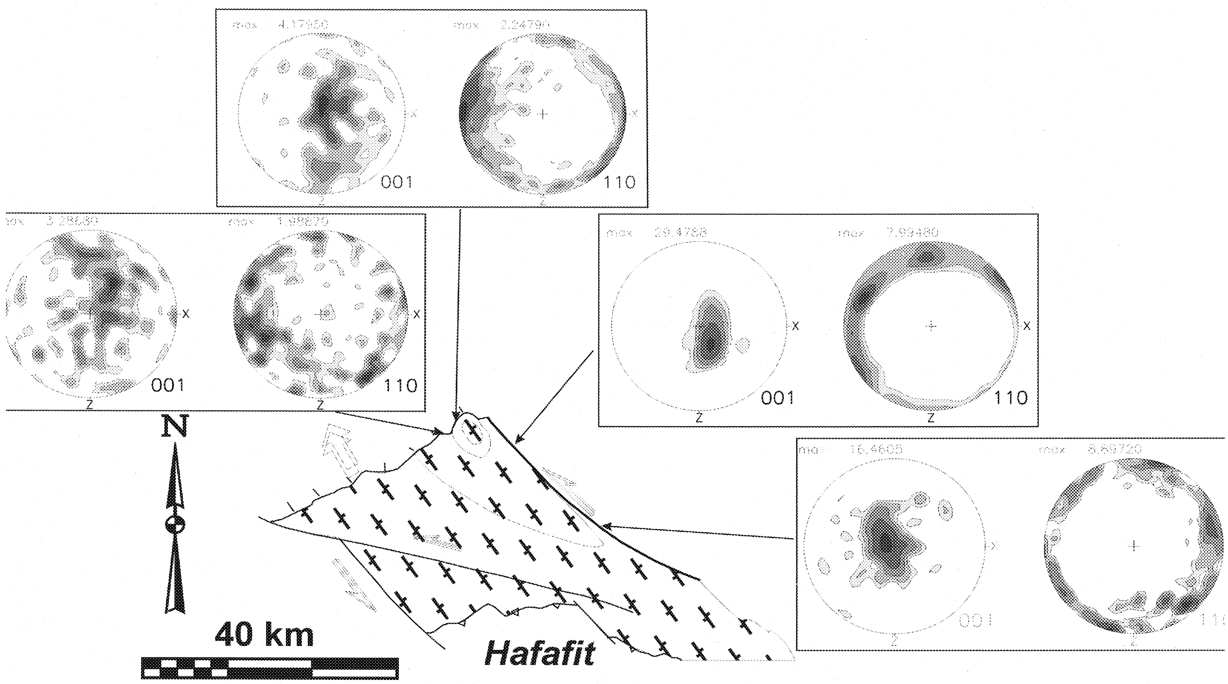

Fig. 3. Tectonic sketch of the Hafafit area with the arrangement of confining strike-slip and low-angle normal faults (for legend see Fig. 1), and related quartz LPOs ([001]: *c*-axes; [110]: *a*-axes); for details concerning the pole figures see Fig. 2.

strong maximum with two sub-maxima near *X* and show a slight tendency to be distributed along a girdle. The slight asymmetry of the *a*-axes with respect to the reference axes of the pole figure documents a top-to-the-north sense of shear.

4.2. Hafafit core complex

The NE shear-zone of the Hafafit core complex (Fig. 3) is characterised by very well pronounced c-axis [001] maxima around *Y*. The *a*-axes [110] form three clusters at the margins of the pole figures, with one cluster around *Z*. Accordingly, a rather weak fabric asymmetry has been observed within this section. Only the southern part of this shear zone is characterised by a weak asymmetric arrangement of *a*-axes, indicating a left-lateral sense of shear. The NW-directed low-angle normal faults in the north of Hafafit (Fig. 3) show slightly oblique single girdles with one maximum in *Y*. The *a*-axes form one maximum near *X* within the NW/SE sector of the pole figure, showing a fabric asymmetry of 5–10°. This indicates a top-to-the-north-west sense of shear.

4.3. Sibai core complex

Sinistral asymmetric crossed girdle to oblique single girdle *c*-axis [001] distributions dominate in the shear-zone along the NE side of the Sibai dome (Fig. 4). Basically, single girdle *c*-axis distributions show remnants of type I (Lister, 1977) crossed girdles. One maximum can be observed around *Y*, a well-developed small circle is documented oblique to *Z*. However, in the northern part of this shear zone the maximum around *Y* is stronger pronounced, and only remnants of former crossed girdles have been observed. This seems to indicate a transitional fabric from type I crossed girdles to single maxima in *Y*. The single girdles show well-developed subsidiary maxima near *Y*. These *c*-axis fabrics with well-developed maxima near *Y* show corresponding *a*-axes [110] distributions that are characterised by three clusters along the margin of the pole figure, and a rather weak fabric asymmetry. Sections that are characterized by oblique cross-girdle *c*-axis distributions show well developed *a*-axis maxima near *X*, with a tendency to be distributed along a girdle oblique to the *X*–*Y*-plane, and a fabric asymmetry of 5–15°. This indicates left-lateral displacement along the NE shear zone. The SW shear-zone (Fig. 4) is characterised by a more complicated structural evolution (Bregar et al., 1997). Here a variation from asymmetric crossed girdles, maxima near *Z*, to maxima around *Y* have been observed. Asymmetric crossed girdles occur along the El Shush shear zone (Fig. 4), which occupies the position of a synthetic shear to the SW shear zone. One strong maximum can be observed around *Y*. The a-axes form a small circle distribution centered on *X*, with one subsidiary maximum near *Z*. The southern part of the SW shear zone is characterised by *c*-axis maxima in *Y*. The *a*-axes form three maxima at the margin of the pole figure; however, they are better pronounced in the SW/NE-sector, which indicates a slight fabric asymmetry with a left-lateral sense of shear. The low-angle normal faults in the SE of the Sibai core complex (Fig. 4) are exclusively characterised by maxima in *Y*. Locally, a slight tendency to oblique single girdles has been observed.

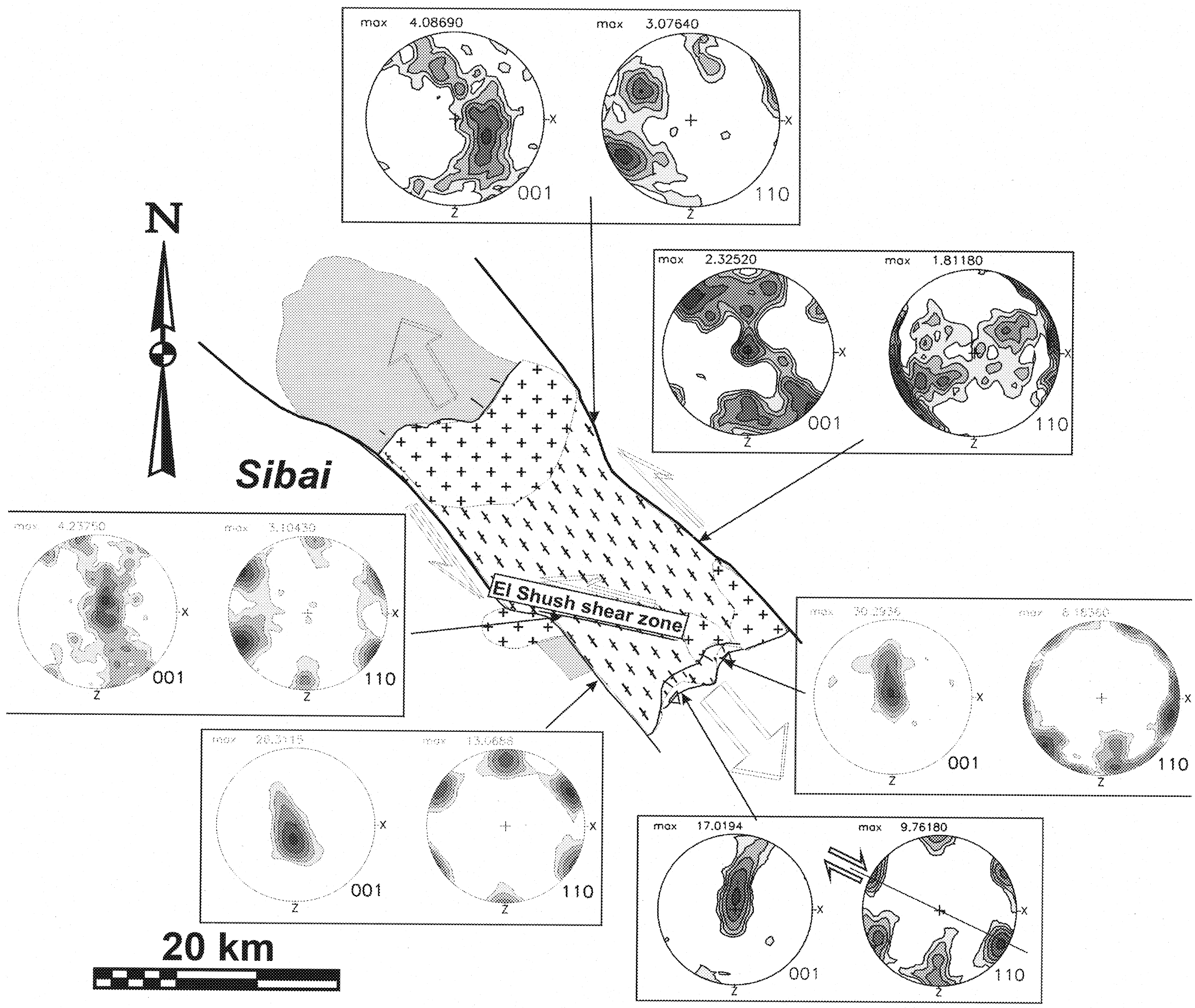

Fig. 4. Tectonic sketch of confining strike-slip and LANFs around the Sibai area (for legend see Fig. 1), and related quartz LPOs ([001]: *c*-axes; [110]: *a*-axes); for details concerning the pole figures see Fig. 2.

4.4. Meatiq core complex

The SW shear zone of the Meatiq core complex (Fig. 5) is characterised by asymmetric crossed girdle *c*-axis [001] distributions. Accordingly, the *a*-axes [110] are distributed along two small circles oblique to the X–Y-plane, showing a fabric asymmetry of 20–25°. This indicates left-lateral displacement along the SW shear zone. Along the SE-directed low-angle normal fault both symmetric cross and single girdles have been observed.

5. Summary and discussion

Quartz LPOs along the Panafrican Orogen of the Eastern Desert of Egypt provide information on the strain path along strike, the deformational conditions, and the variation of kinematics at different positions within the orogen. From the south towards the north, quartz *c*-axis data show a continuous evolution along the orogen-parallel strike-slip faults from maxima in Y with slight tendency to oblique single girdles at the margins of the Wadi Beitan core complex and the Hafafit core complex, to asymmetric crossed girdles, incomplete crossed girdles and oblique single girdles along the margins of the Sibai and Meatiq core complexes. The NW-directed low-angle normal faults (LANFs) to the NW of Hafafit and the SE-directed LANFs in the SE of the Sibai core complex show maxima around Y. The SE-directed LANF at the SE Margin of the Meatiq core complex shows symmetric crossed girdles, which can be related to dominating coaxial deformation geometry under plane strain conditions. Generally, the strong LPO fabrics in the southern sections are characteristic of both high-grade metamorphic conditions and high finite strain. Quartz-*c*-axis patterns showing maxima in Y could be explained by the dominance of prism $<a>$ gliding and are typical for medium to high grade metamorphic conditions (e.g., Schmid and Casey, 1986). The appearance of crossed

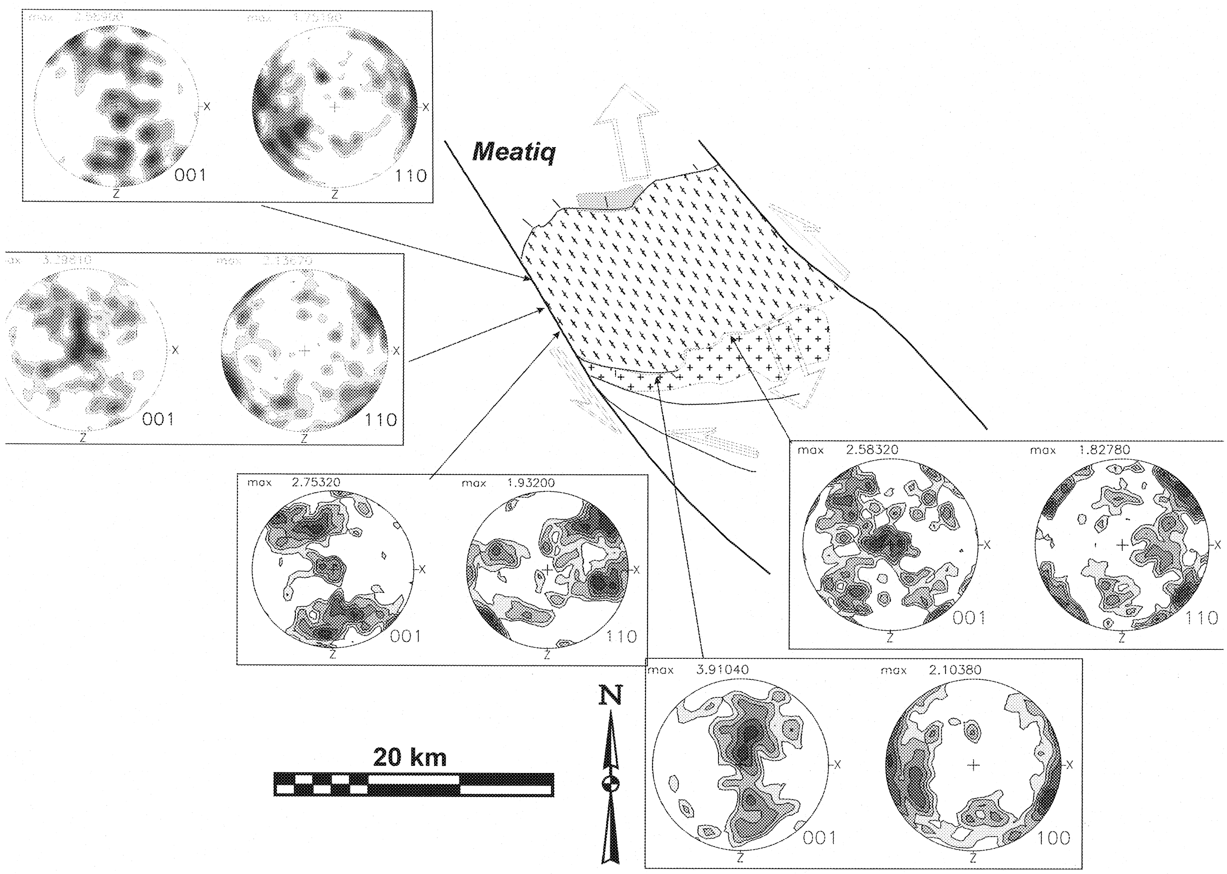

Fig. 5. Tectonic sketch of the Meatiq area, showing the arrangement of confining strike-slip and low-angle normal faults (for legend see Fig. 1), and related quartz LPOs ([001]: *c*-axes; [110]: *a*-axes); for details concerning the pole figures see Fig. 2.

girdles in the northern part implies the dominance of basal $<a>$ gliding, with less pronounced rhombohedral $<a>$ and prism $<a><c>$ gliding, which is common for deformation under lower grade metamorphic conditions. Assuming a similar deformation geometry for the different LANFs, which can be observed from structural data (Bregar et al., 1997; Fritz et al., 1996), these observations might be interpreted in terms of decreasing metamorphic grade during deformation from south to north.

The structural evolution along the strike-slip faults documents a more complex deformation history. Structural observations document a continuous decrease in the amount of shortening from south to north, which is indicated by stronger buckling in the Wadi Beitan and weak buckling in the Meatiq core complex (Bregar et al., 1997; Fritz et al., 1996; Unzog, 1999). This also results in the evolution of a strain gradient, generally characterised by decreasing finite strain from south to north. Therefore, the continuous change in quartz fabrics could also be interpreted in terms of changing deformation geometry and variable finite strain. The *c*-axes form either cross girdle distributions with two well defined maxima between *Y* and *Z*, which can be interpreted in terms of preferred slip on the rhombs (e.g., Schmid and Casey, 1986), single girdle distributions with a well developed *Y* maximum, or a strong maximum near the *Y*-axis with some tendency to be distributed along a single girdle, and with three corresponding maxima of *a*-axes near the margin of the pole figure. Such strong LPO fabrics are both characteristic for high-grade metamorphic conditions and high finite strain. However, LPOs from distinct domains, especially from the NE shear zone of the Sibai complex, show that these strong fabrics developed continuously from type I crossed girdles and single girdle distributions. This shows that several confining shear zones have been initiated under plane strain conditions, which can be observed from the evolution of type I crossed girdles. The continuous evolution of single girdles from crossed girdles is interpreted to record increasing finite strain (e.g., Schmid and Casey, 1986). However, in the northern part of this shear zone a strong maximum can be observed around *Y*, and furthermore, the continuous evolution of well pronounced maxima around *Y* bears evidence for increasing finite strain. This is documented by meso-scale structural observations, too (Bregar et al., 1997; Fritz et al., 1996; Unzog, 1999). Therefore, the different LPOs that have been observed in the area of investigation are best interpreted in terms of locally contrasting finite strain, with a general trend to decreasing strain towards the north. These observations also reflect the progression of deformation along several shear zones from the south towards the north, related to transpression during oblique collision between two crustal blocks (Fritz et al., 1996). The final collision resulted in deformation partitioning between confining orogen-parallel strike-slip faults, and LANFs accommodating orogen-parallel extension. The LPOs might reflect both a relative decrease of the simple shear component to the north, and decreasing temperature conditions. This is consistent with the general progression of deformation and exhumation of the core complexes from the south towards the north (Neumayr et al., 1998), as documented by geochronological data, especially $^{40}Ar/^{39}Ar$ cooling ages, of around 640 Ma from the southern part and 570 Ma in the northern part.

6. Conclusions

LPOs of quartz were used to establish differences in deformation geometry, finite strain, and temperature within a transpressional collision zone of the Panafrican Orogen in the Eastern Desert of Egypt. The orogen is characterised by the occurrence of metamorphic and/or magmatic core complexes that are arranged parallel to the strike of the orogen, which are bordered by distinct ductile subvertical sinistral NW-trending strike-slip zones and LANFs that form the NW and SE limits. Generally, the quartz *c*-axis distributions from these shear zones show a continuous development. The northern part of the orogen is characterised by type I crossed girdle distributions, whereas the southern part show single maxima around *Y*. The central part is characterised by incomplete crossed girdle distribution and single girdles with a strong maximum around *Y*, partly with remnants of crossed girdle distributions. This indicates that single maxima around *Y* developed continuously from initial crossed girdle distributions. The increasing intensity of the maxima around *Y* is interpreted in terms of increasing finite strain from north to south, due to a prograding transpressional deformation from south to north. Additionally, this evolution might also reflect decreasing metamorphic conditions during deformation from south to north. The strain gradient is related to general progression of transpressional tectonics and exhumation of core complexes towards the north.

Acknowledgements

We appreciate discussions on the topics presented in this study with Harry Fritz, Eckart Wallbrecher, Jürgen Loizenbauer, Martin Bregar, Klaus Pelz, Peter Neumayr, and Andreas Bauernhofer. Furthermore we would like to thank Eckart Wallbrecher and Ali Khudier, who gave access to some samples from the Wadi Beitan area. We also greatfully acknowledge the software packages by Helmut Schaeben (University of Freiberg, Germany) for the evaluation of several LPO data, and the help of Klaus Ullemeyer (Dubna, Göttingen) during the neutron texture measurements in Dubna. The studies presented in this paper have been carried out within the projects P9703-GEO and P12179-GEO of the Austrian Research Foundation (FWF).

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