Journal of African Earth Sciences 56 (2010) 167–178

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Quantifying 3D post-accretionary tectonic strain in the Arabian–Nubian Shield: Superimposition of the Oko Shear Zone on the Nakasib Suture, Red Sea Hills, Sudan

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ARTICLE INFO

Article history:
Received 5 March 2009
Received in revised form 18 June 2009
Accepted 5 July 2009
Available online 16 July 2009

Keywords:
3D tectonic strain
Arabian–Nubian Shield
Nakasib Suture
Oko Shear Zone
Post-accretionary structures

ABSTRACT

Deformed conglomeratic clasts exposed along the Neoproterozoic Nakasib Suture and the Oko Shear Zone are used to calculate three-dimensional (3D) tectonic strain associated with the latter to quantify strain associated with post-accretionary deformational belts in the Arabian–Nubian Shield. The Nakasib Suture is a NE-trending fold and thrust belt that is sinistrally offset (~10 km) by the cross-cutting NNW- to NW-trending strike-slip faults of the Oko Shear Zone. The Nakasib Suture was formed as a result of collision between the Haya terrane and the Gebeit terrane at ~750 Ma ago. The Oko Shear Zone was subsequently formed as a result of an E–W directed shortening of the Arabian–Nubian Shield due to collision between East and West Gondwana at ~670–610 Ma ago. This analysis indicates the following: (1) The Nakasib Suture is dominated by flattening strain with the flattening plane of the associated strain ellipsoid oriented at 21°/77°SE. This flattening deformation is interpreted to be associated with nappe emplacement from north to south. (2) Some regions along the Nakasib Suture are characterized by constriction strain that might be due to refolding of the early nappes about NE-trending axes. (3) The Oko Shear Zone is characterized by constriction strain, with the *XY* plane of the strain ellipsoid oriented at 171°/68°E. The strain ellipsoid associated with the Oko Shear Zone manifests superimposition of E–W shortening on the NE-trending fold and thrust belt associated with the Nakasib Suture. (4) The tectonic strain of the Oko Shear Zone, superimposed over the structures of the Nakasib Suture, is characterized by a strain ellipsoid whose flattening plane is oriented at 21°/49°W. The strain ellipsoid of the tectonic strain has a major axis with a quadratic elongation of 3.6 and an orientation of 357°/25°, an intermediate axis with a quadratic elongation of 1.2 and an orientation of 231°/30°, and a minor axis with a quadratic elongation of 0.25 and an orientation of 115°/18°. This suggests that the post-accretionary deformation of the Arabian–Nubian Shield was superimposed as a NW–SE directed shortening that created early N–S shortening zones and late NW-trending sinistral strike-slip faults.

1. Introduction

The Neoproterozoic Arabian–Nubian Shield in Arabia and northeast Africa is characterized by two main types of deformation belts (Fig. 1; Abdelsalam and Stern, 1996a). The older deformation belts are E- to NE-trending ophiolite-decorated arc–arc sutures formed during collision of intra-oceanic island arc-back arc terranes that occurred between ~800 and 700 Ma (Stern, 1994; Abdelsalam and Stern, 1996a; Johnson and Woldehaimanot, 2003; Hargrove et al., 2006). The exception to this is the eastern part of the Arabian Shield where sutures trends NW (Fig. 1). The younger deformation belts, which have been referred to as post-accretionary structures (Fig. 1; Abdelsalam, 1994; Abdelsalam and Stern, 1996a), are N- to NW-trending structures and cross-cut the arc–arc sutures. These belts were developed in response to shortening of the Arabian–Nubian Shield between the converging fragments of East and West Gondwana. Post-accretionary structures in the Arabian–Nubian Shield consist of (among other structures) N-trending shortening zones in the form of upright folds that developed due to E–W directed shortening at ~670–610 Ma, and NW-trending sinistral strike-slip faults, that developed at ~640–560 Ma (Abdelsalam, 1994). This work deals with superimposition of N-trending shortening zones and NW-trending strike-slip faults on older suturing structures.

The Nakasib Suture (arc–arc suture) and Oko Shear Zone (post-accretionary structure) provide examples of both types of deformation belts found in the Arabian–Nubian Shield and of their cross-cutting relationship (Fig. 2). The Nakasib Suture is a NE-trending fold and thrust belt in the central part of the Red Sea Hills

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doi:10.1016/j.jafrearsci.2009.07.003

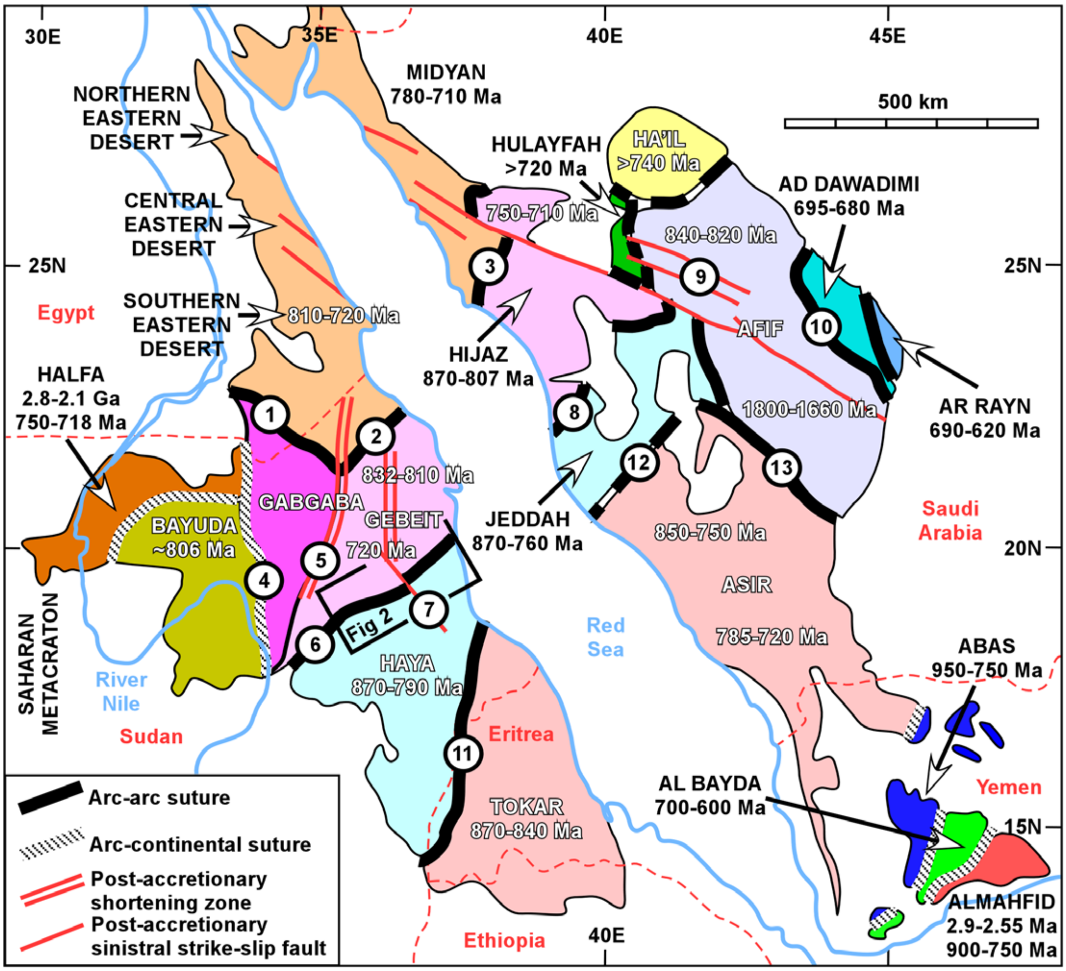

Fig. 1. Tectonic map of the Arabian–Nubian Shield showing the locations and extents of terranes, sutures and post-accretionary structures. Modified after Johnson and Woldehaimanot (2003) and Hargrove et al. (2006). 1 = Allaqi suture, 2 = Sol Hamed suture, 3 = Yanbu suture, 4 = Keraf suture, 5 = Hamisana shear zone, 6 = Nakasib suture, 7 = Oko shear zone, 8 = Bir Umq suture, 9 = Najd fault system, 10 = Al Amar suture, 11 = Baraka lineament, 12 = Afaf belt and 13 = Hulayfah-Ad Dalinah-Ruwah fault zone.

of the Sudan (Fig. 2). It formed as a result of collision between the Haya and Gebeit terranes at ~750 Ma (Fig. 1; Abdelsalam and Stern, 1993a,b; Wipfer, 1996). The Oko Shear Zone, on the other hand, is a NNW- to NW-trending post-accretionary belt that deforms the Nakasib Suture and was formed at ~670–560 Ma (Abdelsalam, 1994). It extends from near the Sol Hamed Suture in the north, to south of the Nakasib Suture (Fig. 1). The Nakasib Suture is apparently sinistrally offset by ~10 km by the Oko Shear Zone (Fig. 2; Abdelsalam, 1994). The intersection of the Oko Shear Zone and the Nakasib Suture forms a ~30 km wide belt of complex deformation (Almond and Ahmed, 1987).

The objective of this work is to quantify the amount and orientation of the three-dimensional (3D) tectonic strain that resulted from the development of the Oko Shear Zone as it was superimposed on the Nakasib Suture. Below, this was accomplished through strain tensor calculations based on in situ measurements of lengths and orientations of three principal axes of deformed conglomeratic clasts exposed along the Nakasib Suture and the Oko Shear Zone (Fig. 2, Table 1). These measurements are used to: (1) Characterize the nature of strain associated with the Nakasib Suture and the Oko Shear Zone using Flinn (Flinn, 1962) and Hsu (Hsu, 1966) Diagrams. (2) Calculate the strain tensor associated with the Nakasib deformation by considering conglomeratic clasts exposed along the suture but outside the Oko Shear Zone. This strain tensor represents the initial state of strain before the superimposition of the Oko deformation. This strain tensor is denoted as (S_I). (3) Calculate the strain tensor associated with the combined Nakasib and Oko deformations by using conglomeratic clasts exposed along the Oko Shear Zone. This strain tensor represents the finite strain and is referred to as (S_F). (4) Calculate the tectonic strain (referred to as S_T) that resulted in the development of the Oko Shear Zone. This is calculated by subtracting S_I from S_F. It should be noted that S_I, S_F, and S_T are all tectonic and the term tectonic strain (S_T) only refers to the increment of strain superimposed on S_I to produce S_F. The results provide a quantitative understanding of the role post-accretionary deformation had in creating the regional structural grain in the Arabian–Nubian Shield. Results of strain tensor calculation thus will be discussed within the framework of regional structures in the Arabian–Nubian Shield especially the evolution of NW-trending sinistral strike-slip faults, and the non-orthogonal nature of collision between the Arabian–Nubian Shield and fragments of East and West Gondwana.

2. Geology of the Nakasib Suture and the Oko Shear Zone

The Nakasib Suture (Figs. 1 and 2) in the central part of the Red Sea Hills is a ~150 km long NE-trending fold and thrust belt with an average width of 40 km (Abdelsalam and Stern, 1993a,b; Wipfer, 1996). The suture continues NE across the Red Sea into Saudi Arabia as the Bir Umq Suture (Fig. 1; Johnson et al., 2003). The Nakasib-Bir Umq Suture juxtaposes the ~870–790 Ma Jeddah–Haya terrane in the south with the ~830–720 Ma Hijaz–Gebeit terrane to the north (Fig. 1; Abdelsalam and Stern, 1996a; Johnson et al., 2003; Johnson

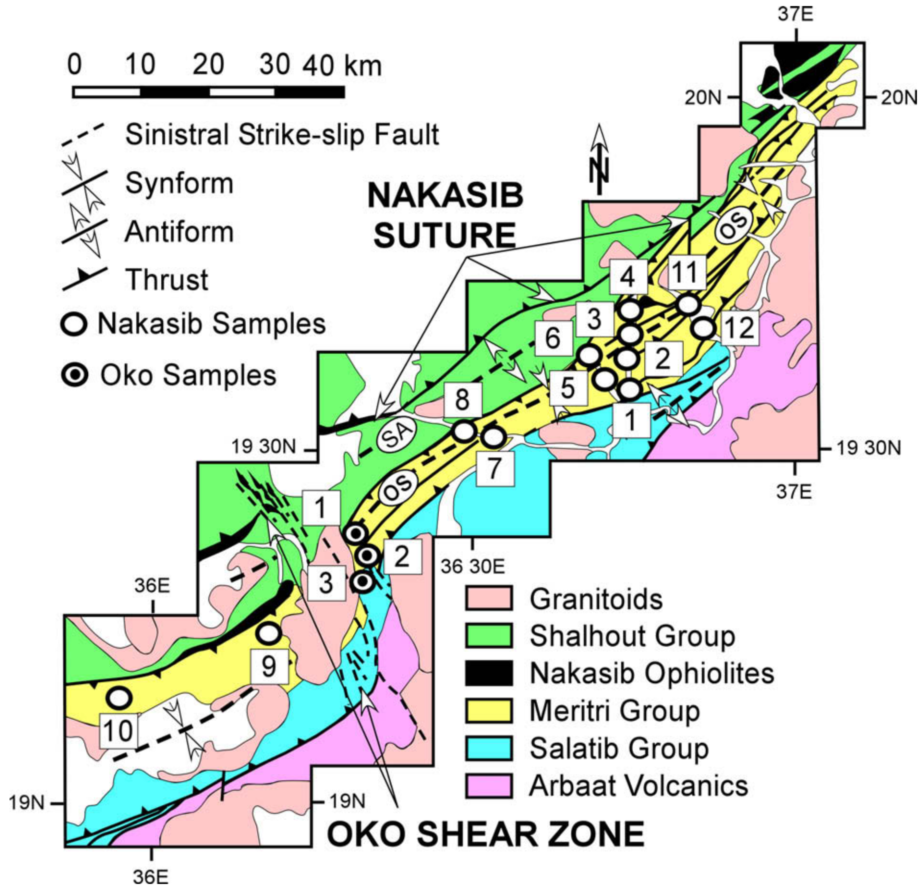

Fig. 2. Geological map of the Nakasib Suture and the Oko Shear Zone. The location of strain measurements from the Nakasib Suture are shown as open circles whereas those from the Oko Shear Zone are shown as nested circles. Numbers corresponds to those in Table 1. SA = Shalhout Antiform and OS = Olig Synform.

and Woldehaimanot, 2003). Deformation across the Nakasib-Bir Umq Suture probably occurred at ~780–760 Ma (Abdelsalam, 1994; Stern and Abdelsalam, 1998; Johnson et al., 2003). The sinistral strike-slip faults of the Oko Shear Zone apparently offset the Nakasib Suture by ~10 km (Fig. 2). These cross-cutting structures form N- to NNW-trending, 30 km wide complex deformational belt (Almond and Ahmed, 1987; Abdelsalam, 1994).

The geology of the Nakasib Suture and the Oko Shear Zone is outlined in Abdelsalam and Stern (1993a,b) and Abdelsalam (1994). Five tectono-stratigraphic groups were identified across the suture (Fig. 2). These are from south to north, the Arbaat volcanics, the sedimentary rocks of the Salatib group and the Meritri group, the Nakasib ophiolites, and the volcanic and sedimentary rocks of the Shalhout group (Fig. 2). These groups are separated by thrusts and intruded by syn-tectonic and post-tectonic granitoids (Fig. 2).

The Arbaat volcanic rocks are ~780 Ma old, thoeliitic, rift-related mafic volcanic rocks with subordinate felsic volcanic rocks and siliciclastic sedimentary rocks. The Salatib and Meritri groups are composed of siliciclastic sedimentary rocks as well as felsic tuffs, ignimbrites, and rhyolites. The Meritri group is characterized by a ~2 km thick polymict conglomerate with predominantly plutonic clasts in the northeastern part of the Nakasib Suture and predominantly volcanic clasts to the southwest. Abdelsalam and Stern (1993a) suggested that the Arbaat, Salatib, and Meritri groups signify development of a passive margin on the northern flank of the Haya terrane prior to collision between that Haya and Gebeit terranes and the formation of the Nakasib Suture.

The Nakasib ophiolites are mafic–ultramafic fragments which occur along the Nakasib Suture and mark the limbs of the NE-trending Shalhout antiform (Fig. 2). Features diagnostic to ophiolites have been identified, including pillow-structures and cumulate layering in gabbroic bodies. These ophiolitic fragments are dominantly NE-trending along the Nakasib Suture to the east and west of the Oko Shear Zone. However, within the Oko Shear Zone the trend of ophiolite fragments change to N and NW due to subsequent deformation.

The Shalhout group occupies the region to the north of the Nakasib ophiolites (Fig. 2). It is made-up of felsic and intermediate volcanics, tuff, agglomerate, ignimberite, fine turbidite, and minor limestone beds. Geochemical data suggests that these rocks are arc-related (Abdelsalam and Stern, 1993a).

Polymict conglomerates from the Meritri group have been used in this study as strain markers. These conglomerates are matrix-supported and occupy the core of the Olig synform (Fig. 2). The matrix consists of lithic wacke and minor carbonates. The clasts are comprised of granites, granodiorites, diorites, rhyolites, ignimbrites and carbonates, with a few clastic sedimentary rocks. Plutonic clasts are the most abundant and they make up ~50% of the total clasts. Volcanic clasts account for ~35% and sedimentary clasts represent ~15%.

3. Structural evolution

Fig. 3, adopted from Abdelsalam and Stern (1993c), summarizes the structural evolution of the Nakasib Suture and the Oko Shear Zone. Deformation associated with both the Nakasib Suture and the Oko Shear Zone occurred under low greenschist facies metamorphism (Abdelsalam and Stern, 1993a,b; Abdelsalam, 1994). This is particularly evident from the mineral assemblages of the metamorphosed mafic volcanic rocks where typical low

Table 1
Dimensions of pebbles and calculated *k*-values, *v*-values and magnitudes of principal axes.

Nakasib Suture	Sample #	*x* (cm)	*y* (cm)	*z* (cm)	*k*	*v*
Location 1	1	12	9	6	0.67	0.17
	2	20	10	5	1.00	0.00
	3	17	13	10	1.03	−0.01
	4	30	12	7	2.10	−0.26
	5	18	11	5	0.53	0.23
	6	19	12	6	0.58	0.20
	7	20	10	7	2.33	−0.32
	8	19	16	9	0.24	0.54
	9	18	14	8	0.38	0.38
	10	30	19	11	0.80	0.09
				Average	0.97	0.10
Location 2	11	10	7	5	1.07	−0.03
	12	9	7	4	0.38	0.38
	13	13	7	6	5.14	−0.60
	14	13	10	6	0.45	0.32
	15	13	8	4	0.63	0.18
				Average	1.53	0.05
Location 3	16	10	8	4	0.25	0.51
	17	14	7	5	2.50	−0.35
	18	17	12	6	0.42	0.33
	19	10	7	6	2.57	−0.40
				Average	1.43	0.03
Location 4	20	10	4	3	4.50	−0.52
	21	11	7	4	0.76	0.11
	22	5	3	2	1.33	−0.11
	23	13	6	5	5.83	−0.62
	24	12	8	3	0.30	0.42
				Average	2.55	−0.15
Location 5	25	23	18	15	1.39	−0.15
	26	15	10	4	0.33	0.39
	27	46	24	14	1.28	−0.09
	28	28	20	9	0.33	0.41
	29	18	14	8	0.38	0.38
	30	28	20	10	0.40	0.35
	31	20	12	10	3.33	−0.47
	32	17	10	4	0.47	0.27
	33	16	12	6	0.33	0.41
	34	40	24	14	0.93	0.03
				Average	0.92	0.15
Location 6	35	34	18	12	1.78	−0.22
	36	22	13	10	2.31	−0.33
	37	17	14	8	0.29	0.48
	38	32	20	14	1.40	−0.14
	39	21	12	6	0.75	0.11
	40	15	12	6	0.25	0.51
	41	12	8	4	0.50	0.26
				Average	1.04	0.10
Location 7	42	20	14	10	1.07	−0.03
	43	10	6	6		−1.00
	44	25	14	14		−1.00
	45	17	10	8	2.80	−0.41
	46	11	6	6		−1.00
				Average	1.94	−0.69
Location 8	47	24	10	4	0.93	0.02
	48	28	20	14	0.93	0.03
	49	24	20	7	0.11	0.70
	50	20	16	7	0.19	0.57
	51	18	12	6	0.50	0.26
				Average	0.53	0.32
Location 9	52	36	18	9	1.00	0.00
	53	14	10	5	0.40	0.35
	54	14	12	8	0.33	0.45
	55	11	10	5	0.10	0.76
	56	18	12	8	1.00	0.00
				Average	0.57	0.31
Location 10	57	20	18	16	0.89	0.06
	58	20	16	12	0.75	0.13
	59	28	16	11	1.65	−0.20
	60	29	24	10	0.15	0.64
	61	24	20	7	0.11	0.70
	62	30	20	9	0.41	0.33

Table 1 (*continued*)

Nakasib Suture	Sample #	*x* (cm)	*y* (cm)	*z* (cm)	*k*	*v*
	63	40	34	12	0.10	0.73
	64	12	8	4	0.50	0.26
	65	24	20	11	0.24	0.53
	66	19	16	7	0.15	0.66
				Average	0.49	0.38
Location 11	67	15	8	4	0.88	0.05
	68	17	12	8	0.83	0.08
	69	12	8	4	0.50	0.26
	70	35	25	15	0.60	0.21
	71	36	30	17	0.26	0.51
	72	50	25	15	1.50	−0.15
	73	40	25	20	2.40	−0.36
	74	70	40	35	5.25	−0.61
	75	8	4	3	3.00	−0.41
				Average	1.69	−0.05
Location12	76	22	9	5	1.81	−0.21
				Average	1.81	−0.21
Oko Shear Zone	Sample #	*a* (cm)	*b* (cm)	*c* (cm)	*k*	*v*
Location 1	1	18	7	6	9.43	−0.72
	2	9	3	2	4.00	−0.46
	3	10	3	3		−1.00
	4	10	5	4	4.00	−0.51
	5	16	7	4	1.71	−0.19
	6	36	14	12	9.43	−0.72
	Sample #	*X* (cm)	*Y* (cm)	*Z* (cm)	*k*	*v*
	7	18	6	4	4.00	−0.46
	8	20	6	6		−1.00
	9	20	10	8	4.00	−0.51
	10	32	14	8	1.71	−0.19
	11	20	9	8	9.78	−0.74
	12	11	5	4	4.80	−0.56
	13	12	5	5		−1.00
	14	12	7	6	4.29	−0.56
	15	18	9	6	2.00	−0.26
	16	17	7	6	8.57	−0.70
	17	21	9	9		−1.00
	18	20	10	5	1.00	0.00
	19	25	15	10	1.33	−0.11
	20	17	8	7	7.88	−0.70
				Average	4.87	−0.57
Location 2	21	14	5	4	7.20	−0.64
	22	21	10	7	2.57	−0.35
	23	12	6	4	2.00	−0.26
	24	14	6	3	1.33	−0.10
	25	8	6	5	1.67	−0.22
	26	28	10	8	7.20	−0.64
	27	42	20	14	2.57	−0.36
	28	24	12	8	2.00	−0.26
	29	28	12	6	1.33	−0.10
				Average	3.10	−0.33
Location 3	30	20	9	7	4.28	−0.52
	31	31	14	10	3.04	−0.41
	32	17	14	10	0.54	−27.00
	33	8	3	2	3.33	−0.42
	34	14	4	3	7.50	−0.63
	35	15	7	4	1.52	−0.15
	36	25	15	14	9.33	−0.76
	37	26	14	12	5.14	−0.60
	38	21	14	8	0.67	0.16
	39	27	10	6	2.55	−0.32
	40	9	6	5	2.50	−0.38
	41	10	5	5		−1.00
	42	13	7	3	0.64	0.16
	43	30	8	6	8.25	−0.64
	44	35	10	6	3.75	−0.42
	45	17	10	8	2.80	−0.41
	46	19	6	4	4.33	−0.48
	47	32	8	4	3.00	−0.33
	48	18	6	6		−1.00
	49	37	10	5	2.70	−0.31
	50	40	10	4	2.00	−0.20
				Average	3.57	−0.40

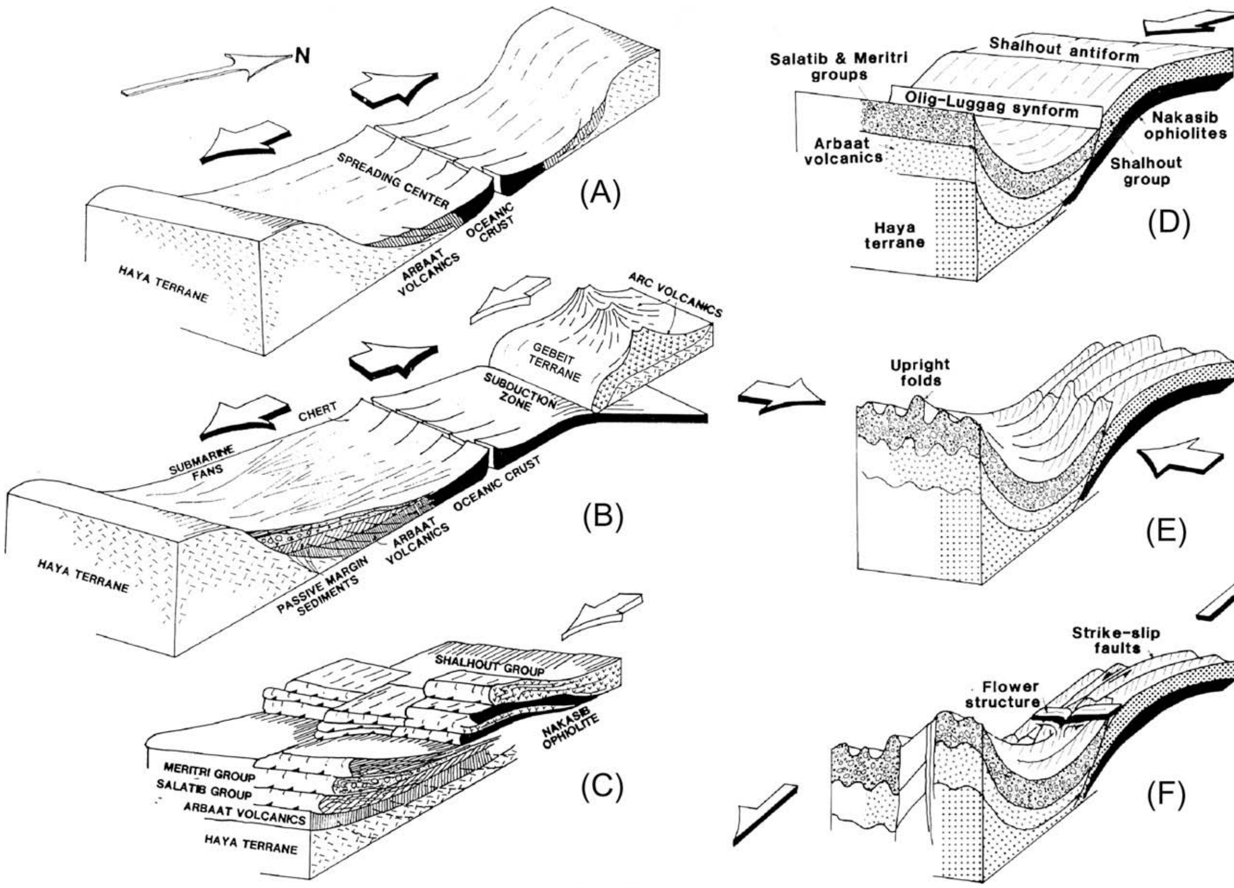

Fig. 3. Six-step, three-dimensional diagrams illustrating the evolution of the Nakasib Suture and the Oko Shear Zone (after Abdelsalam and Stern, 1993c). (A) Rifting of the Haya terrane and the extrusion of the Arbaat volcanic rocks. (B) Deposition of the passive margin sedimentary rocks on the southern flank of the oceanic basin (Salatib and Meritri groups). Extrusion of arc volcanic rocks over a NW-dipping subduction zone beneath the north rifted block of the Haya terrane (the Shalhout group). (C) Emplacement of SE-verging nappes during the early stage of the Nakasib deformation. (D) Refolding of the SE-verging nappes by the NE-trending upright folds. (E) Development of N-trending upright tight folds during the early stage of the Oko deformation as a result of E–W directed shortening. (F) Initiation of NW-trending sinistral strike-slip faults of the Oko deformation.

greenschist facies metamorphic minerals such as chlorites and green amphiboles are observed. Deformation along the Nakasib Suture probably took place between ~780 and 740 Ma in the form of nappe emplacement from northwest to southeast. This was followed by refolding of NE-trending sub-horizontal structures associated with nappes about NE-trending axes. This deformation is interpreted as associated with a Wilson cycle orogeny where rifting of the Haya terrane resulted in the development of an oceanic basin followed by the development of N-dipping subduction zone over which the arc volcanic of the Gebeit terrane were built (Fig. 3a). Closure of the oceanic basin resulted in collision between the Haya and Gebeit terrane and emplacement of nappes from northwest to southeast and subsequent folding of nappes about NE-trending axes (Figs. 3b and c). The Oko Shear Zone was subsequently superimposed on the Nakasib Suture between ~700 and 560 Ma due to shortening of the Arabian–Nubian Shield between converging fragments of East and West Gondwana. E–W directed shortening resulted in the development of early N-trending shortening zones in the form of N-trending upright folds (Fig. 3d) followed by late NW-trending sinistral strike-slip faults (Fig. 3e and f). Structures associated with the Nakasib Suture will be referred to as the "Nakasib deformation," and those associated with the Oko Shear Zone will be referred to as the "Oko deformation".

3.1. The Nakasib deformation

The structures of the Nakasib Suture were formed as a result of the collision between the Haya terrane and the Gebeit terrane ~750 Ma (Abdelsalm and Stern, 1993b,c). As interpreted by Abdelsalam and Stern (1993b), the continuous deformation that resulted in the formation of the Nakasib Suture can be divided into three phases.

The first deformational phase resulted in the formation of SE-verging and SW-plunging tight to isoclinal folds. The transition between the first and second phase is marked by the development of SE-verging thrusts. This was responsible for the tectonic stacking of the Nakasib ophiolites from northwest to southeast (Figs. 2 and 3c). Continued folding of the SE-verging structures by the second phase of deformation was generally coaxial. This created NE-trending, SE-verging tight folds including the Shalhout antiform and the Olig synform (Fig. 3d). These early folds were refolded during the third phase of deformation into NE-trending, gentle, upright and horizontal antiforms and synforms. Associated with these folds are widely spaced, NE-trending, upright to steeply SE-dipping crenulation cleavages and sub-horizontal NE-trending, intersection and crenulation lineations. This phase is also responsible for the NW-verging thrusts which emplaced the Meritri group over the Nakasib ophiolites (Figs. 2 and 3).

3.2. The Oko deformation

The Oko deformation was superimposed onto the structures of the Nakasib Suture (Fig. 2) as a result of early E–W directed shortening that produced early N-trending folds, and late NW-trending sinistral strike-slip faults. The Oko deformation might be due to shortening of the Arabian–Nubian Shield between converging fragments of East and West Gondwana at ∼670–610 Ma (Abdelsalam, 1994).

The Oko deformation can be divided into three phases. The first phase of deformation, initiated by E–W directed shortening and produced N- to NNW-trending upright folds that are generally tight to isoclinal (Fig. 3e). This folding culminated with the formation of the strike-slip faults of the second phase of deformation at ∼640–560 Ma (Fig. 3f). These strike-slip faults formed as a conjugate set of steeply dipping NW- to NNW-trending sinistral strike-slip faults and NE-trending dextral strike-slip faults along the inflection planes of the first phase folds (Fig. 3f). The NW- to NNW-trending sinistral strike-slip faults dominated, rotating the NE-trending Nakasib structures to a northward orientation adjacent to their fault planes. The NE-trending dextral strike-slip faults, in contrast, are not well developed in the Oko Shear Zone.

The deformation continued during the third phase of deformation to form E- and W-verging thrust sheets constituting a flower structure (Fig. 3f), with sub-horizontal kinks and buckles that deform the steeply dipping underlying fabric. The flower structures are likely derived from the strike-slip faults.

4. Strain analysis

The conglomerate clasts used as strain markers in this study are from the Meritri Group along the Nakasib Suture, including its intersection with the Oko Shear Zone. In situ measurements of the length of the long, intermediate and short axes of the clasts, as well as the trend and plunge of their long and short axes, were made during the winter of 1990. The trend and plunge of the clasts intermediate axes were constructed to be perpendicular to the orientations of their long and short axes. Locations of the measurements are shown in Fig. 2. A total of 76 clasts from 12 locations were measured along the Nakasib Suture, with an additional 50 clasts measured from three locations within the Oko Shear Zone. The number of clasts measured per location ranges from 1 to 10 for the Nakasib Suture and from 9 to 21 for the Oko Shear Zone (Table 1). The length of the long axes of the clasts ranges between 5 and 70 cm and the length of the short axes ranges between 2 and 34 cm (Table 1). These measurements do not directly correspond to the 3D strain ellipsoid. Rather, they represent the shape of the clasts which might manifests both initial ellipticity and tectonic strain.

4.1. Clasts rheology, shapes, orientations, and nature of strain ellipsoids

All conglomeratic clasts used in this study are estimated to be deformed through ductile strain. No signs of cataclasis deformation, solution pressure, or veining are observed in the clasts. Table 1 shows the results of the length measurements on X–Y and Y–Z planes of the inferred strain ellipsoid measured from individual clasts. From that the two-dimensional (2D) ellipticity (R) on the X–Y (Rxy) and Y–Z (Ryz) planes, and the three-dimensional clast shape (k-values) were calculated using the equations below (Flinn, 1962).

$$Rxy = x/y \quad (1)$$

$$Ryz = y/z \quad (2)$$

where

x = the length of the long axis in cm,
y = the length of the intermediate axis in cm,
z = the length of the short axis in cm,
Rxy and Ryz are used to calculate the k-values of individual clasts (Table 1) using the equation:

$$k = (Rxy - 1)/(Ryz - 1) \quad (3)$$

A k-value of 1 indicates plane strain, k-values greater than 1 indicate constriction strain (prolate or cigar-shaped strain ellipsoid), and k-values less than 1 indicate flattening strain. The higher the k-value above 1 the more constriction strain. The lower the k-value below 1 the more flattened the strain ellipsoid.

Similarly, the Rxy and Ryz values are used to calculate the v-values and E_s-values (Hsu, 1966) of individual clasts (Table 1) using the equations:

$$v = (\ln Ryz - \ln Rxy)/\ln Rxz \quad (4)$$

$$E_s = [(\ln Rxy)^2 + (\ln Ryz)^2 + (\ln Rzx)^2]/(3^{1/2}) \quad (5)$$

where

$$Rzx = z/x \quad (6)$$

Plane strain has a v-value of zero. Negative v-values indicate constriction strain whereas positive v-values indicate flattening strain. Higher positive v-values indicate more flattening and lower negative v-values indicate more constriction. On the other hand, E_s-values quantify the departure of the strain ellipsoid from the perfect sphere which has an E_s-value of zero. The higher the E_s-value the more flattening or constriction.

Rxy and Ryz for all conglomeratic clasts from the Nakasib Suture and Oko Shear Zone are plotted to produce a Flinn Diagram (Fig. 4a; Flinn, 1962) whereas the v and E_s-values are plotted to produce a Hsu Diagram (Fig. 4b; Hsu, 1966). The averaged k-values per location for conglomeratic clasts from the Nakasib Suture are found to be ranging from 0.49 to 2.55 and v-values ranging from -0.69 to 0.38 (Table 1). The average k-values per location for conglomeratic clasts from the Oko Shear Zone are ranging from 3.1 to 4.87 and v-values ranging from −0.57 to −0.33 (Table 1). This indicates that the majority of the Nakasib clasts are flattened whereas the majority of the Oko clasts are deformed by constriction strain. This is also shown by the Flinn and the Hsu Diagrams (Fig. 4a and b). In addition, the data shown in Flinn Diagram can be interpreted as that the initial flattening strain within the Nakasib Suture was replaced by constriction strain with the onset of the Oko deformation indicating a deformation path that started with flattening strain and was subsequently changed into a constriction strain (Fig. 4a).

Plot of the average k- and v-values for individual locations along the Nakasib Suture and the Oko Shear Zone is shown in Fig. 5. The k-values and v-values along the central part of the Nakasib Suture indicate flattening strain (k-values < 1 and positive v-values), although some k- and v-values indicate minor constriction strain (k-values > 1 and negative v-values). This constriction strain can be explained as resulting from refolding of earlier structures associated with SE-verging nappes by subsequent NE-trending folds (Fig. 3d). In contrast, the k-values and v-values from within the Oko Shear Zone reveal a high degree of constriction strain throughout the zone (Fig. 5).

The orientation of the major and minor axes of conglomeratic clasts for the Nakasib Suture and the Oko Shear Zone is shown in Fig. 6. The orientations of the intermediate axes are determined to be perpendicular to both the major and minor axes. The resulting average orientations of the principal axes of the strain ellipsoids for the Nakasib Suture and the Oko Shear Zone are plotted on equal-area stereonets and are shown in Fig. 7a and b. Stereonet plots show that the overall orientation of the clasts from the Nakasib Suture long axis is 193°/31°, intermediate axis is 42°/56°, and short axis is 291°/14°. The Oko Shear Zone has a major axis with an orientation of 100°/67°, an intermediate axis with an orientation of 354°/8°, and a minor axis with an orientation of 261°/22°.

The quadratic elongation for the principal axes for both the Nakasib Suture and the Oko Shear Zone, $\lambda 1$, $\lambda 2$ and $\lambda 3$, are calculated using the equations:

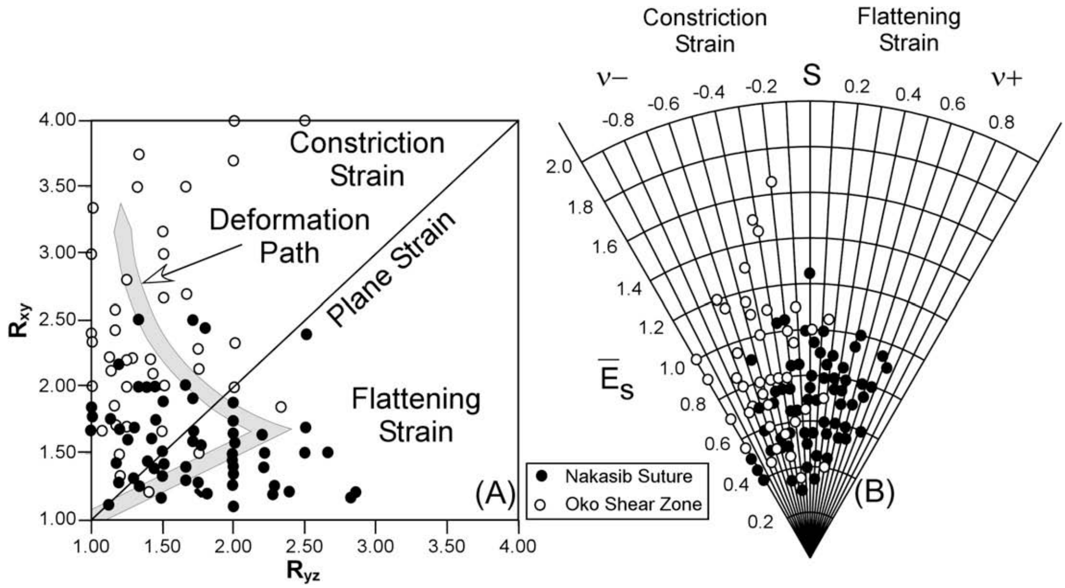

Fig. 4. (A) Flinn and (B) Hsu diagrams of the conglomeratic clasts from the Nakasib Suture and the Oko Shear Zone. The majority of the clasts from the Nakasib Suture plot in the flattening field. The clasts from the Oko Shear Zone plot in the constriction field. Both plots display strain intensity and geometry.

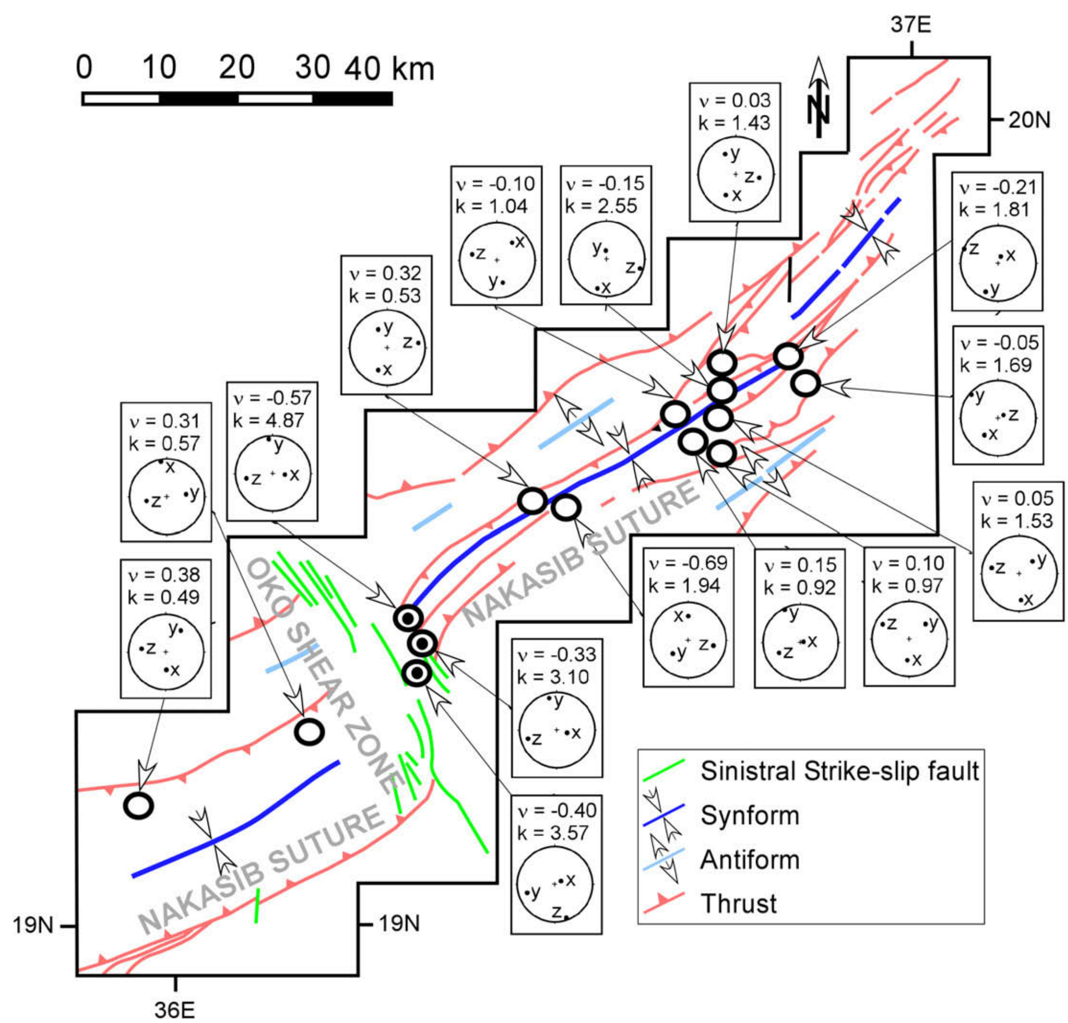

Fig. 5. The *k*- and *ν*-values as well as the orientations of the major, intermediate, and minor principal axes of clasts from the Nakasib Suture and the Oko Shear Zone.

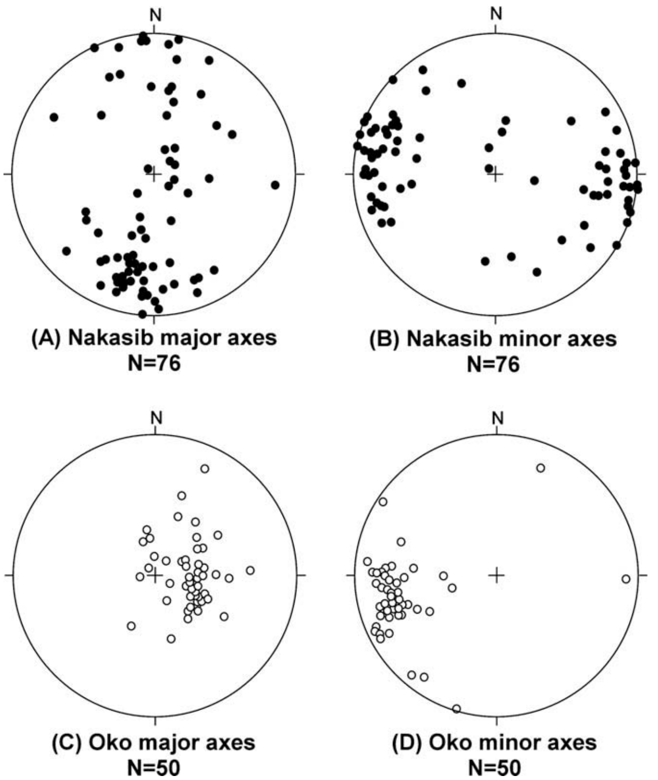

Fig. 6. Stereonet plot of: (A) the orientations of the major axes of clasts from the Nakasib Suture. $N = 76$. The average orientation is 193°/31°. (B) The orientations of the minor axes of clasts from the Nakasib Suture. $N = 76$. The average orientation is 291°/14°. (C) The major axes of clasts from the Oko Shear Zone. $N = 50$. The average orientation is 100°/67°. (D) The minor axes of clasts from the Oko Shear Zone. $N = 50$. The average orientation is 261°/22°.

$$\lambda 1 = x^2/R^2 \quad (7)$$

$$\lambda 2 = y^2/R^2 \quad (8)$$

$$\lambda 3 = z^2/R^2 \quad (9)$$

where

$$R = (xyz)^{1/3} \quad (10)$$

The average quadratic elongations of the principal axes for the Nakasib Suture are: $\lambda 1 = 2.6$, $\lambda 2 = 1.1$ and $\lambda 3 = 0.39$. The average quadratic elongations of the principal axes for the Oko Shear Zone are $\lambda 1 = 4.2$, $\lambda 2 = 0.73$ and $\lambda 3 = 0.39$ (Table 1).

4.2. Strain tensors

The strain tensors, S_I and S_F, for the Nakasib Suture and the Oko Shear Zone, respectively, were calculated by inserting the average quadratic elongation of the principal axes, $\lambda 1$, $\lambda 2$ and $\lambda 3$; the plunge of the principal axes, $\Phi 1$, $\Phi 2$ and $\Phi 3$; and the trend of the principal axes, $\theta 1$, $\theta 2$ and $\theta 3$, into the following tensor in equation below (Nielsen, 1983).

$$S = \begin{vmatrix} \sin\Phi 1 & \sin\Phi 2 & \sin\Phi 3 \\ \cos\Phi 1\cos\theta 1 & \cos\Phi 2\cos\theta 2 & \cos\Phi 3\cos\theta 3 \\ \cos\Phi 1\ \sin\theta 1 & \cos\Phi 2\ \sin\theta 2 & \cos\Phi 3\ \sin\theta 3 \end{vmatrix} \times \begin{vmatrix} \lambda 1 & 0 & 0 \\ 0 & \lambda 2 & 0 \\ 0 & 0 & \lambda 3 \end{vmatrix} \times \begin{vmatrix} \sin\Phi 1 & \cos\Phi 1\ \cos\theta 1 & \cos\Phi 1\ \sin\theta 1 \\ \sin\Phi 2 & \cos\Phi 2\ \cos\theta 2 & \cos\Phi 2\ \sin\theta 2 \\ \sin\Phi 3 & \cos\Phi 3\ \cos\theta 3 & \cos\Phi 3\sin\theta 3 \end{vmatrix} \quad (11)$$

where (1) denotes the major principal axis, (2) denotes the intermediate principal axis, and (3) denotes the minor principal axis.

These calculations transform the 3D strain data from a sample reference frame to an absolute geographic space coordinate, hence enables the calculations of the superimposed 3D strain (Fig. 8). The array elements in the tensor represent parameters to define the trend and plunge of the three principal axes of the strain ellipsoid in the absolute geographic space coordinates as well as values of quadratic elongations along these axes. Subsequent decomposition of the tensor reveals the actual values of the quadratic elongations of the three principal axes in terms of eigenvalues and trend and plunge of these axes defined by direction cosines. The eigenvalues matrix will have positive diagonal elements and zero values for the off-diagonal elements. The $x11$ value is then represents $\lambda 1$; the $x22$ value represents $\lambda 2$, and the $x33$ value represents $\lambda 3$. On the other hand, the eigenvectors matrix contains positive or negative values for all elements. The first column elements in the matrix ($y11$, $y21$, $y31$) are direction cosines of the orientation of the major principal axis of the strain ellipsoid. These values represent cosines of α, β, and γ (Fig. 8), respectively. Equally, the second column in the eigenvector matrix ($y12$, $y22$, $y32$) corresponds to the cosines of α, β, and γ of the intermediate axis (Fig. 8). The third column in the eigenvector matrix ($y13$, $y23$, $y33$) defines the cosines of α, β,

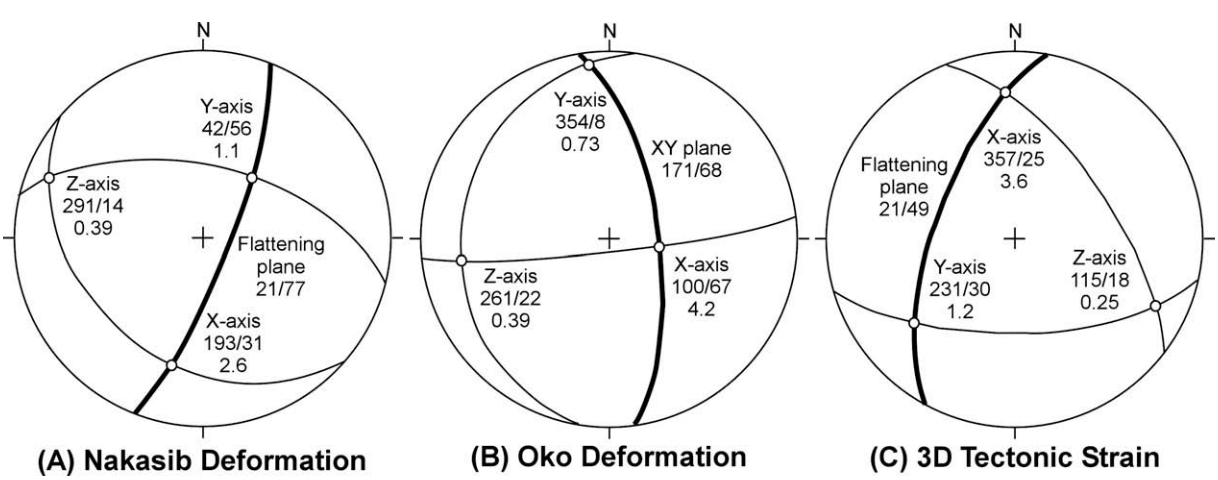

Fig. 7. Stereonet plots of: (A) the overall orientations of the principal axes for the Nakasib Suture, (B) the overall orientations of the principal axes for the Oko Shear Zone, (C) the overall orientations of the principal axes for the 3D tectonic strain.

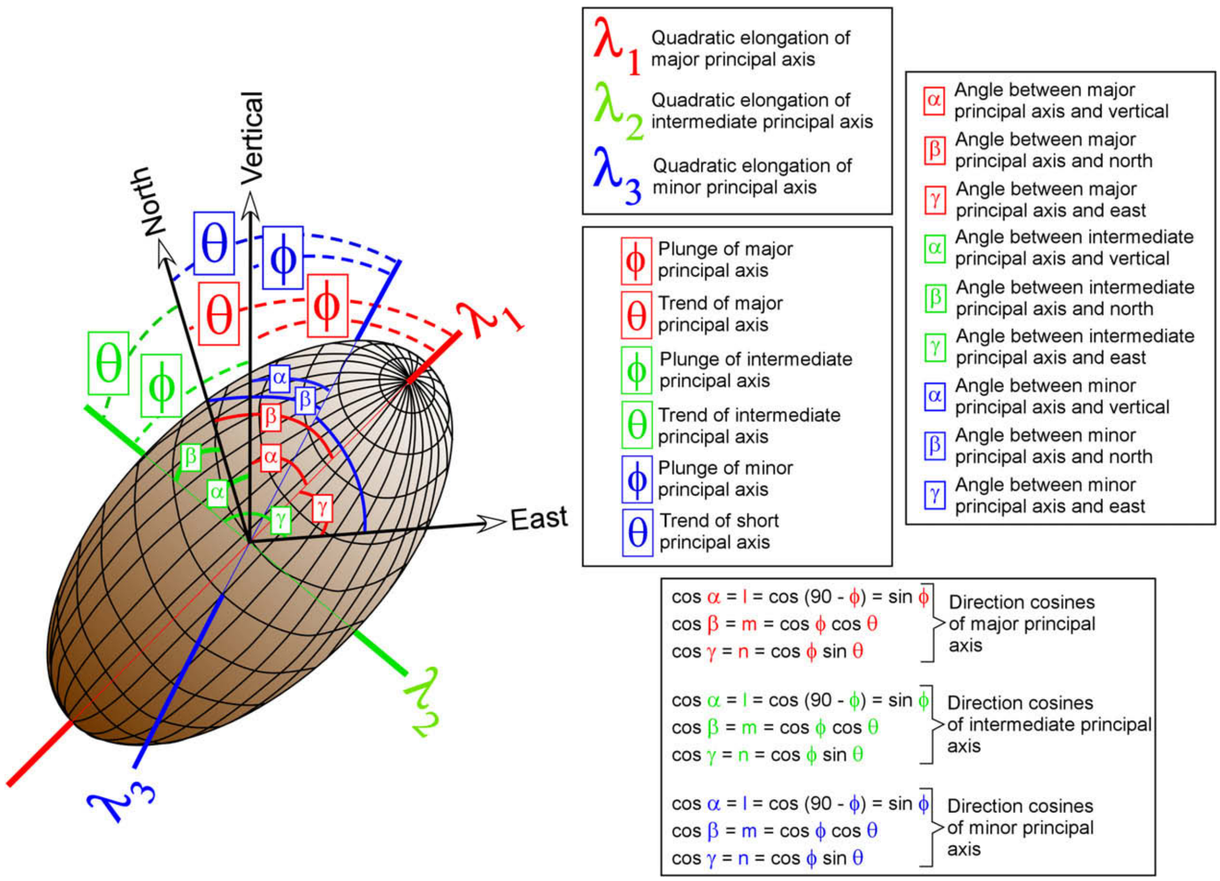

Fig. 8. A diagram illustrating transforming 3D strain data from sample reference frame to an absolute geographic space coordinate using Eq. (11).

and γ of the minor axis of the strain ellipsoid (Fig. 8). The positive and negative numbers in the eigenvector matrix will ultimately results in fixing the trend and plunge of the three principal axes of the strain ellipsoid relative to the geographic coordinates. This will be explained below.

4.2.1. Nakasib strain tensor

The Nakasib strain tensor (S_I) represents the initial strain ellipsoid that was subsequently modified along the Oko Shear Zone by the superimposition of the Oko deformation. The average values for the quadratic elongation and the trend and plunge of the principal axes is used to determine the strain tensor for the Nakasib Suture are as follows:

$$\lambda 1 = 2.624 \quad \Phi 1 = 31^{\circ} \quad \theta 1 = 193^{\circ}$$
$$\lambda 2 = 1.102 \quad \Phi 2 = 56^{\circ} \quad \theta 2 = 42^{\circ}$$
$$\lambda 3 = 0.393 \quad \Phi 3 = 14^{\circ} \quad \theta 3 = 291^{\circ}$$

When these values are inserted into Eq. (11), the following strain tensor results:

$$S_I = \begin{vmatrix} 1.476 & -0.716 & -0.005 \\ -0.716 & 2.068 & 0.470 \\ -0.005 & 0.470 & 0.574 \end{vmatrix}$$

4.2.2. Oko strain tensor

The Oko strain tensor (S_F) represents the finite strain ellipsoid resulting from the superimposition of the Oko Shear Zone on the Nakasib Suture. The average values for the quadratic elongation and the trend and plunge of the principal axes used to determine the strain tensor for the Oko Shear Zone are as follows:

$$\lambda 1 = 4.245 \quad \Phi 1 = 67^{\circ} \quad \theta 1 = 100^{\circ}$$
$$\lambda 2 = 0.729 \quad \Phi 2 = 8^{\circ} \quad \theta 2 = 354^{\circ}$$
$$\lambda 3 = 0.390 \quad \Phi 3 = 22^{\circ} \quad \theta 3 = 261^{\circ}$$

When these values are inserted into Eq. (11), the following strain tensor results:

$$S_F = \begin{vmatrix} 3.666 & -0.186 & 1.360 \\ -0.186 & 0.735 & -0.133 \\ 1.360 & -0.133 & 0.963 \end{vmatrix}$$

4.2.3. 3D tectonic strain tensor

The tectonic strain tensor (S_T) represents the 3D strain ellipsoid superimposed on the Nakasib strain tensor (S_I) to produce the finite strain tensor (S_F), which is the cumulative Nakasib and Oko strain. It can be determined using the equation (Nielsen, 1983):

$$S_F = S_T \times S_I \tag{12}$$

where S_F is the finite strain tensor (Nakasib deformation + Oko deformation), S_I is the initial strain tensor (Nakasib deformation), and S_T is the 3D tectonic strain (Oko deformation). Solving this equation for S_T yields:

$$S_T = S_F \times S_I^{-1} \tag{13}$$

By inserting the Nakasib and Oko strain tensors determined above into this equation, the following 3D tectonic strain tensor is found:

$$S_T = \begin{vmatrix} 2.662 & 0.354 & 2.100 \\ 0.144 & 0.562 & -0.691 \\ 0.832 & -0.196 & 1.844 \end{vmatrix}$$

This strain tensor describes the tectonic strain associated with the Oko Shear Zone that was superimposed on the strain tensor of the Nakasib Suture to yield the strain currently present in the Oko Shear Zone.

It is possible to determine the magnitude and orientation of the principal axes of the 3D tectonic strain ellipsoid from its strain tensor (Nielsen, 1983). First, the eigenvalues and eigenvectors of the squared 3D tectonic strain tensor must be found. The quadratic elongations of the three principal axes can be determined by taking the square root of the three resulting eigenvalues. The columns of the eigenvectors represent the direction cosines of the principal axes. From these the trend and plunge of the principal axes can be determined using these formulae (Nielsen, 1983):

$$\text{plunge} = \arcsin(n) \tag{14}$$

$$\text{trend} = \arctan(m/l) \tag{15}$$

where *l*, *m*, and *n* are direction cosines of the inferred superimposed strain ellipsoid

$$\begin{vmatrix} l \\ m \\ n \end{vmatrix} = \begin{vmatrix} \cos\alpha \\ \cos\beta \\ \cos\gamma \end{vmatrix} \tag{16}$$

The squared 3D tectonic strain tensor is:

$$(S_T)^2 = \begin{vmatrix} 8.885 & 0.731 & 9.220 \\ 0.110 & 0.503 & -1.361 \\ 3.722 & -0.176 & 5.284 \end{vmatrix}$$

Decomposition of the above tensor will yield the following eigenvalues and eigenvectors:

$$\text{Eigenvalues} = \begin{vmatrix} 13.193 & 0 & 0 \\ 0 & 1.419 & 0 \\ 0 & 0 & 0.060 \end{vmatrix}$$

$$\text{Eigenvectors} = \begin{vmatrix} 0.903 & 0.548 & 0.398 \\ -0.054 & 0.672 & -0.862 \\ 0.426 & -0.497 & -0.313 \end{vmatrix}$$

Using the eigenvalues and eigenvector matrices above $\lambda1$, $\lambda2$, and $\lambda3$ and their trend and plunge can be calculated as follows:

$$\lambda1 = 13.193^{1/2} = 3.6$$

$$\lambda2 = 1.419^{1/2} = 1.2$$

$$\lambda3 = 0.060^{1/2} = 0.25$$

For $\lambda1$, $l = 0.903$; $m = -0.054$; $n = 0.426$.
The plunge = arcsin (n) = arcsin (0.426) = 25.226°.
The trend = arctan (m/l) = arctan (−0.054/0.903) = arctan (−0.060) = −3.395°.

For $\lambda2$, $l = 0.548$; $m = 0.672$; $n = -0.497$.
The plunge = arcsin (−0.497) = −29.817°.
The trend = arctan (0.672/0.548) = arctan (1.226) = 50.814°.

For $\lambda3$, $l = 0.398$; $m = -0.862$; $n = -0.313$.
The plunge = arcsin (−0.313) = 18.220.
The trend = arctan (−0.862/0.398) = arctan (−2.166) = −65.223.

The signs (positive or negative) of the trend and plunge control their measurement relative to north and whether or not the plunge is in the same direction of the trend azimuth or opposite to it. Positive signs indicate measurement of the trend in a clockwise direction from north whereas negative signs indicate measurement of the trend in an anticlockwise direction from the north. Positive sign indicate that the plunge is in the same direction of the azimuth of the trend whereas negative signs indicate that it is opposite to it. Hence, the major axis has a quadratic elongation of $\lambda1 = 3.6$ and a trend and plunge of 357°/25°. The intermediate axis has a magnitude of $\lambda2 = 1.2$ and a trend and plunge of 231°/30°. The minor axis has a magnitude of $\lambda3 = 0.25$ with a trend and plunge of 115°/18° (Fig. 7c).

5. Results and comparison between strain analysis and field observations

Results of this work can be summarized as follows:

1. The Nakasib Suture is characterized by dominant flattening deformation that can be approximated by strain ellipsoids whose major principal axes plunge SSW and flattening plane dips steeply to the SSE (Fig. 7A). This suggests an overall SE-NW directed shortening consistent with the generally NE-SW trend of the structures associated with the Nakasib Suture (Figs. 2 and 5). The presence of constriction strain (Figs. 4 and 5) combined with the steep nature of the flattening plane (Fig. 7A) may reflect the refolding of the early SE-verging sub-horizontal folds and thrusts of the Nakasib Suture about a NE-trending axis. This produced the antiforms and synforms which dominate the entire length of the Nakasib Suture (Figs. 2 and 5).
2. The Oko Shear Zone is dominated by constriction deformation that can be represented by a strain ellipsoid with a sub-vertical major principal axis and a *XY* plane steeply dipping to the E (Fig. 7B). This is consistent with the observed structures where tight steeply plunging to the north folds dominate the Oko Shear Zone (Abdelsalam, 1994). The steep nature of the major principal axis of the strain ellipsoid suggests that the E–W directed shortening associated with the Oko Shear Zone was superimposed on the NW–SE directed shortening associated with the Nakasib Suture, hence producing a prolate strain ellipsoid with a sub-vertical major principal axis.
3. The strain ellipsoid developed from the 3D tectonic strain tensor has a sub-horizontal major principal axis and a flattening plane that strikes NNW–SSE and dips moderately to the NW (Fig. 7C). The minor principal axis of the strain ellipsoid is oriented NW–SE. This indicates that the overall shortening was NW–SE directed and therefore not orthogonal to the N-trending structures observed along the Oko Shear Zone.

6. Discussion and conclusions

The Nakasib Suture, developed through collision of the Haya terrane and the Gebeit terrane at ~750 Ma, is characterized by a flattening strain whose strain ellipsoid has a flattening plane that strikes 21° and dips 77° to the SE. The minor zones of constriction present in the Nakasib Suture may be the result of subsequent refolding of these initial SE-verging nappes about NE-trending axes to produce NE-trending upright folds (Figs. 2 and 5). The strain present in the Oko Shear Zone represents the composite strain of the Nakasib deformation and the Oko deformation. It is characterized by constriction strain whose *XY* plane strikes 171° and dips 68° to the E. The early E–W and late NW–SE directed shortening associated with the Oko Shear Zone is represented by a strain ellipsoid with a flattening plane that strikes 21° and dips 49° to the W. Its major axis has a quadratic elongation of 3.6 with a trend and plunge of 357°/25°, its intermediate axis has a quadratic elongation of 1.2 with a trend and plunge of 231°/30° and its minor axis has a quadratic elongation of 0.25 with a trend and plunge of 115°/18°.

The orientation of the minor axis of the 3D tectonic strain ellipsoid (115°/18°), which corresponds to the direction of imposed shortening, is not completely orthogonal to many of the N-trending shortening zones of the Arabian–Nubian Shield, especially the Oko Shear Zone and the Hamisana Shear Zone (Fig. 1). These N-trending shortening zones have been interpreted as due to E–W directed shortening imposed on the Arabian–Nubian Shield due to convergence between East and West Gondwana. (Stern et al., 1990; Miller and Dixon, 1992; Abdelsalam, 1994; de Wall et al., 2001). The non-orthogonal relationship between the calculated orientation of the imposed shortening and the orientation of the shortening zones can be explained as follows: (1) shortening in the Arabian–Nubian Shield might have started as perfectly E–W directed but was rotated into a more ESE–WNW directed in a later stage; or (2) shortening was imposed as ESE–WNW directed throughout convergence between East and West Gondwana. However, strain localization within the Arabian–Nubian Shield into N-trending shortening zones might be due to N-trending controlling zones of lithospheric dimension, such as lithospheric attenuation (Stern et al., 1990). However, the presence of NW-trending stretching lineation that has been interpreted as approximating plate motions of East and West Gondwana (Shackleton, 1986), as well as the conclusion that collision between East and West Gondwana was oblique (Berhe, 1990), make results of this work support the explanation that convergence between East and West Gondwana was dominantly non-orthogonal. This is further supported by the fact that at least the tectonic boundary (Keraf Suture in Fig. 1) between the Arabian–Nubian Shield and West Gondwana (represented by the Saharan Metacraton of Abdelsalam et al. (2002)) in northern Sudan is defined by a transpressional zone associated with an overall sinistral transpression (Abdelsalam et al., 1995, 1998; Abdelsalam and Stern, 1996b). However, this interpretation should be taken with the understanding that it assumes the absence of within-plate deformation except within discrete deformation belts where strain was homogeneously accommodated. Although this assumption is difficult to adopt for many orogenic belts, it might not be far from accurate in the Arabian–Nubian Shield given the linear and discrete nature of deformation belts, especially in its central and southern parts.

The relationship between N-trending shortening zones and NW-trending sinistral strike-slip zones within the Arabian–Nubian Shield has been explained by that the NW-trending structures were developed as zones of high shear strain within an overall E–W shortening strain that produced the N-trending structures (Abdelsalam, 1994). This interpretation requires the presence of NE-trending dextral strike-slip faults in the Arabian–Nubian Shield as complementary conjugate set to the NW-trending sinistral strike-slip faults. Such NE-trending dextral strike-slip faults have been reported in the Arabian–Nubian Shield, although not well developed (Berhe, 1990; Stern et al., 1990). Considering that the early N–S trending shortening zones and late NW-trending sinistral strike-slip faults of the Arabian–Nubian Shield resulted from a post-accretionary ESE–WNW directed shortening, then it is more likely that NW-trending sinistral-strike slip faults will prevail over NE-trending dextral strike-slip faults if the two evolved as conjugate sets. This explains why the NW-trending sinistral strike slip faults dominated over the complimentary NE-trending dextral strike-slip faults.

Acknowledgements

The field work in the Nakasib Suture and the Oko Shear Zone was partially supported by the Geological Authority of the Sudan (GRAS). The author would like to thank Tahir Belo for assistance during strain data collection. The author also thank Dr. David Dunn for review and comments during the preparation of the manuscript. Thanks are also due to two anonymous reviewers for detailed comments and constructive criticism.

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