Terrane rotation during the East African Orogeny: Evidence from the Bulbul Shear Zone, south Ethiopia

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Abstract

The 100 km long, N-trending, Neoproterozoic–Early Paleozoic Bulbul Shear Zone in southern Ethiopia is marked by sheared ophiolites at the interface between the Arabian–Nubian Shield in the north and the Mozambique Belt in the south. This shear zone separates the low-grade metavolcanic and meta-sedimentary rocks of the Bulbul Terrane in the east from the medium- to high-grade gneisses, migmatites and granulites of the Alghe Terrane in the west. Stretching lineations along the Bulbul Shear Zone vary from NE-plunging in the northern part, shallowly N- and S-plunging in the central part, to SE-plunging in the south. These lineations are developed along N-trending mylonitic foliation that is moderately to steeply E-dipping. The northern part of the Bulbul Shear Zone is dominated by SW-verging fold and thrust belt indicating top-to-the southwest tectonic transport. The central part is characterized by dextral strike-slip displacement. The southern part is dominated by E-dipping oblique normal-slip planes associated with top-to-the southeast tectonic transport. Down dip stretching lineations along E-dipping slip planes are well-developed in the eastern part of the Algte terrane and the western part of the Bulbul terrane. We interpret the along-strike variation of stretching lineations and kinematic indicators as due to NE–SW directed oblique collision between the Bulbul Terrane and the Alghe Terrane accompanied by anti-clockwise rotation of the Bulbul Terrane. Such collision and rotation are manifested by SW-verging fold and thrust belt in the north, N-trending dextral strike-slip shear zone in the center, and SE-directed normal-slip displacement in the south. This tectonic event might have occurred between 820 and 580 Ma. This was followed by E-ward slipping of the Bulbul Terrane relative to the Algte Terrane, probably between 580 and 500 Ma.

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1. Introduction

Southern Ethiopia is underlain by Neoproterozoic–Early Paleozoic rocks, which were formed and/or deformed during the East African Orogeny associated with collision between East and West Gondwana (Stern, 1994; Fig. 1) after the closure of the Mozambique Ocean (Santosh et al., 2006; Vaughan and Pankhurst, 2008). Meert (2003) and Meert and Lieberman (in press) have proposed two phases during the assembly of Gondwana. The first phase includes the East African Orogeny (eastern Africa and Arabia) which spanned the period between 700 and 570 Ma whereas the second phase was the Kuunga Orogeny which occurred between 570 and 530 Ma and this is now preserved mainly in southeastern Africa, western and northern Antarctica, and western India. Recent ⁴⁰Ar/³⁹Ar age data from the Ross Orogen in Antarctica suggest that the final suturing between East and West Gondwana was accompanied by short-lived, but regional constriction deformation between ~515–510 and ~495 Ma (Paulsen et al., 2007).

The Bulbul Shear Zone is a Neoproterozoic–Early Paleozoic structure in southern Ethiopia (Fig. 2) separates the low-grade metavolcanic and meta-sedimentary rocks of the Bulbul Terrane in the east from the medium- to high-grade gneisses, migmatites and granulites of the Alghe Terrane in the west (Fig. 3). It is one of three (Megado, Kenticha, and Bulbul) 13 km wide and ~100 km long, N-trending belts in southern Ethiopia (Fig. 2). These belts occur as low-grade volcano-sedimentary-ophiolite zones within
medium- to high-grade gneisses, migmatites and granulites rocks (Beraki et al., 1989; Worku and Yifa, 1992; Worku and Schandelmeier, 1996; Yibas et al., 2002; Yihunie and Tesfaye, 2002; Tsige and Abdelsalam, 2005; Fig. 1).

The Arabian–Nubian Shield (dominated by juvenile Pan-African (900–500 Ma) accreted island arc, back-arc and oceanic plateaus terranes, and abundant ophiolites, all metamorphosed under greenschist condition) and the Mozambique Belt (characterized by medium- to high-grade gneisses and granulites, and scarce juvenile Pan-African materials, especially ophiolites) are collectively referred to as the East African Orogen (Stern, 1994, in press). The current understanding is that the Arabian–Nubian Shield and the Mozambique Belt were formed in structural and metamorphic continuity during Tibetan-style collision between East and West Gondwana occurred along the Mozambique Belt (Chen, 2001; Muhongo et al., 2001) and a contemporaneous Andean-type oblique collision occurred in the Arabian–Nubian Shield (Divi et al., 2001). This accounts for the differences in lithospheric thickness, grade of metamorphism, and intensity of deformation, which is generally higher in the Mozambique Belt relative to the Arabian–Nubian Shield (Stern, 1994).

Three models have been proposed to explain the relationship between the Megado, Kenticha, and Bulbul Belts on one hand, and the surrounding medium- to high-grade grade gneisses, migmatites and granulites on the other hand: (1) These belts represent remnants of a once coherent E-verging nappe that was subsequently refolded about N-trending axes. Erosion of this E-verging, refolded nappe left behind the Megado, Kenticha, and Bulbul Belts as distinct N-trending zones preserved within N-trending synforms (Beraki et al., 1989; Worku and Yifa, 1992; Worku and Schandelmeier, 1996). This model implies E–W directed shortening due to convergence between East and West Gondwana. In addition, the model suggest a “basement-cover” relationship between the Mozambique Belt and the Arabian–Nubian Shield in which the continental lithosphere of the Mozambique Belt extends north underneath the juvenile low-grade belts of the Arabian–Nubian Shield. (2) These belts represent the escape roots of N-ward expulsion of the Arabian–Nubian Shield from the Mozambique Belt due to Tibetan-type collision between East and West Gondwana along the Mozambique Belt (Burke and Sengor, 1986; Bonavia and Chorowicz, 1992; Stern, 1994). This model predicts that the Megado, Kenticha, and Bulbul belts are dominantly strike-slip faults and most probably with dextral sense of shearing in the east and sinistral sense of shearing in the west. (3) Some of these belts are dominated by low-angle oblique normal faults developed in association with late Neoproterozoic–Early Paleozoic regional gravitational collapse following over-thickening of the lithosphere underlying the East African Orogen (Tsige and Abdelsalam, 2005).

Structural styles along the Bulbul Shear Zone points out to a combination of the three end-member models outlined above. Yihunie and Tesfaye (2002), Yihunie (2003), and Yihunie et al. (2004) have examined the northern part of the shear zone and identified NE-plunging stretching lineation associated with SW-verging fold and thrust belt. These structures have been interpreted as indicating top-to-the southwest tectonic transport and that the Bulbul Terrane is an allochthon that has been emplaced in a southwestward direction over the Alghe Terrane. In addition, the presence of steep N-trending mylonitic foliation and abundance of Z-folds in parts of the shear zone have led these authors to suggest that the SW-verging fold and thrust belt was subsequently deformed by N-trending dextral strike-slip shearing. On the other hand, Tsige and Abdelsalam (2005) have used the presence of SE-plunging lineation, sheath folds, rotated feldspar porphyroblasts, displaced quartz veins, and SC fabric, all indicating top-to-the-southeast tectonic transport in the southern part of the Bulbul Shear Zone to conclude that the belt is an E-dipping oblique normal-slip shear zone across which the Bulbul Terrane has slipped southeastward marking a regional gravitational tectonic collapse.

In this work, we have systematically collected stretching lineations and kinematic indicators to address the significance of structural variation along the Bulbul Shear Zone. We have used these data to produce a new tectonic model that involves SW-directed oblique collision between the Bulbul and Alghe Terranes.
accompanied by anti-clockwise rotation of the Bulbul Terrane. This was subsequently followed by eastward slipping of the Bulbul Terrane. Our model reconciles the contrasting structural styles along the Bulbul Shear Zone and document the involvement of terrane rotation about vertical axis during the East African Orogeny. Farther, we discuss the importance of terrane rotation in the evolution of orogenic belts by comparing the evolution of the Bulbul Shear Zone to other orogenic belts where terrane rotation is documented from paleomagnetic and kinematic studies.

2. Geological setting

Geological, geochemical and geochronological data (Fig. 2) presented by Rogers et al. (1965), Jelenc (1966), Kazmin (1975, 1976), Kazmin et al. (1978), De Wit and Chewaka (1981), Beraki et al. (1989), Berhe (1990), Tolessa et al. (1991), Abraham et al. (1992), Worku and Yifa (1992), Ghebreab (1992), Woldehaimanot (1995), Worku (1996), Worku and Schandelmeier (1996), Hussien (1999), Teklay et al. (1998), Tsige (1999, 2003), Yibas (2000), Yihunie and Tesfaye (2002), Yibas et al. (2002), Yihunie (2003), Yihunie et al. (2004), and Tsige and Abdelsalam (2005) have helped in constraining the tectonic evolution of the Neoproterozoic–Early Paleozoic terranes of southern Ethiopia within the East African Orogen (Stern, 1994). Most age data obtained from these rocks range between 870 and 500 Ma with the exception of older Mesoproterozoic ages obtained from detrital zircons in different rock units (Yibas et al., 2002). In this regard, southern Ethiopia is considered as the southernmost part of the Arabian–Nubian Shield since no Neoproterozoic island arc-ophiolitic assemblages are observed south of the Ethiopian–Kenyan border (Fig. 2). The low-grade volcano-sedimentary-mafic/ultra-mafic assemblages have been interpreted as remnants of oceanic or back-arc basins now preserved as suture zones. A Wilson cycle orogenic process has been advocated to explain the
The Bulbul Shear Zone is one of the Neoproterozoic–Early Paleozoic N-trending belts in southern Ethiopia. It separates the Alghe Terrane in the west from the Bulbul Terrane to the east (Fig. 3). Below is a brief description of the Alghe and the Bulbul Terranes. The Bulbul Shear Zone will be addressed in a separate section since it is the focus of this study.

2.1. The Alghe Terrane

The Alghe Terrane (Yihunie and Tesfaye, 2002) is the southern extension of the Alghe gneiss of Kazmin (1975) and Kazmin et al. (1978), and it is the equivalent of the Zembaba domain of Worku and Schandelmeier (1996). The Alghe Terrane consists of biotite-hornblende and biotite gneisses, quartz-feldspathic gneisses and granitic migmatites. These are intruded by pre-, syn- and post-tectonic granitoids. These rocks crop out as low-lying, small to larger domed masses. The gneisses are well-layered with individual layers commonly a few centimeters thick but rarely reach a thickness of 1 m. The most common migmatite structures include stromatic, nebulitic, agmatic, schollen, and contorted or folded structures. In the western part of the Alghe Terrane, local mobilisates-rich in garnet and pyroxenes suggest that the metamorphic grade may have exceeded the amphibolite facies.

The gneisses and migmatitic layering of the Alghe Terrane is NNW- to NNE-trending (Fig. 4A) folded by rootless intra-folial folds (Fig. 4B). However, the gneissic layering is generally moderately to steeply E- and W-dipping suggesting the presence of a NNE-trending map-scale open antiform (Fig. 4C).
Numerous mesoscopic N- to NNE-trending open folds are associated with the map-scale antiform.

2.2. The Bulbul Terrane

The Bulbul Terrane (Yihunie and Tesfaye, 2002) is made-up of semi-pelitic schists, amphibole schist, and ultramafic slivers. This layered sequence comprises well-foliated medium-grained rocks. These rocks crop out as patches or small equant rounded blocks due to spheroidal weathering, and rarely in small sheet-like outcrop patterns. The layered rocks of the Bulbul Terrane are intruded by pre- and syn-tectonic granitic bodies, and the eastern and southern extensions of the terrane are covered by Jurassic limestone and Quaternary soil (Yihunie and Tesfaye, 2002).

The schistosity of the Bulbul Terrane is generally N- to NNW-trending, moderately to steeply E-dipping and commonly cross-cut by N-trending step, but still E-dipping axial planar cleavage associated with W- to SW-verging mesoscopic folds (Fig. 5A). The intersection of the two foliation sets produces a strong N-trending, sub-horizontal pencil structure (Fig. 5B). The mesoscopic folds are associated with map-scale NNE-trending, sub-horizontal W- to SW-verging antiform (Fig. 5C).

3. Structures within the Bulbul Shear Zone

The Bulbul Shear Zone is 5–7 km wide, N-trending belt that extends for more than 100 km. The northern extent of the shear zone is not clear since it is intruded by a post-shear zone granitic body (Fig. 2). In the south, the shear zone terminates against the bow-shaped dextral Didesa-Adoba Shear Zone (Fig. 2). The northern exposures of the Bulbul Shear Zone occupy relatively low-lying land while its southern part is defined by N-trending ridges. The Bulbul Shear Zone is strongly sheared and is marked by prominent N-trending mylonitic foliation that contains variably NE-plunging, sub-horizontal N- and S-plunging, and SE-plunging stretching lineation. In the southern exposures the foliation is overprinted by NE- and E-trending foliation associated with the Didesa-Adola Shear Zone (Fig. 3).

The western contact of the Bulbul Shear Zone is defined by anastomosing shear zones enclosing lenses of various units from the Alghe Terrane. Rocks from the Alghe Terrane that are enclosed within the Bulbul Shear Zone are deformed by N-trending, moderately to steeply E-dipping mylonitic foliation. Similarly, the schistosity in various rocks of the Bulbul Terrane is strongly overprinted by the mylonitic foliation close to the eastern contact of the Bulbul Shear Zone.

Thin section investigation indicates that the mylonites are mainly composed of quartz (up to 45%) and orthoclase and...
microcline (up to 44%). Plagioclase is not common but when present it reaches between 3 and 20%. Opaque minerals, dominantly decomposed sulfides, range from trace amounts to up to 25%. Other accessory minerals include biotite, calcite, chlorite, muscovite, sphene, zircon, apatite, and epidote. Muscovite and chlorite occur as alteration products of biotite, and calcite replaces plagioclase. Fine to ultra-fine matrix (mylonitic to ultra-mylonitic texture) is common. Porphyroclasts of K-feldspar and quartz are embedded in the fine-grained matrix. Deformation lamellae (low-angle grain boundaries) in quartz are common. Typical fabric of dynamically recrystallized quartz and feldspars (such as the development of neocrystals at the margins of porphyroclasts) is observed in most of the thin sections.

We conclude that the N-trending mylonitic foliation and the enclosed NE-plunging, sub-horizontal N- and S-plunging, and SE-plunging stretching lineations in the Bulbul Shear Zone were formed during a single tectonic pulse rather than representing the superimposition of more than one deformation event. We base this on the following: (1) The stretching lineations are enclosed within a uniform mylonitic foliation without evidence for superimposition of more than one generation of planar fabric. (2) To the best of our observations, stretching lineations with different trends are almost exclusive to different parts of the Bulbul Shear Zone. No superimposition of lineations of different orientations is observed in any segment of the shear zone. It is important to note that down-dip E-plunging stretching lineation enclosed within E-dipping slip planes is observed in various parts of the Bulbul Shear Zone as well as the Bulbul and Alghe Terranes. These planar and linear fabrics, however, are clearly younger that the dominant regional structures of the Bulbul Shear Zone.

Below we discuss structures, especially stretching lineations and kinematic indicators, within the Bulbul Shear Zone by dividing it into northern, central and southern segment (Fig. 3). Each segment shows distinctive structural style, but merging gradationally into each other. Additionally, we describe E-dipping slip planes and associated E-plunging stretching lineation separately, since these represent a separate set of planar and linear structures.

3.1. The Northern Bulbul Shear Zone

This part of the Bulbul Shear Zone extends in a NNE direction for more than 40 km with 5 to 10 km width on average (Fig. 3). It is dominated by N- to NNE-trending mylonitic foliation dipping steeply to moderately to the E and ESE (Fig. 6A). The mylonitic foliation contains NE-plunging stretching lineation (Fig. 6A and B). This foliation is well-defined and overprints the schistosity in the western margin of the Bulbul Terrane and the gneissic and migmatitic layering in the Alghe Terrane. The mylonitic foliation is particularly well-developed in pre-shear zone granodioritic rocks although slivers from the meta-volcanic and meta-sedimentary rocks of the Bulbul Terrane and gneisses and migmatites of the Alghe Terrane are not uncommon, especially in...
the eastern and western margins of the shear zone. The NE-plunging stretching lineation is defined by strongly stretched quartz grains (Fig. 6B). The trend of the stretching lineation is clearly oblique to the easterly dip direction of the mylonitic foliation with a pitch angle averaging ~45° (Fig. 6B).

Within the shear zone, the mylonitic foliation contains isoclinal intra-folial tight to isoclinal folds, sometimes showing evidence of co-axial, but non co-planar refolding (Fig. 6C). The axial surfaces of these folds closely coincide with the N- to NNE-trend of the mylonitic foliation whereas their hinges are sub-vertical or steeply E-plunging. The presence of such intra-folial folds indicates a strong E–W directed constriction component in the northern part of the Bulbul Shear Zone. Additionally, the northern part of the Bulbul Shear Zone is characterized by the presence of numerous open to tight asymmetrical reclined Z-folds. The axial surfaces of these folds are sub-vertical and NNW-trending oblique to the N- and NNE-trend of the mylonitic foliation. The presence of asymmetrical Z-folds indicates dextral strike-slip component within the northern part of the Bulbul Shear Zone. This gives place to dominantly SW-verging mesoscopic folds and thrusts in the east within the Bulbul Terrane (Fig. 5B, C and D).

3.2. The Central Bulbul Shear Zone

The central part of the Bulbul Shear Zone extends for ~20 km in a N–S direction with ~5 km width on average (Fig. 3). This part of the shear zone is characterized by the presence of N-trending, moderately to steeply E-dipping mylonitic foliation that contains shallowly N- and S-plunging stretching lineation (Fig. 7A, B, and C). The stretching lineation is defined by highly-stretched quartz grains. Similar to the northern Bulbul Shear Zone, the mylonitic foliation in the central part is well-developed and deforms pre-shearing granodiorite rocks. Kinematic indicators, such as mesoscopic shear zones (Fig. 7D) and reclined Z-folds with sub-vertical, NNW-trending axial surfaces indicate dextral-strike slip shearing. However, unlike the northern part, the central part of the Bulbul Shear Zone lacks isoclinal intra-folial folds and mesoscopic thrusts suggesting that constriction deformation might have not played a significant role in the evolution of this part of the shear zone.

3.3. The Southern Bulbul Shear Zone

The southern part of the Bulbul Shear Zone extends in a N–S direction for ~40 km with ~5 km width on average (Fig. 3). In the south, it deflects into the NW-trending Didesa-Adola Shear Zone (Fig. 3). This part of the shear zone is defined by well-developed N-trending, moderately to steeply E-dipping mylonitic foliation which contains SE-plunging stretching lineation (Fig. 8A and B). The stretching lineation is defined by elongated quartz and feldspar grains and rarely by alignment of aggregates of amphibole and biotite grains. The trend of the stretching lineation is oblique.

Fig. 7. Orientation data and mesoscopic structures from the central part of the Bulbul Shear Zone. (A) Plot of poles to mylonitic fabric (solid circles, \( N = 61 \)) and stretching lineation (solid triangles, \( N = 23 \)). (B) Steep, N-trending mylonitic foliation. (C) Sub-horizontal stretching lineation within mylonitic foliation. (D) Dextral strike-slip shearing on N-trending plane.
to the E-dipping direction of the mylonitic foliation with a pitch angle averaging ~45°. The mylonitic foliation transsects the N-trending gneissic and migmatitic layering in the Alghe Terrane and the schistosity in the Bulbul Terrane. These relations are especially clear at the contacts of the Bulbul Shear Zone.

Z-folds, sheath folds, asymmetric rotated feldspar porphyroclasts, and S–C fabrics are the most common mesoscopic structures and kinematic indicators in this part of the Bulbul Shear Zone. All these kinematic indicators point to top-to-the-southeast tectonic transport. Mesoscopic folds within the southern part of the Bulbul Shear Zone and around its margins deform earlier planar fabric including the gneissic and migmatitic layering and the mylonitic foliation. The hinge zones of the Z-folds plunge steeply to the southeast whereas their fold axial surfaces strike NW to NNW and are very steep to vertical. The cone axes of the sheath folds dominantly plunge to the southeast parallel to the stretching lineation. Asymmetric recrystallized tails on K-feldspar porphyroclasts observed on exposure cuts parallel to strike and dip directions show sigma structures consistent with a shear sense on the mylonites involving both strike and dip directions. This indicates both dextral strike-slip and dip-slip components. S–C fabric is observed in the southern part of the Bulbul Shear Zone on exposure cuts parallel to the dip direction and shows the same shear sense as the porphyroclasts.

3.4. Younger slip planes

Down-dip E-plunging stretching lineation (Fig. 9A) contained within E-dipping slip planes (Fig. 9B and C) is widely spread throughout the Bulbul Shear Zones as well as in the eastern margin of the Alghe Terrane and the western margin of the Bulbul Terrane. The slip planes are in the form of discrete spaced fabric that are clearly superimposed on the mylonitic foliation within the Bulbul Shear Zone (Fig. 9C) as well as on the gneissic and migmatitic layering of the Alghe Terrane and the schistosity of the Bulbul Terrane. Most of the E-plunging stretching lineation observed within these slip planes are defined by the elongation of mafic minerals, especially biotite and brown amphibole.

4. Structural and tectonic synthesis

We summarize the structural and tectonic evolution of the Bulbul Shear Zone and the surrounding Alghe and Bulbul Terranes into: (1) NE–SW directed oblique collision; (2) Anti-clockwise terrane rotation; and (3) E-ward gravitational slip.

4.1. NE–SW directed oblique collision

The Alghe and Bulbul Terranes have been affected by a major deformational event resulting in the development of the
N–S trending gneissic and migmatitic layering in the Alghe Terrane later folded about a sub-horizontal NNE-trending antiform (Fig. 10A). This event was likely the result of a regional constriction tectonic event that pre-dated the development of mylonitic foliation and stretching lineation in the Bulbul Shear Zone. We suggest that this event was associated with an early stage of oblique NE–SW directed collision between the Alghe and Bulbul Terranes along a suture that has been subsequently overprinted by the Bulbul Shear Zone. Our interpretation is based on the following: (1) The presence of mafic and ultramafic rocks in the Bulbul Terrane as well as in the eastern margin of the Bulbul Shear Zone that have been interpreted as remnants of ophiolites and referred to as the Negele ophiolites (Kazmin, 1976; Yibas et al., 2002; Yihunie and Tesfaye, 2002). (2) The presence of deep sea sediments associated with ophiolites east of the study area (Kazmin, 1976; Yibas et al., 2002). (3) The SW-verging folds and thrusts in the western margin of the Bulbul Terrane consistent with a southwestward tectonic transport oblique to the N-trend of the orogen front.

4.2. Anti-clockwise terrane rotation

As convergence between the Alghe and Bulbul Terrane continues, The Bulbul Terrane started emplaced over the Alghe Terrane as an allochthon. However, because of the oblique NE–SW collision between the Alghe and Bulbul Terranes relative to the N-trend of the organic front, the Bulbul Terrane rotated anti-clockwise relative to the Alghe Terrane. Such a rotation led to: (1) Continuation of the emplacement of the Bulbul Terrane from northeast to southwest over the Alghe Terrane as an allochthon. This resulted in the development of
the northern part of the Bulbul Shear Zone as a dominantly SW-verging fold and thrust belt (Fig. 10B). This fold and thrust belt have been documented by Yihunie and Tesfaye (2002), Yihunie (2003), Yihunie et al. (2004) and this work through the presence of SW-verging mesoscopic folds and NE-plunging stretching lineation. (2) Development of the central part of the Bulbul Shear Zone as dominantly N-trending, E-dipping dextral strike-slip shear zone (Fig. 10C). (3) Development of the southern part of the Bulbul Shear Zone as an oblique normal slip zone (Fig. 10D). This has been documented by Tsige and Abdelsalam (2005) through the presence of SE-plunging stretching lineation coupled with numerous kinematic indicators suggesting top-to-the-southeast tectonic transport direction across dominantly E-dipping planes.

The timing of suturing and anti-clockwise rotation of the Bulbul Terrane is not well constrained due to lack of sufficient geochronological data. However, we summarize the available geochronological data as follows: (1) The age of the Alghe Terrane can be bracketed between 890 and 750 Ma. Teklay et al. (1998) obtained a single zircon Pb/Pb age of 884.2±0.8 Ma and Yibas et al. (2002) obtained a U/Pb age of 876±7 and 778±23 Ma from gneisses of this domain (Fig. 2). (2) No ages have been obtained for the low-grade volcano-sedimentary and mafic and ultramafic rocks of the Bulbul Terrane. However, Sm/Nd age as old as ~820 Ma has been obtained for a meta-mafic rock in the Megado ophiolite belt of the Adola area further west (Fig. 2; Worku, 1996). (3) Yihunie (2003) obtained a U–Th–Pb age as young as 580 Ma for a syn-shearing granite that intrudes the northern part of the Bulbul Shear Zone (Fig. 2). Based on these data the age of the suturing event can be bracketed between 820 and 580 Ma.

4.3. E-ward gravitational slip

Thrusting of the Bulbul Terrane across the Alghe Terrane as well as folding might have resulted in thickening of the lithosphere. Subsequently, this might have caused tectonic instability resulting in the detachment and E-directed gravitational slipping of the Bulbul Terrane from the Alghe Terrane as indicated by the presence of down-dip E-plunging stretching lineation within E-dipping slip planes.

The age of this event is not certain, but numerous K/Ar and 40Ar/39Ar (Rogers et al., 1965; Jelenc, 1966; Yibas et al., 2002), and few U/Pb, Pb/Pb, and Th–U–Pb zircon ages (Abraham et al., 1992; Worku, 1996; Teklay et al., 1998; Yibas et al., 2002; Yihunie, 2003) concentrate around 550 and 500 Ma (Fig. 2). This can be explained by that K/Ar and 40Ar/39Ar isotopic systematics had been reset as a consequence of lithospheric exhumation in southern Ethiopia leading to tectonic gravitational collapse about that time. The U/Pb, Pb/Pb, and Th–U–Pb ages are obtained from granitic intrusions (Fig. 2) and might reflect crystallization age of igneous bodies that have been emplaced close to the time of lithospheric exhumation. This suggests that the latest event in the tectonic evolution of the East African Orogeny, at least in southern Ethiopia, might have continued beyond the Neoproterozoic into Early Paleozoic.

5. Discussion

Terrane rotation about vertical axis is now widely appreciated as an important deformation component in the evolution of orogenic belts resulting from oblique collision. This deformation component might have been overlooked in many orogenic belts because it is difficult to detect from the documentation of map-scale and mesoscopic structures alone (Bol and Roeske, 1993). Additionally, structures associated with oblique collision have been traditionally interpreted in the form of an early fold and thrust belt that is subsequently overprinted by a strike-slip shearing. Such interpretation relies on the fact that the two structural styles are the result of two different deformation events.

Detailed paleo-magnetic studies in the past ten years have documented the presence of significant rotation about vertical axis of tectonic terranes and thrust sheets in different orogenic belts worldwide and through different geological times. Examples include the Ramu-Markham Fault Zone of the northeastern Papua New Guinea active collision zone (Weiler and Coe, 1997); the Oligocene Malaguid allochthon of the internal zone of the Betic Cordillera in southern Spain (Platzman et al., 2000); the Miocene External Betic-Rif arc (Plat et al., 2003); the Charleston–Nebo Salient of Utah (Conder et al., 2003); the Tertiary Southern Pyrenees Provinces in Spain (Sussman et al., 2004); the Late Miocene Taitao Ophiolite of southern Chile (Veloso et al., 2005); the Late Cretaceous Fort Knox Terrane of Alaska (Symons and McCausland, 2006); and the Early Cretaceous–Early Paleocene central Andes fore-arc in Chile (Taylor et al., 2007). In addition to paleo-magnetic studies, kinematic studies have also been used to document terrane rotation about vertical axis during oblique collision. For example Bol and Roeske (1993) have used kinematic analysis to conclude that litho-tectonic domains within the belt which separates the Mesozoic–Paleogene Chugach and Prince William Terranes (Gulf of Alaska) have been affected by clockwise rotation. This has been attributed to synchronous thrusting and dextral strike-slip faulting that occurred during accretion.

The along-strike structural variation that might accompany terrane rotation is not fully documented and understood. So far, this deformation component has been explained through the rotation of distinctive blocks bounded by relatively steep faults. The rotation of individual blocks relative to each other is accommodated as strike-slip component along domain boundaries. Bol and Roeske (1993) have explained the structural style of the contact fault system between the Chugach and Prince William Terranes in the form of clockwise rotation of structural domains with respect to each other. This rotation is accommodated by dextral strike-slip faults that post date the initial terrane accretion. This may be accounted for the apparent near-surface structural styles which are dominated by strike-slip faulting. However, rotation of structural domains about vertical axes has to be accompanied at depth with a significant sub-horizontal shearing component. It is likely that horizontal shearing is accommodated at the detachment zone separating the two colliding terranes. Moreover, it is not unlikely that the
entire terrane undergoes a coherent rotation about vertical axis as in the case of the central Andes fore-arc in Chile (Taylor et al., 2007). Hence, much of the deformation that accompanies terrane rotation will be accommodated at the interface between the colliding terranes. Additionally, depending on the trend of this zone, structural styles can vary significantly. A combination of thrusting, strike-slip shearing and normal slip shearing can be observed within the same belt as in the case of the Bulbul Shear Zone.

Recent analogue structural experiments (Soto et al., 2006) have shown a significant along-strike variation in structural styles associated with an emplacement of a rotating thrust sheets. The work of Soto et al. (2006) has emphasized strike-slip displacement as an important deformation component necessary for the accommodation of variable along-strike shortening during thrusting and vertical axis rotation. Soto et al. (2006) work has also pointed to the importance of “ductile basal conditions” during block rotation about vertical axis. In natural examples, such “ductile basal conditions”, when favorable, results in dominantly accommodation of vertical rotation at the interface between the footwall and the hanging-wall (over-riding) of the colliding terranes.

6. Conclusion

The Bulbul Terrane has rotated in an anti-clockwise direction following oblique NE–SW directed collision with the Alghe Terrane at 820 and 580 Ma along the Bulbul Shear Zone. This oblique collision and terrane rotation is manifested by a SW-verging fold and thrust belt in the northern part of the Bulbul Shear Zone, dextral strike-slip shearing in its central part, and oblique SE-directed normal-slip in the southern part. This was followed by an overall E-ward slipping of the Bulbul Terrane relative to the Alghe Terrane sometime between 580 and 500 Ma.

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