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SCIENCE

Geology of the Tekeze River basin (Northern Ethiopia)

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ABSTRACT
We present a geologic map of the Tekeze River basin that covers an area of ~69,000 km^2 of northern Ethiopia. The map synthesizes new data collected in two campaigns between March, 2012 and January, 2013 and compiled at a scale of 1:500,000 with published geologic surveys. The map focuses on the main geologic and tectonic features relevant to a modern interpretation of the geologic evolution of northern Ethiopia and as such, it represents an important synthesis for environmental and natural resource management.

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Ethiopia; Tekeze River; Tigray Province; geological map; Mekele outlier

1. Introduction

The Tekeze River basin is located in northern Ethiopia and spans an area of 69,000 km^2. The basin is bound by the Ethiopia-Eritrea border to the north, the western escarpment of the Afar Depression to the east and the Simien Mts. range to the west and south.

The geology of the area is characterized by a Precambrian basement unconformably overlain by a Paleozoic-Mesozoic sedimentary succession capped by Tertiary volcanics. These rocks are deformed by several Neoproterozoic to Present tectonic structures including folds, faults, shear zones and lineaments.

The geology of northern Ethiopia is described at various scales in several geological maps (1:250,000 – Hailu, 1975; Kazmin, 1976; Garland, 1980; Zenebe & Mariam, 2011; 1:150;000 – Gebreyohannes et al., 2010; 1:100,000 – Russo, Fantozzi, & Solomon, 1997); however each map covers an area much smaller than the entire Tekeze River basin.

Here we compile a 1:500,000 scale geological map of the Tekeze River basin (see Main Map) by synthesizing new data with these previous geological maps. Comprehensive and detailed coverage of the Tekeze River basin treats the watershed as an integrated system that we maintain is important for public and private sector considerations of thematic, environmental and natural resource management decisions.

2. Methods

The geological map of the Tekeze River basin (Main Map) is compiled by using stratigraphic and structural data collected in two campaigns between March, 2012 and January, 2013. The first survey is focused mainly on the southern part of the Tekeze River basin while the second one concentrates on the eastern and northern portion. Data are georeferenced in a SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) database and analyzed in GIS environment by using ArcGIS software. The result is compared and integrated with satellite image analysis and published geological maps.

3. Lithology and stratigraphy

The geology of the Tekeze River basin is the result of a complex evolution that involves: (1) the Precambrian collision between East and West Gondwana generating the East African Orogen (900–550 Ma; Stern, 1994); (2) a relative tectonic quiescence during Early Paleozoic (Coltorti, Dramis, & Ollier, 2007); (3) glaciation between Late Ordovician and Early Silurian (Bussert & Schrank, 2007); (4) intercontinental rifting and break-up of Gondwana from Late Carboniferous to Late Cretaceous (Wopfner, 1994 and references therein); (5) Jurassic marine transgression from southeast (Bosellini, Russo, Fantozzi, Assefa, & Tadesse, 1997); (6) tertiary continental flood basalt volcanism, plateau uplift and formation of the East African Rift System related to mantle upwelling underneath East Africa (Ebinger, Yemane, Woldegabriel, Aronson, & Walter, 1993; George, Rogers, & Kelley, 1998; Sembroni, Molin, Pazzaglia, Faccenna, & Abebe, 2016a; Sembroni, Faccenna, Becker, Molin, & Abebe, 2016b).

The stratigraphic succession of northern Ethiopia can be divided into 10 units (from the oldest to the youngest one): Precambrian basement, Enticho Sandstones, Edaga Arbi Glacials, Adigrat Sandstones, Antalo

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Limestones, Agula Shales, Amba Aradam Formation, Trap series, Mekele Dolerites and Axum-Adua Plugs.

3.1. The Precambrian basement

The Precambrian basement forms a transition zone between the low-grade metamorphosed rocks (volcano-sedimentary succession and mafic-ultramafic complexes) of the northern East African Orogen (Arabian Nubian Shield) and the high-grade metamorphosed and deformed rocks (schists, gneisses, migmatites, ophiolite fragments and granulites) of the southern East African Orogen (Mozambique Belt; Miller et al., 2003; Stern & Abdelsalam, 1998; Tadesse, Hoshino, Suzuki, & Iizumi, 2000; Worku, 1996; Yibas et al., 2002).

In northern Ethiopia, the basement ages between 830 and 650 Ma and is characterized by deformation, metamorphism and intensive plutonism up to 520 Ma (Miller et al., 2003; Stern & Abdelsalam, 1998; Tadesse et al., 2000; Worku, 1996; Yibas et al., 2002).

3.2. Palaeozoic and Mesozoic sedimentary successions

3.2.1. Enticho sandstones

The Enticho Sandstones unconformably overlie Neoproterozoic basement rocks (Paleozoic planation surface; Coltorti et al., 2007) and consist of eolian quartzarenites with a maximum thickness of 200 m (Figure 1(a, b)). The upper part of the sandstones is locally heteropic with the Edaga Arbi Glacials (see description below; Beyth, 1972a, 1972b; Dow, Beyth, & Hailu, 1971; Garland, 1980). The Enticho Sandstones are Ordovician in age on the base of fossil siphonoromid impressions (Saxena & Assefa, 1983).

3.2.2. Edaga Arbi Glacials

The Edaga Arbi Glacials consist of grey, black or purple clay and silt often containing dispersed pebbles or boulders up to 6 m in diameter (Figure 1(c, d); Beyth, 1972a). Their thickness is variable but attains a maximum of 150 m in the northern portion of the basin. The formation deposits in N–S trending glacial troughs and valleys up to several kilometers wide and tens of meters deep, carved into Precambrian basement and Early Paleozoic sediments (Beyth, 1972a; Enkurie, 2010).

The Edaga Arbi Glacials are Late Carboniferous to Early Permian in age according to palynological investigations (Bussert & Schrank, 2007).

3.2.3. Adigrat Sandstones

The Adigrat Sandstones increase their thickness from north to south and present the maximum values (~600 m) aligned in a NNE–SSW trend, west of Mekele Outlier (Figure 2a). They thin westward to ~80 m and disappear north of Adigrat-Axum road (Beyth, 1972a; Figure 2(a)).

The formation is divided into four members (from bottom to top): Member 1 is composed of white and yellow to brown, well-sorted, fine- to medium-grained

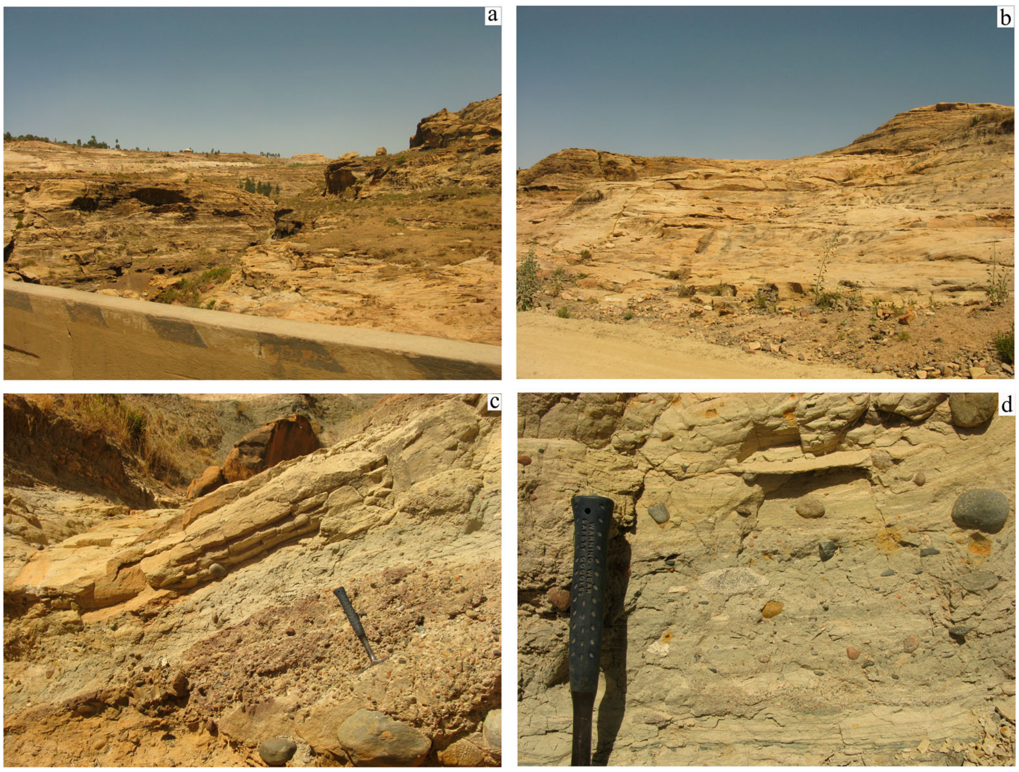

Figure 1. (a) Enticho Sandstones outcrop near Sinkata village (south of Adigrat city); (b) eolian faces of the Enticho Sandstones near Adigrat city; (c) stratigraphic contact between Edaga Arba Glacials (bottom) and Enticho Sandstones near Wukro village; (d) Edaga Arbi Glacials outcrop near Wukro.

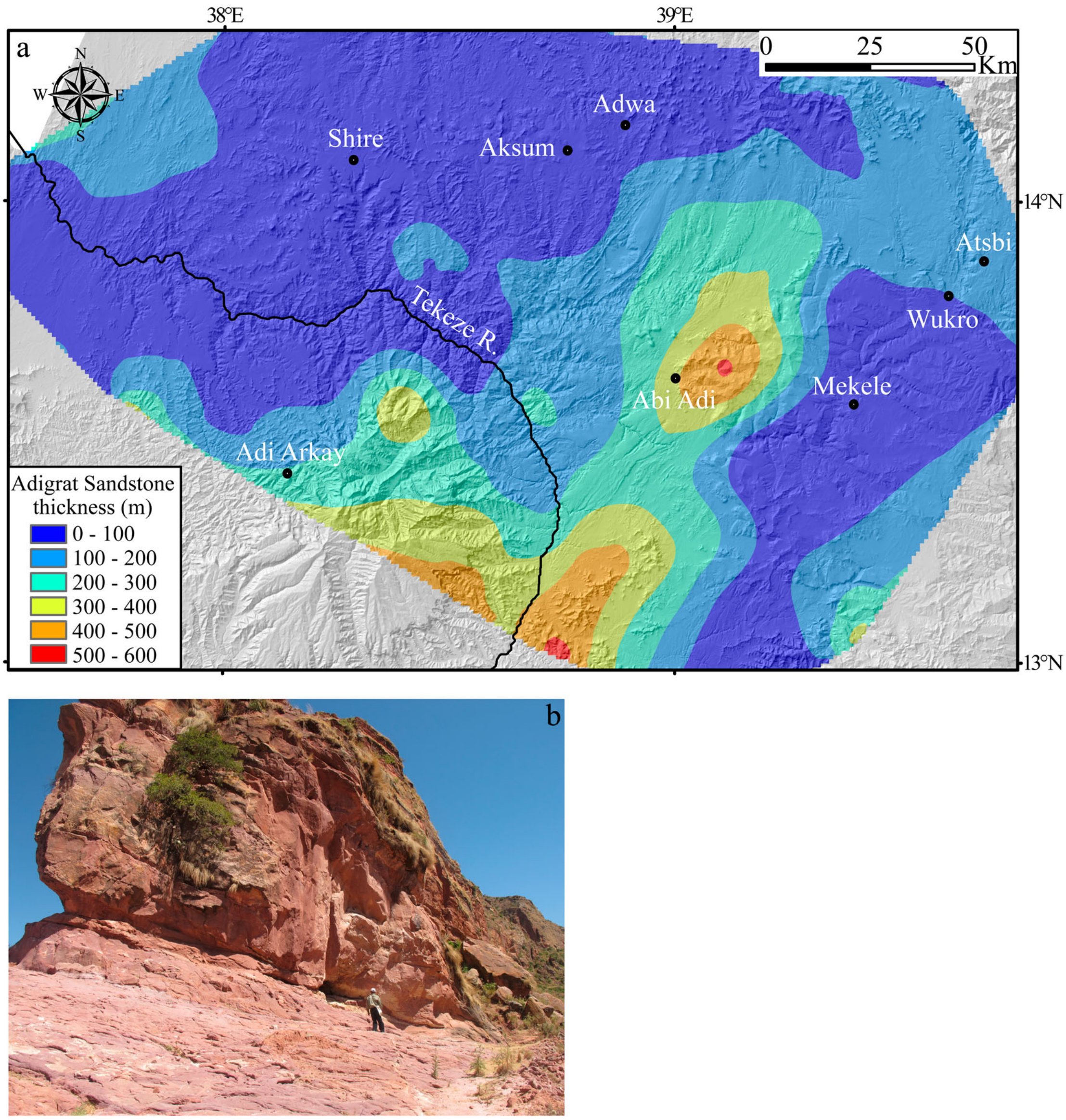

Figure 2. (a) Map of the thickness of the Adigrat Sandstones resulted from the subtraction (in GIS environment) of the top (Antalo Limestones/Adigrat Sandstones contact) and the bottom (Adigrat Sandstones/Basement rocks contact) surfaces of the formation mapped by using field work data and the published geological maps (SRTM DEM database); (b) Adigrat Sandstones outcrop west of Wukro city.

sandstones; Member 2 is made up poorly sorted medium- to fine-grained reddish sandstones with abundant quartz pebbles; Member 3 is composed of friable, medium- to coarse-grained, cross-bedded white quartz sandstones with well-distributed lenses of ferruginous silt showing turbidity structures; Member 4 consists of fine- to medium-grained yellow to red sandstones interbedded with variegated silt- and claystones (Enkurie, 2010) (Figure 2(b)).

Since the abundance of ferruginous/lateritic beds and the presence of fossil wood fragments, Beyth (1972a, 1972b) and Bosellini et al. (1997), interpret the sandstones as deposits of estuarine, lacustrine-deltaic or continental environments.

The age of the upper limit of Adigrat Sandstones is between Late Callovian (?)–Early Oxfordian (Bosellini et al., 1997) whereas the lower boundary is thought to be diachronous and Triassic in age (e.g. Beyth, 1972b; Bosellini et al., 1997; Merla & Minucci, 1938; Mohr, 1962).

3.2.4. Antalo Limestones

The thickness of the Antalo Limestones (Figure 3(a)) ranges from 300 m in the west to 800 m in the east. Four different facies can be identified (from bottom to top): (i) a sandy oolite limestones with low amount of marls, few chert beds and a fauna of corals, gastropods, and echinoids; (ii) an interbedding of marls and limestones with brachiopods and algal and chert beds; (iii) reef limestones interbedded with marls and stromatolites; (iv) black to grey microcrystalline limestones interbedded with marls (Figure 3(a); Bosellini et al., 1997).

The limestones deposit in a homoclinal ramp or in a wide cratonic margin gently dipping to the southeast (Bosellini et al., 1997).

Figure 3. (a) Sub-horizontal Antalo Limestones near Mekele city (Mekele outlier); (b) Agula Shales outcrop near May Keyih, SE of Mekele; (c) Amba Aradam Formation outcrop south of Mekele; (d) laterite deposit lying on top the Amaba Aradam Formation south of Mekele.

A Late Callovian to Kimmeridgian age is assigned to the Antalo Limestones on the base of a benthic foraminifera fauna (Bosellini et al., 1997). Since the Adigrat Sandstones are continental, Bosellini (1989) and Bosellini et al. (1997) hypothesize a Late Callovian sea transgression in northern Ethiopia.

3.2.5. Agula Shales

The Agula Shales (Figure 3(b)) crop out only on top of the Antalo Limestones, reaching a maximum thickness of 300 m (Enkurie, 2010). They are composed, from bottom to top, of well-sorted, cross-bedded fine quartzarenites (tidal bars), laminated black shales and mudstones, dolomites and gypsum beds, and oolitic limestones (storm beds) (Beyth, 1972a, 1972b; Bosellini et al., 1997; Enkurie, 2010). This facies association is typical of peritidal, lagoonal and sabkha environments (Beyth, 1972a, 1972b; Bosellini et al., 1997).

The Agula Shales indicate the regression of the Jurassic sea from northern Ethiopia (Bosellini, 1989).

3.2.6. Amba Aradam Formation

The Amba Aradam Formation has a maximum thickness of 200 m and lies unconformably (Cretaceous planation surface, Coltorti et al., 2007) on the Agula Shales (Figure 4(c, d); Bosellini et al., 1997). The formation is made up of white or red sandstones (Figure 3(c)) with interbedded purple to violet silt- and mudstones, lateritic paleosols and lenses of conglomerates (Figure 3(d)). The sandstones are interpreted as 'point bar sequences' deposited in a fluvial meandering river system (Bosellini et al., 1997). The lower- and uppermost parts of the formation are strongly lateritized (Figure 3(d)).

Despite the absence of age diagnostic fossils, the formation is correlated with the Debre Libanos Sandstones, in the Blue Nile Basin (Assefa, 1991), and with the Aptian–Albian Upper Sandstone Unit, in the Harar region of southeastern Ethiopia (Assefa, 1991; Bosellini et al., 1997).

3.3. Tertiary volcanics

3.3.1. Trap series

The Tertiary Trap series of Ethiopia is associated with the Afar hotspot and covers most of Ethiopia, Eritrea and Yemen (Ebinger & Sleep, 1998; George et al., 1998; Richards, Duncan, & Courtillot, 1989). In the Tekeze River basin the Traps are characterized by a series of Late Eocene and Oligocene fissure basalts with total thickness ranging between ~1000 m to the south and southwest, and ~400 m to the north (Figure 4(a)). In the south and southwest of the basin, Traps are covered by shield volcanoes (Mt. Ras Dashen, Mt. Guna, Mt. Abune Yosef) 30–10 Ma in age (Kieffer et al., 2004).

3.3.2. Mekele Dolerites

The Mekele Dolerites are Oligocene in age (Justin-Visentin, 1974) and outcrop mainly in the eastern sector of the Tekeze River basin (Figure 5(a)). They consist of

Figure 4. (a) Sub-horizontal Trap basalts near May Tsemre village, immediately north of Adi Arkay; (b) plugs east of Aksum.

basaltic to gabbroid sills and dykes (Figure 5(b, c)) with aphanitic to phaneritic texture (Gebreyohannes et al., 2010). The thickness of the sills ranges from 80 to 130 m with a maximum areal extent of 20 km^2 (Beyth, 1972a, 1972b; Gebreyohannes et al., 2010). The major conduits of the dolerites are the NW–SE faults and the NNE–SSW fractures (Gebreyohannes et al., 2010).

3.3.3. Axum-Adwa Plugs

The Axum-Adwa Plugs are constituted of silica-poor volcanic to hypabyssal rocks (phonolite–trachyte; Hagos, Koeberl, Kabeto, & Koller, 2010), 7–3 Ma in age (Beyth, 1972a) (Figure 4(b)). Such plugs overlie Trap basalts and locally intrude and deform the basaltic flow layers.

4. Tectonic structures

The tectonic structures of the Tekeze River basin can be gathered into three groups:

(1) Structures related to the collision between east and west Gondwana (Neoproterozoic) which affect mainly the basement rocks. The collision is

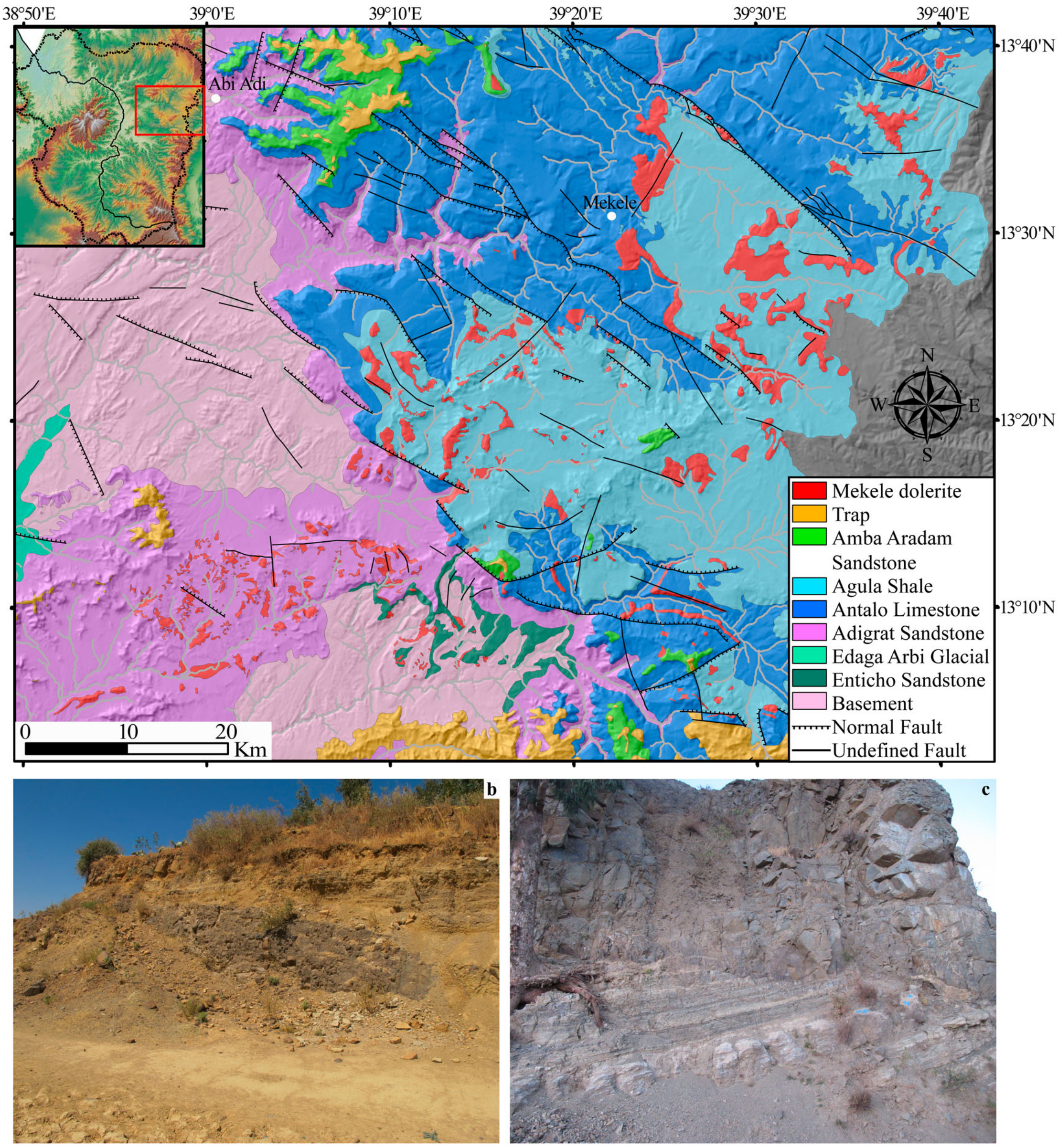

Figure 5. (a) Map of the dorerite outcrops (zoom from the Main Map); (b) dolerite dike intruded in Agula Shales near Mt. Amba Aradam (Mekele outlier); (c) dolerite deposit lying on top the Agula Shales immediately east of Mekele city.

marked by north- to east-trending thrusts, folds, faults (Figure 6(a, b)). These structures reactivate as extensional or oblique faults forming depressions and topographic highs during Paleozoic and Triassic. Evidences of this tectonic activity are: (i) the westward step-like lowering of the basement accommodated by NNE–SSW trending normal faults cutting the stratigraphic succession up to the Adigrat Sandstones (see section A-A' in the map); (ii) the tectonic contact between Adigrat Sandstones and Paleozoic-Precambrian rocks north of Wukro (Beyth, 1972; Russo et al., 1997; Figure 7); (iii) the maximum thickness values of Adigrat Sandstones aligned along a NNE–SSW trend between Mekele and Tekeze River (Figure 2(a)).

(2) Four NW–SE trending normal fault belts located north of the study area. They deform the whole basement and sedimentary succession with the exception of the Amba Aradam Formation. Such structures are associated to the polyphase break-up of Gondwanaland between the Early Permian and the Paleogene (Corti, 2009). These fault belts are visible in the Mekele outlier and along the transect between the cities of Shire and Adi Arkay (respectively northeast and northwest of the study area) where they form steep scarps lowering the deposits towards SSW. The northernmost three belts dip southward while the forth dip northward.

(3) The faults related to the opening of the Afar depression. The fault system trends N–S and NNW–SSE and is active from the Tertiary (Upper Miocene; Corti, Bastow, Keir, Pagli, & Baker, 2015) to the Quaternary. The faults are normal, dip eastward, and present a total downthrow of more than 3000 m across a horizontal distance of ~50 km.

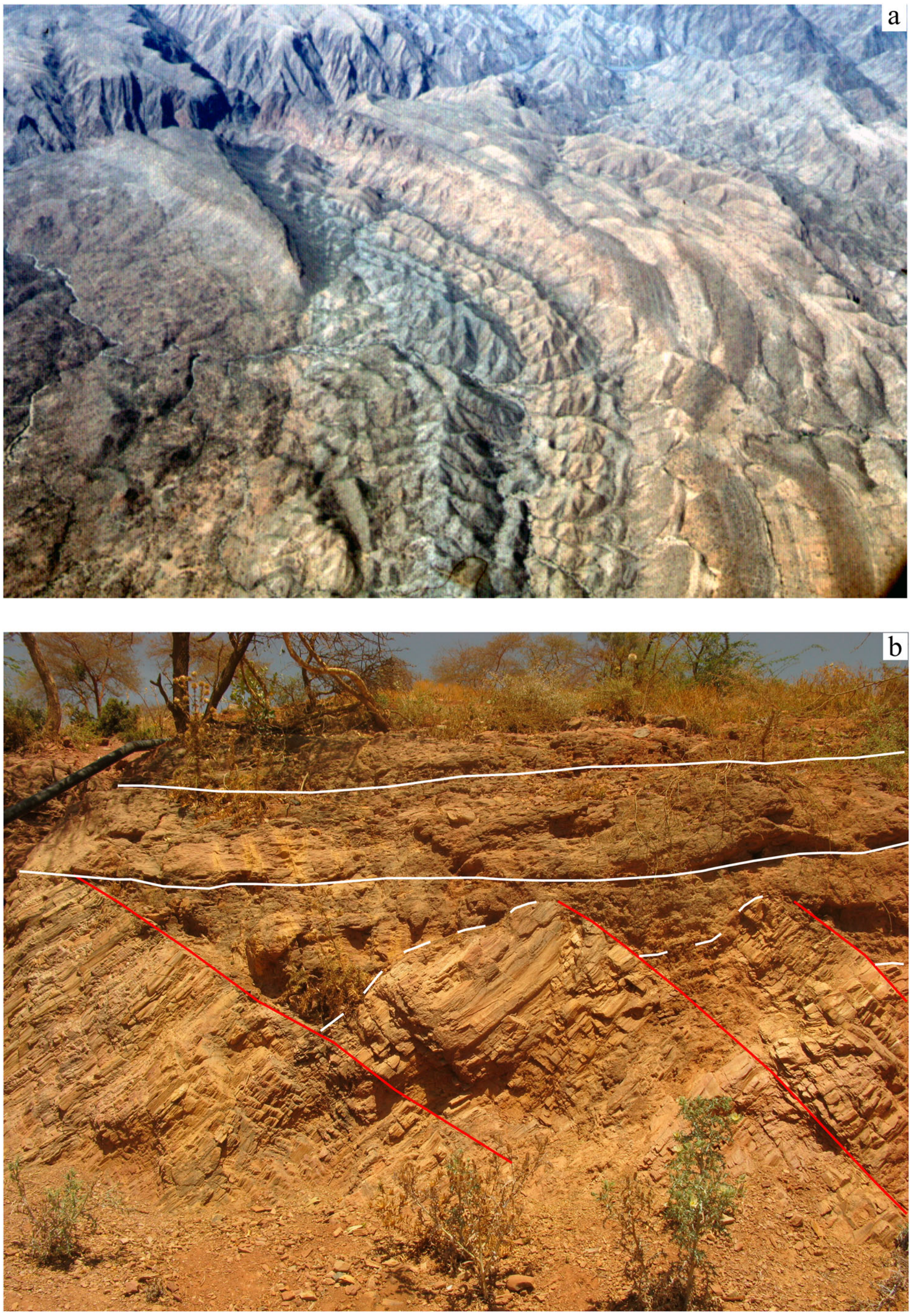

Figure 6. (a) Folds in the basement rocks located east of Tekeze River valley (in the background) around 13°29′N, 38°45′E; (b) domino faulting in basement rocks near Abi Adi village: the faults (in red) appear truncated by an angular unconformity (white) on the top.

5. Geomorphology

The Tekeze River basin presents an elevation ranging between 676 and 4549 m with a general decreasing in mean elevation from East to West. The highest peak is Mt. Ras Dashen (4549 m) in the Simien range.

The Tekeze River sources from Mt. Abune Yosef (4260 m) and flows into the Nile in Sudan, outside the study area.

Four planation surfaces are identified in northern Ethiopia (Coltorti et al., 2007): PS1 (Early Palaeozoic), PS2 (Late Triassic), PS3 (Early Cretaceous) and PS4 (Early Tertiary). These features represent exhumed unconformities and indicate the occurrence of long episodes of tectonic quiescence when erosion processes planate the surface at altitudes not far from sea level (Coltorti et al., 2007).

Despite the widespread deep erosion, the S–SW portion of the Tekeze River basin and the Mekele Outlier result almost completely preserved because of the low susceptibility to erosion of their lithologies. The first is mainly covered by flood basalts and presents a ‘mesa’ morphology with flat remnants surrounded by steep scarps. The Mekele Outlier, nearly circular in shape, is characterized by pseudo-horizontal

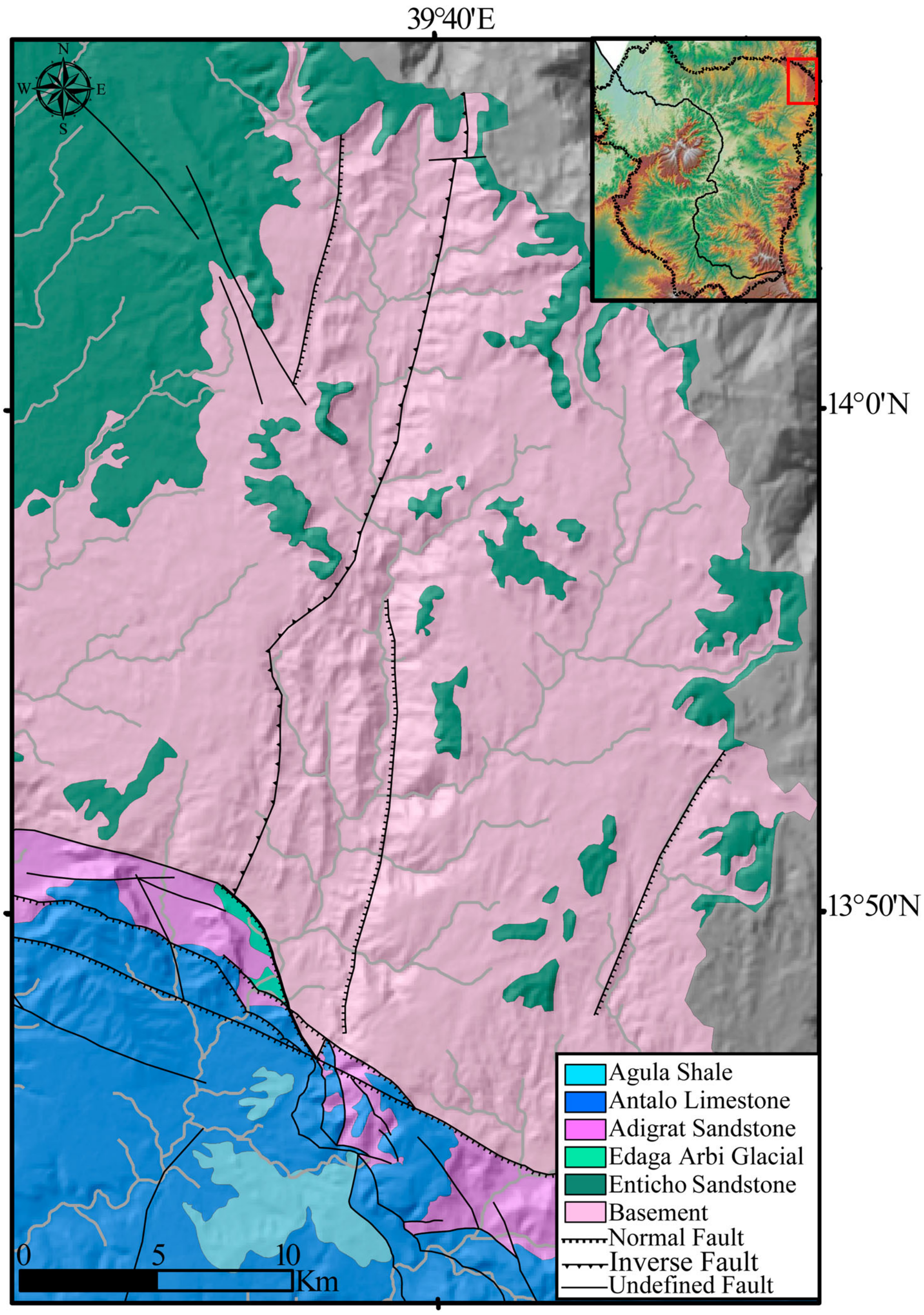

Figure 7. Geological configuration of the Wukro area (zoom from the Main Map).

Mesozoic sediments (Adigrat Sandstones, Antalo Limestones, and Agula Shales) intruded by dolerite sills and dykes.

North of Wukro village, there is a classical example of fault line erosional scarp where the footwall shows the Edaga Arbi Glacials and the Enticho Sandstones (Figure 1(c, d)) covered by the Adigrat Sandstones.

6. Geological evolution of the Tekeze River basin

The geological evolution of northern Ethiopia can be recognized in the tectonic and stratigraphic configurations of the Tekeze River basin. In the Precambrian the accretion and dismantle of the East African Orogen occurs. The tracks of these processes are the N–S and NNE–SSW trending tectonic structures (Figure 8(a)) and the Paleozoic planation surface (Coltorti et al., 2007). Between Paleozoic and Triassic, the Precambrian tectonic structures, reactivated as extensional/oblique faults, guide the deposition of eolian and glacial deposits (Edaga Arbi Glacials and Enticho Sandstones), and successively of alluvial plain sediments (Adigrat Sandstones; Figure 8(b)). During the break-up of the Gondwana continent (Late Paleozoic to Early Triassic), an extensional NW–SE trending tectonic phase causes the lowering of the southern portions of the study area (Figure 8b). The progressive lowering allows the transgression of the sea from southeast and the consequent deposition of marine sediments (Antalo Limestones

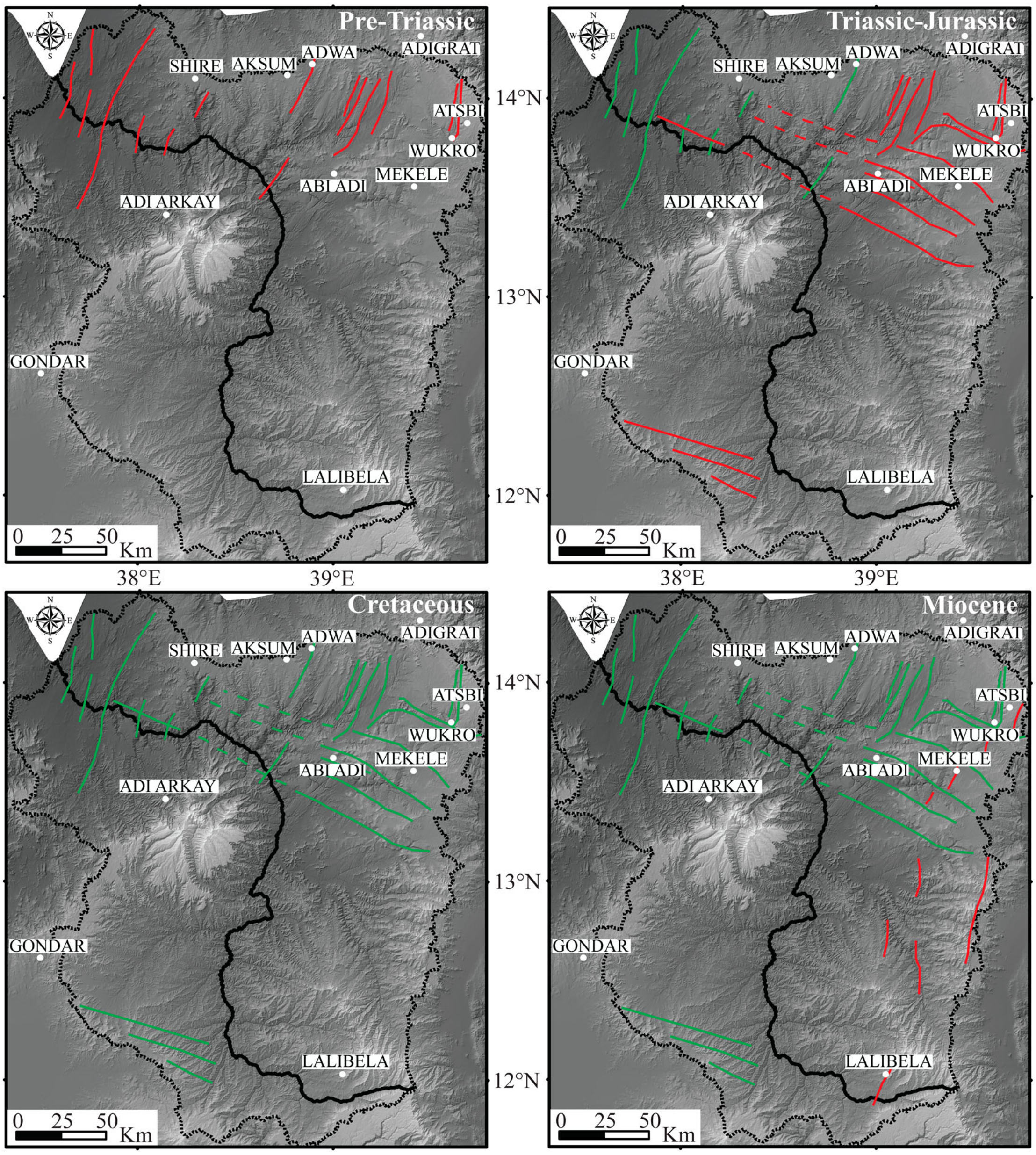

Figure 8. Model of the tectonic evolution of the Tekeze basin since Pre-Triassic up to the Miocene. Red lines indicate the active faults while the green ones evidence the inactive tectonic lineaments. The dashed lines represent the inferred faults.

and Agula Shales). The interaction between the N–S and NW–SE faults is visible north of Wukro village (Figures 7 and 8(b)). Here a N–S tectonic structure displaces the Precambrian and Paleozoic rocks as well as the relative planation surface, of ∼200 m. In the meantime the Adigrat Sandstones start depositing and the NW–SE fault system activates forming the Mekele depocentre.

The Cretaceous planation surface records the end of the Mesozoic tectonic phase (Coltorti et al., 2007; Figure 8(c)). The successive deposition of the continental Amba Aradam Formation on the Cretaceous planation surface and on the relatively deep marine Agula Shales indicates a lowering of sea level probably due to a regional uplift (Bosellini et al., 1997). In the Ceno-zoic, during a period of relative tectonic quiescence, the Amba Aradam Formation is partially eroded and a new planation surface forms (Coltorti et al., 2007). Around Eocene, the impingement of the Afar plume starts to deform the lithosphere causing a regional broad uplift and the emplacement of the flood basalts (Figure 4(a); Ebinger et al., 1993; Sengor, 2001; Sembroni et al., 2016b). The outpouring of magma is guided by the pre-existing tectonic lineaments (Mege & Korme, 2004). The thickness of the basalts is variable according to the pre-Traps topography. In the northern portion of the study area the value is ∼400 m, indicating a more elevated topography with respect to the south (Sembroni et al., 2016b). Contemporarily or immediately after the emplacement of the flood basalts, the Mekele Dolerites intrude the Mesozoic sediments (Figure 5) following the intersections of NNE–SSW and NW–SE trending fault systems.

Starting from the Upper Miocene the rift tectonics takes place forming the Afar escarpment to the east (Figure 8(d)). Successively, a new magma intrusion gives rise to the Axum-Adwa plugs (Figure 4(b)).

At present, the landscape configuration is still strongly dominated by the fluvial erosion induced by the uplift related to the Afar plume impingement (Sembroni et al., 2016a, 2016b and references therein).

7. Conclusions

We present the first 1:500,000 scale geological map of the Tekeze River basin compiled by integrating fieldwork data with the published geological maps of Ethiopia. The most important geological, tectonic and geomorphological features are described and a geological evolution of northern Ethiopia is traced. We maintain that this comprehensive and detailed coverage of the Tekeze River basin is important for public and private sector considerations of thematic, environmental and natural resource management decisions.

Software

Fieldwork data and geological information are compiled in GIS environment by ESRI ArcGIS software.

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Disclosure statement

No potential conflict of interest was reported by the authors.

References

Assefa, G. (1991). Lithostratigraphy and environment of deposition of the late Jurassic–early Cretaceous sequences of the central part of the Northwestern Plateau, Ethiopia. *Neues Jahrbuch fur Geologie und Paleontologie Abhandunglen*, *182*, 255–284.

Beyth, M. (1972a). *To the geology of Central-Western Tigre* (Ph.D. thesis), Friedrichs Wilhelms Universität, Bonn.

Beyth, M. (1972b). Paleozoic–Mesozoic sedimentary basin of Mekelle Outlier, Northern Ethiopia. *AAPG Bulletin*, *56*, 2426–2439.

Bosellini, A. (1989). The continental margins of Somalia: Their structural evolution and sequence stratigraphy. *Memoirs of the National Science Museum (Tokyo) Sciences Géologiques - Memoires*, *41*, 373–458.

Bosellini, A., Russo, A., Fantozzi, P. L., Assefa, G., & Tadesse, S. (1997). The Mesozoic succession of the Mekelle Outlier (Tigrai Province, Ethiopia). *Memoirs of the National Science Museum (Tokyo) Sciences Géologiques - Memoires*, *49*, 95–116.

Bussert, R., & Schrank, E. (2007). Palynological evidence for a latest Carboniferous–early Permian glaciation in Northern Ethiopia. *Journal of African Earth Sciences*, *49*, 201–210.

Coltorti, M., Dramis, F., & Ollier, C. D. (2007). Planation surfaces in Northern Ethiopia. *Geomorphology*, *89*, 287–296. doi:10.1016/j.geomorph.2006.12.007

Corti, G. (2009). Continental rift evolution: From rift initiation to incipient break-up in the main Ethiopian Rift. *Earth-Science Reviews*, *96*, 1–53.

Corti, G., Bastow, I. D., Keir, D., Pagli, C., & Baker, E. (2015). Rift-related morphology of the Afar Depression. In P. Billi (Ed.), *Landscapes and landforms of Ethiopia, series: World geomorphological landscapes* (pp. 251–274). Dordrecht: Springer.

Dow, D. B., Beyth, M., & Hailu, T. (1971). Palaeozoic glacial rocks recently discovered in northern Ethiopia. *Geological Magazine*, *108*, 53–60.

Ebinger, C., & Sleep, N. H. (1998). Cenozoic magmatism in central and east Africa resulting from impact of one large plume. *Nature*, *395*, 788–791.

Ebinger, C. J., Yemane, T., Woldegabriel, G., Aronson, J. L., & Walter, R. C. (1993). Late Eocene–recent volcanism and faulting in the southern main Ethiopian rift. *Journal of the Geological Society*, *150*, 99–108.

Enkurie, D. L. (2010). Adigrat Sandstone in Northern and Central Ethiopia: Stratigraphy, Facies, Depositional Environments and Palynology (PhD thesis), University of Berlin.

Garland, C. R. (1980). Geology of the Adigrat Area. Ministry of Mines, Addis Ababa Memoir No.1, p. 51.

Gebreyohannes, T., de Smedt, F., Miruts Hagos, Gebresilassie, S., Amare, K., Kabeto, K., … Moeyersons, J. (2010). Large-scale geological mapping of the Geba basin, northern Ethiopia [Tigray Livelihood Papers; 9]. Unpublished manuscript.

George, R., Rogers, N., & Kelley, S. (1998). Earliest magmatism in Ethiopia: Evidence for two mantle plumes in one flood Basalt Province. *Geology*, *26*, 923–926.

Hagos, M., Koeberl, C., Kabeto, K., & Koller, F. (2010). Geochemical characteristics of the alkaline basalts and the phonolite–trachyte plugs of the Axum area, northern Ethiopia. *Austrian Journal of Earth Sciences*, *103*, 153–170.

Hailu, T. (1975). Geological Map of Adiarkay Sheet (ND 37 -10) 1:250,000. EIGS.

Justin-Visentin, E. (1974). Petrografia, chimismo e petrogenesi dei corpi subvulcanici di Macallè (Tigrai Etiopia). *Memorie dell'Istituto di Geologia e Mineralogia Università di Padova*, *31*, 1–33.

Kazmin, V. (1976). Geological Map of Adigrat Sheet (ND 37 -7), 1:250,000. EIGS.

Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., … Meugniot, C. (2004). Flood and shield basalts from Ethiopia: Magmas from the African Superswell. *Journal of Petrology*, *45*, 793–834.

Mege, D., & Korme, T. (2004). Dyke swarm emplacement in the Ethiopian large igneous province: Not only a matter of stress. *Journal of Volcanology and Geothermal Research*, *132*, 283–310.

Merla, G., & Minucci, E. (1938). Missione geologica nel Tigrai. Roma: Regia Accademia Italiana.

Miller, N. R., Alene, M., Sacchi, R., Stern, R. J., Conti, A., Kröner, A., & Zuppi, G. (2003). Significance of the Tambien Group (Tigrai, Northern Ethiopia) for snowball earth events in the Arabian-Nubian Shield. *Precambrian Research*, *121*, 263–283.

Mohr, P. A. (1962). *The geology of Ethiopia*. Addis Ababa: Addis Ababa University Press.
Richards, M. A., Duncan, R. A., & Courtillot, V. E. (1989). Flood basalts and hotspot tracks: Plume heads and tails. *Science*, *246*, 103–107.
Russo, A., Fantozzi, P. L., & Solomon, T. (1997). Geological map of Mekelle Outlier (Western Sheet), 1:100,000. Italian cooperation – Addis Ababa University.
Saxena, G. N., & Assefa, G. (1983). New evidence on the age of the glacial rocks of northern Ethiopia. *Geological Magazine*, *120*, 549–554.
Sengor, A. M. C. (2001). Elevation as indicator of mantle-plume activity. *Geological Society of America*, *352*, 183–225.
Sembroni, A., Faccenna, C., Becker, T. W., Molin, P., & Abebe, B. (2016b). Long-term, deep-mantle support of the Ethiopia-Yemen Plateau. *Tectonics*, *35*, 469–488. doi:10.1002/2015TC004000
Sembroni, A., Molin, P., Pazzaglia, F. J., Faccenna, C., & Abebe, B. (2016a). Evolution of continental-scale drainage in response to mantle dynamics and surface processes: An example from the Ethiopian Highlands. *Geomorphology*, *261*, 12–29. doi:10.1016/j.geomorph.2016.02.022
Stern, R. J. (1994). Arc assembly and continental collision in the Neoproterozoic East African Orogen: Implications for the consolidation of Gondwanaland. *Annual Review of Earth and Planetary Sciences*, *22*, 319–351.
Stern, R. J., & Abdelsalam, M. G. (1998). Formation of juvenile continental crust in the Arabian-Nubian Shield: Evidence from granitic rocks of the Nakasib suture, NE Sudan. *Geologische Rundschau*, *87*, 150–160.
Tadesse, T., Hoshino, M., Suzuki, K., & Iizumi, S. (2000). Sm–Nd, Rb–Sr and Th–U–Pb zircon ages of syn- and post-tectonic granitoids from the Axum area of northern Ethiopia. *Journal of African Earth Sciences*, *30*, 313–327.
Wopfner, H. (1994). The Malagasy rift, a chasm in the Tethyan margin of Gondwana. *Journal of Southeast Asian Earth Sciences*, *9*, 451–461.
Worku, H. (1996). Structural control and metamorphic setting of the shear zone-related Au vein mineralization of the Adola Belt (southern Ethiopia) and its tectono-genetic development. *Journal of African Earth Sciences*, *23*, 383–409.
Yibas, B., Reimold, W. U., Armstrong, R., Koeberl, C., Anhaeusser, C. R., & Phillips, D. (2002). The tectonostratigraphy, granitoid geochronology and geological evolution of the Precambrian of southern Ethiopia. *Journal of African Earth Sciences*, *34*, 57–84.
Zenebe, B., & Mariam, D. H. (2011). Geological Map of Yifag area (scale 1:250000). Addis Ababa: Ethiopian Institute of Geological Surveys.