1 **Extent, Kinematics and Tectonic Origin of the Precambrian Aswa Shear Zone in**
2 **Eastern Africa**

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24 **Abstract**

25 The Aswa Shear zone (ASZ) is a fundamental Precambrian lithospheric structure that has
26 been shaped by many tectonic events in eastern Africa. It separates the Saharan Metacraton in
27 the northeast from the Northern Uganda terrane (which represents part of the Northeastern
28 Congo block of the Congo craton) to the southwest. Nonetheless, its tectonic evolution is not
29 fully understood. We used high-resolution airborne magnetic and radiometric data over Uganda
30 integrated with Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) in
31 South Sudan to assess the extent, kinematics and contribute to the understanding of the tectonic
32 origin of the ASZ. (1) Our results showed that the ASZ extends in a NW-SE for ~550 km in
33 Uganda and South Sudan. (2) The airborne magnetic and radiometric data revealed a much wider
34 (~50 km) deformation belt than the 5-10 km of the exposed surface expression of the ASZ. The
35 deformation belt is defined by three NW-trending sinistral strike-slip shear zones bounding
36 structural domains with magnetic fabric showing splays of secondary shear zones and shear-
37 related folds. These folds are tighter close to the discrete shear zones with their axial traces
38 becoming sub-parallel to the shear zones. A similar fold pattern is observed in South Sudan from
39 the SRTM DEM. We interpreted these folds as due to ENE-WSW contraction associated with
40 the sinistral strike-slip movement. (3) To the northeast, the magnetic patterns and radiometric
41 signature suggest the presence of a series of W-verging nappes indicative of strong E-W to NE-
42 SW contraction deformation. (4) We relate the evolution of the ASZ to E-W to NE-SW
43 Neoproterozoic oblique collision between East and West Gondwana. The deformation related to
44 this collision was partitioned into E-W to NE-SW contraction resulting in W-verging thrusts in
45 the east and a sinistral strike-slip movement along the NW-trending ASZ with the strain
46 localized at the boundary between the Saharan Metacraton and the Northern Uganda terrane.

Keywords: Aswa Shear Zone, Saharan Metacraton, Congo craton, East African Orogen, Gondwana.

1. Introduction

The Aswa Shear Zone (ASZ) is a fundamental NW-trending Precambrian structure in the central part of Gondwana (Figure 1A). Traces of the shear zone have been mapped in eastern and central Africa extending in a NW-SE direction from South Sudan in the northwest through Uganda, Kenya and Tanzania to the southeast and possibly into Madagascar as the Ranotsara shear zone (Figure 1A; Collins et al., 2003). It has been proposed that the ASZ extends further southeast into south India as the Achankovil shear zone in a Greater Gondwana reconstruction (Figure 1A; Santosh and Collins, 2003; Pradeepkumar and Krishnanath, 2000). Until recently, only a few generalized studies have attempted to explain the Precambrian evolution of the ASZ and most of these attempts correlated the shear zone to other Neoproterozoic NW-trending strike-slip shear zones in the Arabian-Nubian Shield, the most prominent of which is the Najd fault system which is exposed in northwestern Saudi Arabian and the Eastern Desert of Egypt (Figure 1A; Berhe, 1990; Stern 1994). Both Berhe (1990) and Stern (1994) suggested that the development of the ASZ can be linked to the collision between East and West Gondwana similar to other NW-trending strike-slip shear zones in the Arabian-Nubian Shield.

Besides its importance in understanding the Precambrian evolution of East and West Gondwana and their lithospheric structure, the ASZ is also important for understanding the development of Mesozoic and Cenozoic rifts, seismicity distribution, and controls on the Nile drainage system in eastern Africa. Recent studies in Uganda (Westerhof et al., 2014; Ruotoistenmaki, 2014; Nyakecho and Hagemann, 2014) have highlighted the importance of the

ASZ, especially as a major Precambrian structure. However, the lack of geological investigations in the better exposed part of the ASZ in South Sudan hinders full understanding of the geodynamic evolution of this structure.

In this work, we attempt to define the extent and explain the kinematics of the ASZ in Uganda and South Sudan benefiting from the availability of Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) and the newly acquired high resolution airborne geophysical data from Uganda. Additionally, we propose an origin for the ASZ within the context of East and West Gondwana tectonics.

1.1. The ASZ and Gondwana tectonics

Abdelsalam et al. (2002, 2011) suggested that the ASZ might represent the boundary between the Saharan Metacraton in the northeast and the Congo craton to the southwest (Figure 1A). The extent of the Congo craton in northeastern Congo and northwestern Uganda is referred to as the Northeastern Congo block (Figure 1B; Tack et al., 2010; Fernandez et al. 2012). This region has been further divided by Westerhof et al. (2014) into the Northern Uganda terrane, the West Nile terrane, the Lake Victoria terrane, and the West Tanzania terrane (Figure 1B). This new sub-division makes the ASZ in Uganda the boundary between the Saharan Metacraton in the northeast and the Northern Uganda terrane to the southwest (Figure 1B). However, Westerhof et al. (2014) considered the portion of the Saharan Metacraton immediately northeast of the ASZ to represent the continuation of the Northern Uganda terrane. Based on geophysical evidence that will be discussed below, we consider the region to the northeast of the ASZ in Uganda and South Sudan as part of the Saharan Metacraton.

The ASZ has been correlated to other NW-trending shear zones (including the Najd fault system) in the Mozambique belt in the south and the Arabian-Nubian Shield to the north that are collectively named the East African Orogeny (Figure 1; Stern, 1994). Burke and Sengor (1986) and Berhe (1990) postulated that the NW-trending shear zones together with minor NE-trending strike-slip shear zones represent conjugate sets of sinistral and dextral strike-slip fault systems, respectively. Further, Burke and Sengor (1986) and Berhe (1990) proposed that the shear zones were formed as a result of Neoproterozoic oblique collision between East and West Gondwana as escape roots due to northward expulsion of the Arabian-Nubian Shield from the Mozambique belt. However, Abdelsalam and Stern (1991) pointed out that the locations, trends and kinematics of these fault systems do not reconcile with an escape tectonics model as predicted by scaled models and observations from the indentation of India into Eurasia (Tapponnier et al., 1982).

A recent model for the geodynamic evolution of the ASZ (Westerhof et al. (2014)) explained the early stages of its development as a sinistral strike-slip shear zone associated with northward escape of the Arabian-Nubian Shield and the northeastern segment of the Northern Uganda terrane (shown in Figure 1B as the Saharan Metacraton) because of oblique collision between East and West Gondwana. Further, Westerhof et al. (2014) proposed that the ASZ subsequently witnessed an E-W extension triggered by N-S collision between the proto-Congo craton and the Saharan Metacraton (Figure 1A) and that the final assembly of Gondwana allowed for northwest and southeast propagation of the shear zone.

1.2. The lithospheric structure of the Aswa Shear Zone

It has been suggested that the ASZ represents the boundary between the Congo craton in the southwest (represented in Uganda by the Northern Uganda terrane of Westerhof et al. (2014))

and the Saharan Metacraton to the northeast (Figure 1B; Abdelsalam et al., 2002; 2011). Seismic tomography results suggested that the Saharan Metacraton has a lithospheric thickness of ~100 km compared to the Congo craton which has a lithospheric thickness of ~175-250 km (Abdelsalam et al., 2011). South of the ASZ, in the upper 100 km of the lithospheric column, the S-wave velocity is 2 to 6% faster relative to the Primary Reference Earth Model (PREM) while it is 2% slower relative to PREM north of the shear zone (Figure 2A; Abdelsalam et al., 2011). A similar pattern is also present in the 100-175 km depth interval of the lithosphere (Figure 2B). Additionally, from a N-S S-wave velocity profile, Abdelsalam et al. (2011) have shown that the northwestern continuation of the ASZ, which intersects the Oubanguide orogen (Figure 1A), has a much slower S-wave velocity compared to both the Congo craton and the Saharan Metacraton (Figure 2C). In addition, Craig et al. (2011) have shown that there is a sharp transition in earthquake focal depths across the ASZ where the seismogenic thickness is less than 20 km northeast of the shear zone and it is greater than 20 km southwest of it (Figure 2D). Craig et al. (2011) also observed that this sharp transition from shallow to deep seismogenic thickness coincides with a change from thin (~100 km) lithosphere northeast of the ASZ to a thick (~175 km) lithospheric southwest of the shear zone (Figure 2E).

1.3. The Aswa Shear Zone and evolution of Mesozoic and Cenozoic rifts in eastern Africa

Although no detailed information is available, the parallelism between the NW-trending ASZ and the NW-trending Mesozoic rifts in eastern Africa, especially in South Sudan, led Daly et al. (1989) to consider strain localization during the Mesozoic rifting event as being facilitated by the ASZ and other related NW-trending shear zones. In contrast, relatively more research has been carried out to explain the influence of the ASZ on the evolution of the Cenozoic-aged East

African Rift System, especially its bifurcation into an Eastern and a Western Branch and the apparent termination of the Western Branch against the shear zone (Figure 3A). The bifurcation of the East African Rift System southwest of the ASZ led Chorowicz (2005) to suggest that the shear zone has been reactivated as a “continental transform fault” where WNW-ESE extension exerted by the east-southeast motion of the Somali plate relative to the Nubian plate (Calais et al., 2006; Stamps et al., 2008; Saria et al., 2014) has been accommodated as a strike-slip motion along the shear zone.

The northern segment of the Western Branch of the East African Rift System represented by the Albertine-Rhino grabens sharply terminates against the ASZ (Figure 3B). However, the 1990-1991 earthquake events of South Sudan have been interpreted as an indication of the continuation of the Western Branch further northeast beyond the Albertine-Rhino grabens (Girdler and McConnell, 1994). Contrary to this suggestion, Katumwehe et al. (2015) have shown from airborne magnetic data that the Albertine-Rhino grabens do not extend in a northeast direction beyond the ASZ. Further, Katumwehe et al. (2015) suggested that the presence of the heterogeneous and thinned lithosphere of the Saharan Metacraton that lacks well-developed pre-existing lithospheric fabric might have prevented strain localization during the onset of rifting, hence leading to the apparent termination of the Western Branch against the ASZ.

Some of the Cenozoic shield volcanoes associated with the development of the Eastern Branch of the East African Rift System are found at or close to the intersection of the ASZ with the Cenozoic structure. For example, Mt Elgon, which is found in the Elgon depression to the west of the main trend of the Eastern Branch, is located along the trace of the ASZ (Fig. 3A). Similarly, Mt Kilimanjaro is located at the intersection of the ASZ with NE-trending structures

related to the Eastern Branch (Figure 3A). This led Fairhead (1980) to refer to the ASZ as the “leaky transform fault”.

1.4. The Aswa Shear Zone and seismicity in eastern Africa

The vicinity of the ASZ has been the site of seismic activities in eastern Africa (Figures 3A and C; Gaulon et al., 1992; Girdler and McConnell, 1994; Moussa, 2008; Craig et al., 2011), especially the 1990-1991 earthquakes in South Sudan. A significant number of earthquakes with magnitudes 7.2 and focal depth of 20-50 km were reported in 1990-1991 in South Sudan. Fault plane solutions from these earthquakes suggest sinistral strike-slip movement along NW-trending planes, normal-slip movement within WNW-trending planes, and oblique-slip movement within WNW-trending planes (Figure 3C; Moussa, 2008; Craig et al., 2011). The normal-slip movement was considered to indicate northward continuation of the East African Rift System to the northeast of the ASZ (Gaulon et al., 1992; Girdler and McConnell, 1994) whereas the strike-slip movement was interpreted to be associated with the reactivation of the ASZ into sinistral strike-slip fault due to east-southeast movement of the Somali plate away from the stationary Nubian plate (Moussa, 2008). The reactivation of the ASZ from ductile Precambrian structure to younger brittle NW-trending fractures is also apparent in remote sensing data where morphologically-defined structures are observed to coincide with the trace of the shear zone (Figure 4). This part of the shear zone has influenced the evolution of the Nile drainage system where the NE-flowing Albert Nile shifted its flowing direction by making a sharp left turn when it encountered the ASZ to become the NW-flowing Bahr el Jabal (Figure 4).

2. Regional Geology of the Aswa Shear Zone

The ASZ occupies an important region in the East African orogeny since it is exposed close to the interface between the Arabian-Nubian Shield in the north and the Eastern Granulite belt to the south which represent part of the Mozambique belt (Figure 1B). The exposed part of the shear zone in Uganda seems to separate Precambrian regions that differ in their characters. The region to the southwest of the shear zone is dominated by the Northern Uganda terrane (Figure 1B) which is composed of Mesoarchean granulites and Neoarchean gneisses, migmatites, and granitoids (Westerhof et al., 2014; Nyakecho and Hagemann, 2014). The northern part of this terrane is introduced by a largely un-deformed Neoproterozoic granitic body. Differently, the region to the northeast of the ASZ is characterized by the presence of Neoproterozoic exposures of banded granulites-charnockites complexes together with highly-sheared Neoproterozoic gneisses and granitoids, and Archean-Paleoproterozoic gneisses (Westerhof et al., 2014; Nyakecho and Hagemann, 2014). Westerhof et al. (2014) concluded that the Neoproterozoic granulites-charnockites complexes are tectonically emplaced and they represent three allochthonous sheets referred to as the Morungole, Akur and Ukatat massif (Figure 1B). These allochthonous sheets were thrust above the Archean-Paleoproterozoic gneisses. Further, Westerhof et al. (2014) proposed that the source of the Neoproterozoic banded granulites-charnockites allochthonous sheets is the deeper roots of the suture between East and West Gondwana. Fritz et al. (2013), Westerhof et al. (2014) and Nyakecho and Hagemann (2014) agreed that the Neoproterozoic rocks in the northeastern-most part of Uganda belong to the East African orogen. Westerhof et al. (2014) referred to these exposures as the Pan-African Karamoja belt (Figure 1B).

Fritz et al. (2013) linked the evolution of the ASZ to that of the Nyangere shear zone, which marks the western boundary of the Arabian-Nubian Shield (Figure 1B). Also, Fritz et al. (2013) suggested that the ASZ continues to the southeast into Tanzania and merged into a NW-trending sinistral strike slip fault referred to as the 'Jailhouse rock fault' (Figure 1B). Based on regional correlation between the ASZ and the Nyangere shear zone, Fritz et al. (2013) suggested that sinistral strike-slip activities in the ASZ might have commenced prior to ~590 Ma. This is based on cross-cutting relationships where the Nyangere shear zone is cut by an un-deformed granitic body which gave a whole rock Rb/Sr isochron age of 593 $\pm$ 50 Ma (Ries et al., 1992). Recently, Westerhof et al. (2014) reported U-Pb zircon ages of ~2,660 Ma and ~690 Ma from a migmatite granitic body that is deformed by the ASZ and interpreted the younger age as due to overprint of blasto-mylonite peak metamorphism associated with the onset of the ASZ activities. Further, Westerhof et al. (2014) interpreted a U-Pb zircon age of 659 $\pm$ 15 Ma obtained from an elongated granitic body (2-4 km wide and ~75 km long) that intrudes the northwestern part of the ASZ to indicate the age of an extensional activity in the shear zone exerted by N-S collision between the proto-Congo craton and the Saharan Metacraton.

Almond (1962) described the ASZ as a ~6 km wide zone of sinistral strike-slip shearing characterized by the development of mylonitic fabric that deforms older gneissic layering. Almond (1962) pointed out that the gneisses across the shear zone are of different character because the sinistral strike-slip movement along the shear zone brought different rock types to juxtaposition. Recent observations by Ruotoistenmaki (2014) from airborne magnetic data have shown that the ASZ is wider than what has been mapped from the surface geology. Westerhof et al. (2014) described the ASZ as a complex zone of steeply NE and NW-dipping ductile-brittle sinistral strike-slip fabric characterized by the presence of discrete blasto-mylonite high-strain

zones that enclose lenses which are relatively not affected by the shearing. Westerhof et al. (2014) also observed that in many places, the planar fabric of the ASZ deforms the gneisses of the North Uganda terrane resulting in the transposition of the older gneissic banding leading to the formation of rootless isoclinal folds. Westerhof et al. (2014) documented in some outcrops the transitioning of the blasto-mylonite fabric into pseudotachylite as well as the formation of boudinage structure due to the deformation of a pre-existing dolerite dike by the sinistral strike-slip movement of the ASZ.

3. Data and Methods

3.1. Airborne Magnetic Data

The airborne total field magnetic data we used in this study (Figure 5A) was part of a 2006-2009 data acquisition campaign by the Ugandan Department of Geological Survey and Mines (DGSM) that covered 80% of the country. The data were collected with a flight altitude of ~80 meters, line spacing of ~500 meters, and a flight orientation of ~N55°. The low magnetic inclination in the study area that ranges between -14° and -22° did not allow us to identify the sources of the magnetic anomalies using conventional methods such as the reduction to the pole. Alternatively, to highlight the general trends of the Precambrian structures through the magnetic anomalies, we have extracted a horizontal derivative map from the total field magnetic data (Figure 5B). The results of this edge detection filtering technique are not affected by the magnetic inclination, declination or remanence (Thurston and Smith, 1997; Smith and Salem, 2005). Hence, because the horizontal derivative map images the edges of the magnetized bodies, we were able to use the resulting magnetic fabric (Figure 5B) as a proxy for mapping regional Precambrian structures

We have developed a new method to measure the orientation of the strike and the dip amount and direction of the regional Precambrian structures from the airborne magnetic data. First, we used the magnetic fabric defined by the horizontal derivative map to measure the strike of the regional Precambrian structures in specific locations of the study area. Second, using the technique established by Thurston and Smith (1997), Verduzco et al. (2004), Smith and Salem (2005) and Salem et al. (2007) we developed a tilt derivative image by obtaining the ratio of the vertical derivative to the horizontal derivative of the total field airborne magnetic data (Figure 5C). In this image, the tilt distribution defines the contacts between geological materials that have alternating high and low magnetic susceptibility (Salem et al., 2007). The calculated tilt angles range between $+90^{\circ}$ and -90° with the angle values with (+) sign represent the tilt of the magnetic source towards the northeast and southeast quadrants. The angle values with (-) sign indicate tilt direction towards the SW and NW quadrants. Third, we extracted the tilt angles and directions from the tilt derivative image for the same locations where we used the horizontal derivative image to measure the strike of the magnetic fabric. This allowed us to establish strike and dip dataset for the study area.

3.2. Airborne Radiometric Data

The airborne radiometric data we used in this study (Figure 5D) was simultaneously acquired with the airborne magnetic data. The emission of gamma rays through radioactive decay of naturally occurring radioisotopes has proven useful for mapping the boundaries of geological units (Duval, 1983; Minty, 1997). Hence, gamma ray surveys have been used to image the geochemical characteristics of the Earth surface and near surface to a depth of 30 cm (Erdi-Krausz et al., 2003). The three radioisotopes that have been traditionally used for

geological mapping include Potassium (K), Uranium (U) and Thorium (Th). The emission of gamma rays during the decay of ^{40}K to the stable isotope Argon (^{40}Ar) can be used to estimate the amount of K in the geological unit. Radioisotopes ^{238}U and ^{235}U decay to stable Lead isotope (^{206}Pb) and (^{207}Pb), respectively. The naturally occurring radioisotope ^{232}Th decay series ends in producing isotope ^{208}Pb . The concentration of radioisotopes ^{238}U and ^{232}Th in any geological unit can be indirectly estimated from the gamma ray emission of their radioactive daughter products. This is because these radioisotopes do not emit gamma ray in their initial radioactive decay process. Assuming that the radioactive daughter products of radioisotopes ^{238}U and ^{232}Th are under equilibrium, the concentration of the two radioisotopes can be estimated as the equivalents eU and eTh in parts per million (ppm).

After removing the noise from the airborne radiometric data using the noise-adjusted value decomposition method, we used the minimum curvature gridding algorithm (Briggs, 1974; Grasty, 1997; Minty and McFadden, 1998) to obtain K, eTh, eU concentrations from the airborne radiometric data with a grid cell spatial resolution of 50 m. Subsequently, we created a ternary image by assigning the K concentration to red, the eTh concentration to green, and the eU concentration to blue (Figure 5D). Areas with high concentration in all three radioisotopes appear white in the ternary image. Differently, areas that lack concentration of all radioisotopes appear black as in the case of water bodies (Figure 5D). The color yellow in the ternary image is indicative of high K and Th concentration, magenta reflects high concentration of K and U, whereas cyan manifests high Th and U concentration.

4. Results

4.1. *The Extent of the Aswa Shear Zone*

The SRTM DEM enabled us to map the extent of the ASZ in Uganda and South Sudan for over ~550 km extending from longitude 30° 20'E and latitude 5° 20'N in the northwest to longitude 33° 30'E and latitude 2° 10'N in the southeast (Figure 6A). In the northwest, the shear zone bifurcates into a number of NW-trending splays before disappearing under what seems to be unconsolidated sediments (Figure 6A). To the southeast, in Uganda the trace of the shear zone disappears under the volcanic pile of Mt Elgon (Figure 3A). In Uganda, the SRTM DEM shows the shear as a single linear trend that persists in a NW-SE direction for ~250 km (Figure 6A).

The surface expression of the ASZ is more apparent in South Sudan where the southeastern end of the shear zone is dominated by what appears to be tight folds that lie sub-parallel to the prominent trend of the shear zone itself (Figure 6B). The central part of the shear zone in South Sudan is characterized by the presence of splays of regional fabric originating from the main trace of the shear zone resulting in the presence of N and NE-trending structures (Figure 6C). Although the ASZ in Uganda has a limited surface expression observable in the SRTM DEM, the airborne total field magnetic image revealed it as a much wider structure similar to its extent in South Sudan (Figure 6D).

Extraction of structural lineation from the horizontal derivative (Figure 5B) and the ternary image (Figure 5D) revealed a more complicated picture of the ASZ in Uganda (Figure 7A) than what is apparent in the SRTM DEM. This image shows that the ASZ is characterized by the presence of three branches that are separated from each other with distances ranging between 5 and 30 km (Figure 7A). Here, we refer to these branches as the northeastern ASZ, central ASZ, and southwestern ASZ (Figure 7A). The central ASZ corresponds to the exposed

part of the shear zone that is traced from the SRTM DEM as a single linear feature (Figure 6A). This branch of the shear zone is also distinct in the ternary image by its bright to white color indicating high K, Th and U concentrations (Figure 5D). The northeastern ASZ exhibits a curvilinear pattern by changing orientation from NW-trending in the northwest to N-trending in the central part and back to NW-trending in its southeastern end (Figure 7A). This branch seems to separate a domain of variable K, Th and U concentrations in the southwest from a domain with no specific radiometric concentration in the northeast (Figure 5D). The southwestern ASZ is less obvious in the ternary image suggesting that it does not separate two distinct lithologies (Figure 5D). However, this branch is more apparent in the horizontal derivative image because it separates domains with different orientations of the magnetic fabric (Figures 5B and 7A). The domain in the southwest is dominated by magnetic lineation that defines N-trending broad open folds (Figures 5B and 7A). On the other hand, the domain that is bounded by the southwestern and the central ASZ is characterized by sigmoidal N-S-trending magnetic fabric sometimes defined by what appears to be tight folds (Figures 5B and 7A).

The region to the northeast of the ASZ is dominated by well-defined and strong linear magnetic fabric that we interpret as indicating the presence of at least two major structural boundaries (Figures 5B and 7A). These two boundaries bound a funnel-shaped region shown by cyan color in the ternary image indicative of high Th and U concentration (Figure 5D). This is followed further northeast by a domain that lacks any significant magnetic fabric (Figure 5B) with either Th or no radioisotopes concentrations as indicated by its green to black color in the ternary image (Figure 5D).

4.2. *Kinematics of the Aswa Shear Zone*

4.2.1. *Sense and amount of displacement along the Aswa Shear Zone*

Ruotoistenmaki (2014) used offsets of magnetic anomaly to suggest ~60 km horizontal sinistral strike-slip movement along the ASZ. The displacement of a similar magnetic anomaly to the northwest of the one that was measured by Ruotoistenmaki (2014) also gave ~60 km horizontal displacement (Figure 5B). Additionally, a similar amount of horizontal sinistral strike-slip displacement has been observed from drag features related to the shear zone that appear in the SRTM DEM in South Sudan (Figure 3B).

4.2.2. *Structural complexity of the Aswa Shear Zone*

The strike and dip of the magnetic fabric defining the ASZ and surrounding structures extracted from the airborne magnetic data were used to outline the three-dimensional (3D) geometry of these structures. For this, we established a number of structural domains that are separated by the three branches of ASZ as well as the two additional localized deformation zones to the northeast (Figure 7A). Subsequently, to analyze the dominant orientation of the deformation zones, the strike and dip of the magnetic fabric along the entire length of each boundary were plotted as poles to planar fabric in equal area stereonet (Figure 7B-F). Additionally, to analyze the geometry of the structures dominating the domains between the deformation zones, the magnetic fabric from these domains were plotted as poles to planar fabric in equal area stereonet (Figure 7G-K).

We drew the following observations from these plots:

- 1) The three branches of the ASZ (Figure 5A) show a consistent pattern of stereonets indicative of the presence of sub-horizontal NW-SE trending fold axes (Figure 7B-D).

Assuming that the magnetic fabric defines the regional NW-trending, steeply NE and

SW-dipping mylonitic fabric associated with the sinistral strike-slip shearing of the ASZ as observed by Westerhof et al. (2014), our results suggest that the mylonitic planar fabric itself has been subsequently folded. This is consistent with field observations from outcrops where re-folding of the mylonitic fabric is apparent (Figure 7A; Almond, 1962). This in turn suggests a strong role of an E-W to NE-SW contraction component in the development of the ASZ.

- 2) The stereonet plot in the localized deformation zone to the northeast of the northeastern ASZ does not support the presence of NW-SE trending folding of the magnetic fabric (Figure 7E). Rather, the plot suggests the presence of shallow to moderately dipping to the northeast planar fabric within the localized deformation zone. Farther to the northeast, the magnetic fabric from the northeastern-most deformation zone produced a stereonet plot that lacks clear presence of any preferred orientation of the planar fabric. (Figure 7F). This deformation zone bounds a region in the east that lacks obvious magnetic lineation possibly due to the presence of sub-horizontal magnetic fabric (Figure 5B). Comparing the airborne magnetic images with the geological map of Westerhof et al. (2014) and Nyakecho and Hagemann (2014) revealed that this region is dominated by one of the Neoproterozoic banded granulites-charnockites complexes that structurally underlain by the highly-sheared Neoproterozoic gneisses and granitoids. The Neoproterozoic banded granulites- charnockites complex fall within the northwestern along-strike continuation of the Eastern Granulite belt which is better defined in Tanzania and Kenya (Figure 1B). This belt is interpreted as dominantly W-verging nappe (Fritz et al., 2013). As initially proposed by Westerhof et al. (2014), we consider the two deformation zones to the northeast of the ASZ to represent W-verging thrusts where the

highly-sheared Neoproterozoic gneisses and granitoids on the one hand and the granulites-charnockites complex on the other hand were thrust westward over the Archean-Paleoproterozoic gneisses. This observation further reinforces the notion that a strong E-W to NE-SW contraction component played a significant role in the final architecture of the ASZ.

- 3) The domain to the southwest of the southwestern ASZ is characterized by the presence of open folds defined by NW and NE-trending magnetic fabric (Figures 5B and 7A). Plotting the poles of the magnetic fabric in equal area stereonet indicates that the fold axis is shallowly plunging to the south-southeast (Figure 7G). Westerhof et al. (2014) documented that these open fold are younger Neoproterozoic structure that refolded the planar fabric and isoclinal folds of the older Archean rocks of the Northern Uganda terrane.
- 4) The stereonets of the domains bounded by the three branches of the ASZ show a common pattern indicating folding about NW-SE trending axes (Figure 7H-J). One example of these folds is found within the domain that is bounded by the southwestern and central ASZ where the magnetic fabric defines what appears to be a tight NW-SE trending fold (Figure 8A). This is similar to the fold geometry observed in the SRTM DEM ~150 km to the northwest (Figure 8B). The axial traces of these folds (as estimated from the magnetic fabric and SRTM DEM) are at slight angle to the NW-trend of the ASZ. This suggests the development of these folds as due to secondary ENE-WSW contraction component associated with the overall sinistral strike-slip movement on the NW-trending planes of the shear zone.

5) The plot of poles to the magnetic fabric from the domain to the northeast of the ASZ doesn't seem to define any particular π -circle in the equal area stereonet (Figure 7K). This might be due to superimposition of more than one folding event since this domain is bounded by curved boundaries that have been interpreted as W-verging thrusts.

5. Discussion - Understanding the Tectonic Origin of the ASZ

We outline observations that are important for understanding the tectonic origin of the ASZ. (1) Our results show that the mylonitic fabric which was developed due to sinistral strike-slip shearing was subsequently refolded (Figure 7B-D). The sterenets in Figures 7B-D show folding of the planar fabric about NW-SE axes indicating that an E-W to NE-SW contraction component is recorded throughout the region. (2) Our results also show that the domains bounded by the three branches of the ASZ are dominated by NW-SE trending folds (Figure 7G-J). (3) Our observations agree with those of Westerhof et al. (2014) in that the region to the northeast of the ASZ is dominated by W-verging thrusts where Neoproterozoic banded granulites- charnockites complexes form allochthonous units overlying highly-sheared Neoproterozoic gneisses and granitoids which themselves overly Archean-Paleoproterozoic gneisses. (4) Farther east, along the Uganda-Kenya border, previous studies documented the presence of a heterogeneous W-verging nappe consists of Neoproterozoic granulites, granitic gneisses, amphibolite, quartzites and marbles (Figure 9A) and these lithologies have been referred to by Westerhof et al. (2014) as the Pan-African Karamoja belt. This nappe represents the western margin of the Arabian-Nubian Shield as evidenced by the presence of Sekerr ophiolite found in Kenya just to the east (Figure 1B; Fritz et al., 2013)..

The observations above indicate the presence of a strong E-W to NE-SW contraction component that has affected this part of the East African Orogen, the Saharan Metacraton, and the Northern Uganda terrane. We attribute this contraction to E-W to NE-SW oblique collision between East and West Gondwana. This interpretation is in good agreement with a model previously proposed by Westerhof et al. (2014) to explain the early stages of the development of the ASZ. The collision obliquity must have had contributed to the partitioning of strain into E-W to NE-SW contraction and NW-trending sinistral strike-slip component. Hence, we suggest that the oblique collision resulted in the development of W-verging nappes on the eastern edge of the Saharan Metacraton, and these nappes represent part of the Arabian-Nubian Shield (Figure 9B). The collision also resulted in the westward emplacement of the Neoproterozoic banded granulites-charnockites complexes onto the Archean-Paleoproterozoic gneisses of the Saharan Metacraton (Figure 9B). To the west, the collision was accommodated as dominantly sinistral strike-slip movement accompanied by E-W to NE-SW contraction. It is possible that the strain localization within the ASZ was facilitated by the presence of a pre-existing boundary between the Saharan Metacraton and the Northern Uganda terrane.

Fritz et al. (2013), from regional geologic correlation, considered the ASZ to be active prior to ~590 Ma. However, U-Pb zircon ages obtained by Westerhof et al. (2014) suggest that the Neoproterozoic activities of the ASZ might have been between ~690 and ~660 Ma. The 690-660 Ma age of the ASZ activities seems to be older than the 640-560 Ma timing of activities of the Najd fault system in the northern part of the Arabian-Nubian Shield (Stern, 1994). Hence, although the orientation and kinematics similarities between the ASZ and the Najd fault system (both are regional NW-trending sinistral strike-slip shear zones) is tempting to suggest a common origin for the two structures within the Neoproterozoic collisional tectonics between

East and West Gondwana, the age difference might suggest separate evolutionary development for them.

6. Conclusions

The analysis of airborne magnetic and radiometric data over Uganda and SRTM DEM covering Uganda and South Sudan allowed tracing the Precambrian ASZ for over 550 km in a NW-SE direction with a width of ~50 km in Uganda. Unlike its exposed part in Uganda, the airborne geophysical data revealed three branches of the shear zone which bound structural domains characterized by the presence of secondary shear zones and shear-related folds. The shear-related folds are also apparent in the SRTM DEM covering South Sudan. Both the airborne geophysical data and the SRTM DEM indicate that the ASZ is a sinistral strike-slip system with ~60 km horizontal displacement. The region to the northeast of the shear zone in Uganda is dominated by magnetic fabric indicating the presence of W-verging nappes. The folding of magnetic fabric defining the ASZ about NW-SE trending axis, presence of NW-SE folds within the structural terrains bounded by the shear zone branches, and the presence of W-verging nappes to the northeast of the shear zone all indicate a strong E-W to NE-SW contraction component that played an important role in the evolution of the shear zone. This contraction component is possibly related to Neoproterozoic E-W to NE-SW oblique collision between East and West Gondwana. This collision resulted in the development of the ASZ as a NW-trending sinistral strike-slip and E-W to NE-SW contraction belt between the Archean-Paleoproterozoic crusts of the Saharan Metacraton in the northeast and the Northern Uganda terrane to the southwest. This collision also resulted in the emplacement of the W-verging nappes of the

479 Arabian-Nubian Shield and the Eastern Granulite belt emplaced on the eastern edge and atop the
480 Saharan Metacraton, respectively.

481

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Figure Caption

Figure 1: (A) The Arabian-Nubian Shield and the Mozambique belt representing the East African orogen between East and West Gondwana. Modified after Meert and Lieberman (2008). M = Madagascar. WA = West Africa Craton. S = Saharan Metacraton. C = Congo Craton. K = Kalahari Craton. AS = Aswa Shear Zone. NF = Najd Fault System. RS = Ranotsara shear zone. ACS = Achankovil shear zone. The NW-trending shear zones are from Berhe (1990) and Stern (1994). (B) Precambrian tectonic map of eastern Africa. Modified from a compilation by Katumwehe et al. (2015). Dotted yellow lines approximate the boundaries suggested by Westerhof et al. (2014) to divide the Northeastern Congo block in Uganda into the Western Nile terrane (WNT), Northern Uganda terrane (NUT), Lake Victoria terrane (LVT) and West Tanzania terrane (WTT). ANS = Arabian-Nubian Shield. GT = Galana terrane. EGB = Eastern Granulite belt. SO = Sekerr ophiolite. MM = Morungole massif. AM = Akur massif. UM = Ukutat massif. KB = Karamoja belt. NSZ = Nyangere shear zone. JF = Jailhouse rock fault.

Figure 2: Lithospheric structure of the Aswa Shear Zone. (A) and (B) Shear wave velocity anomalies beneath eastern and central Africa at 0-100 km and 100-175 km depth, respectively. (C) N-S S-wave velocity profiles across the Aswa Shear Zone along longitude 20°E at 0-100 and 100-175 km depth. (A) (B) and (C) are adopted from Abdelsalam et al. (2011). (D) Depth distribution of earthquake foci across the Aswa Shear Zone. Grey = 0-9 km. Violet = 10-19 km. Yellow = 20-29 km. Red = Greater than 30 km. (E) Lithospheric thickness variation across the Aswa Shear Zone. Figures (D) and (E) are adopted from Craig et al. (2011).

Figure 3: (A) Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) showing the bifurcation of the East African Rift System into the Eastern and Western Branches southwest of the Aswa Shear Zone. (B) SRTM DEM showing the Western Branch represented by the Albertine-Rhino grabens terminating against the Aswa Shear Zone. (C) Fault plane solutions of earthquakes occurred along the Aswa Shear Zone from Mousa (2008) and Craig et al. (2011). Red = Compressional stress. White = Tensile stress.

Figure 4: A 7-4-2 Landsat Thematic Mapper (TM) image showing the reactivation of the Precambrian ductile structure of Aswa Shear Zone to younger brittle and morphologically-defined fractures that changed the flow direction of the Nile from northeast (Albert Nile) to northwest (Bahr el Jabal).

Figure 5: Airborne geophysical data of northeastern Uganda. (A) Total field magnetic image. (B) Horizontal derivative magnetic image. (C) Tilt derivative magnetic image. (D) Ternary radiometric image.

Figure 6: (A) Trajectories of the main structural trends of the Aswa Shear Zone in Uganda and South Sudan extracted from the interpretation of Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). (B) SRTM DEM showing tight NW-SE trending folds related to the Aswa Shear Zone. (C) SRTM DEM showing N and NE-trending structural splays related to the Aswa Shear Zone. (D) Integration of SRTM DEM from South Sudan and airborne total field magnetic image from Uganda showing the extent and structural complexity of the Aswa Shear Zone.

Figure 7: (A) Structural trajectories of the Aswa Shear Zone and surrounding domains and deformation belts in Uganda extracted from the horizontal derivative image in Figure 5B.

(B-K) Plot of poles to magnetic fabric in equal area stereonet with contouring interval at 1% per unit area. (B-D) π -diragrams from the three branches of the Aswa Shear Zone showing folding around NW-SE trending axis. (E) Plot of planar magnetic fabric from the deformation belt northeast of the Aswa Shear Zone indicating shallowly-dipping to the northeast planar fabric. (F) Plot of magnetic fabric from the deformation belt in the far northeastern part of the study area showing the lack of any preferred orientation of the planar fabric. (G) π -diragram of the domain southwest of the Aswa Shear Zone showing folding about SSE-plunging axis. (H-J) π -diragrams of the domains bounded by the three branches of the Aswa Shear Zone and the one to the northeast showing folding about NW-SE axes. (K) Plot of planar magnetic fabric from the domain bounded by the two thrusts showing no obvious preferred orientation of the planar fabric. The red star indicate the location of folded mylonite fabric reported by Almond (1962).

Figure 8: Horizontal derivative image from the domain bounded by the central and southwestern branched of the Aswa Shear Zone in Uganda (A) and Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) from Aswa Shear Zone in South Sudan (B) showing NW-SE trending folds. See Figure 6 for location.

Figure 9: (A) Geological map of the Aswa Shear Zone and the surrounding structures in northeast Uganda generated from the structural analysis of airborne geophysical data and geological maps published by Westerhof et al. (2014) and Nyakecho and Hagemann (2014) showing distribution of different lithological units. (B) Three-dimensional (3D) diagram illustrating the evolution of the Aswa Shear Zone as a NW-trending sinistral strike-slip shear zone due to E-W to NE-SW contraction that accompanied Neoproterozoic oblique collision between East and West Gondwana.

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