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PRELIMINARY SEDIMENTOLOGY AND STRATIGRAPHY OF THE ENIGMATIC MIDDLE LAKE BEDS SUCCESSION (PLEISTOCENE?) IN THE RUKWA RIFT BASIN, TANZANIA

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ABSTRACT

This paper presents sedimentology and stratigraphic overview of a series of previously unrecognized lithostratigraphic unit in the Rukwa Rift Basin, Tanzania. Based on the cross-cutting relationship and pilot detrital zircon geochronology, these isolated, enigmatic strata are herein informally termed the middle Lake Beds (mLB). Facies analysis reveals that the mLB units were deposited within a complex array of depositional environments, ranging from alluvial to fluvial channels, floodplains and shallow lakes. The mLB are characterised herein as isolated outcrop exposures with uncertain age relationships, but which can be divided into five distinctive lithostratigraphic units herein identified as informal members (A-E). These are:(1)at least 36 m-thick lacustrine (limestone) unit (member A); (2) a thin (<15 m-thick) volcaniclastics succession of alluvial sandstones, siltstones, mudstones and thin conglomerates (member B); (3) well-sorted siliciclastic fluvial sandstones (member C); (4) tuffaceous/ash-rich siliciclastics fluvial sandstones and conglomerates (member D); and (5) thin lacustrine volcaniclastics siltstone unit, termed member E. Deposition of the mLB was most likely transpired during tectonically active periods, at times contemporaneously with explosive and effusive volcanism associated with the Rungwe Volcanic Province. The identification of the mLB unit provides an important insight into revising the Lake Beds stratigraphy, and establishing a formal nomenclature of this uppermost mega-sequence in the basin.

Keywords: Facies Analysis; Pleistocene; Rukwa Rift Basin

INTRODUCTION AND BACKGROUND

The late Cenozoic Lake Beds succession of the Rukwa Rift Basin (RRB) was deposited in response to modern tectonic development of the East African Rift System (EARS) (Ebinger et al. 1989; Wescott et al. 1991), yet it represents the least studied and youngest tectono-sedimentary unit in the basin. Rifting history in the RRB goes back to late Carboniferous-Permian, and was initiated by reactivation of the Paleoproterozoic-Neoproterozoic Ubendian shear zones (Theunissen et al. 1996). There is a consensus that the Rukwa Rift opened in a general E-W direction, sub-orthogonal to the NW-SE rift trend of normal faulting regime (Ebinger 1989; Morley et al. 1990; Delvaux et al. 2012). The Rukwa Rift has undergone at least three other tectonic rifting episodes preceding the late Cenozoic East Africa rift event, including: 1) a Permo-Triassic event that deposited Karoo Supergroup (Kilembe and Rosendahl 1992; Morley et al. 1999); 2) a Cretaceous; and 3) late Oligocene rifting events that deposited the Red Sandstone Group, Galula and Nsungwe formations, respectively (Roberts et al. 2004, 2010, 2012). Geologic studies and seismic profiles reveal that the RRB has half-graben geometry, with sedimentary strata thickening north-easterly towards the depocenters and the main border fault (Lupa

Fault) located in the eastern margin of the basin (Pierce and Lipkov 1988; Kilembe and Rosendahl 1989; Morley et al. 1992, 1999, 2000).The western margin of the rift is characterized by uplifted Ufipa Block, along with a series of active fault lines including the Kalambo, Kanda, Songwe and Mbeya faults (Fig. 1; Delvaux et al. 1998, 2012), where active erosion occurs, and a large part of paleo- and modern fluvial systems originate from (see Mtelela et al. 2016, 2017).

The Lake Beds succession unconformably overlies the older Cretaceous Galula Formation or the late Oligocene Nsungwe Formation, and in places, it rests directly above Permo-Triassic Karoo rocks (Fig. 1; Roberts et al. 2004, 2010, 2012). The Lake Beds were first mentioned by Grantham et al. (1958) during regional geologic mapping of the southern part of the rift, in which they are described as conglomerate, sandstone and mud rocks associated with fluvial, floodplain and lacustrine environments. Since then, the Lake Beds have received very little geologic attention until very recently; when Cohen et al. (2013) began work on invertebrate biostratigraphy, and members of our team (Rukwa Rift Basin Project) began conducting extensive geologic mapping, sedimentology and geochronologic investigations of the Lake Beds succession (Hilbert-Wolf and Roberts 2015; Hilbert-Wolf et al. 2017; Mtelela et al. 2016, 2017). Indeed, the understanding of the sedimentology and stratigraphy of the Lake Beds succession has evolved considerably since the beginning of our projects on late Cenozoic Rukwa rift basin-fill history, which resulted in: (1) identification and sedimentologic description of at least three major depositional successions, termed the upper, middle (focus of this paper), and lower lake beds; (2) improved chronostratigraphy of these units; (3) refined understanding of the timing and relationships between sedimentation and climate, tectonics and volcanism; and (4) discovery of a series of important and previously unknown Miocene-Pleistocene vertebrate fossil localities in the East African Rift System (Mtelela et al. 2016, 2017).

The lower Lake Beds succession crops out along the uplifted western margin of the rift (Fig 1), where a well-developed angular unconformity can be observed between it and the Red Sandstone Group. Hilbert-Wolf et al. (2017) dated a basal ash bed from this unit, confirming a late Miocene age for the lower Lake Beds, which is consistent with proposed initiation of the final sedimentary succession in the rift and the initiation of the Rungwe Volcanic Centre (Ebinger 1989; Kilembe and Rosendahl 1992; Morley et al. 1990, 1999; Delvaux et al. 2012). Grantham et al. (1958), who first mapped the distribution of the Lake Beds strata, appears to have only recognized what we now refer to as the upper Lake Beds, and did not fully appreciate the complexity of this geologic sequence. These workers suggested an informal subdivision of the Lake Beds into lower and upper units; however, Mtelela et al. (2017) demonstrated that this subdivision represented lateral facies changes in the upper Lake Beds, rather than a stratigraphic subdivision. This is a situation that closely mimics the complexity of the Red Sandstone Group in the rift, which was mapped as a single depositional unit and alternatively considered to be Cretaceous or Miocene by various workers. However, more detailed sedimentological investigations by Roberts et al. (2004, 2010, and 2012) demonstrated a more complex depositional history, represented by at least two formations, each with two distinct members, spanning the Cretaceous-Paleogene.

During the course of our extended geologic mapping of the Lake Beds, we repeatedly encountered isolated lithostratigraphic units that looked similar, but different to the lower

Lake Beds unit and to parts of the Red Sandstone Group (and distinctly different from the upper Lake Beds). Our investigation revealed that these isolated series of small, often fault-bounded units observed in the Magogo area, the Songwe Valley, along the Ikumbi River (Fig. 1), and as far south as the Tukuyu area, could not be linked to any known depositional units in the rift, but were clearly located below the horizontally bedded upper Lake Beds, and above the lower Lake Beds. The relationship between these units is complex and remains poorly understood. However, preliminary radioisotopic dates obtained from detrital zircons (via LA-ICP-MS) and basalt flows capping these deposits (e.g. Tukuyu) indicate that these various units are most likely early to mid-Pleistocene (~2-1 Ma) in age. Herein, the term middle Lake Beds (mLB) is used to refer to this series of previously unmapped stratigraphic units in the rift. The focus of this study is to describe the distribution and sedimentology of these deposits, and to develop a preliminary, informal lithostratigraphic framework for the mLB.

MATERIALS AND METHODS

Geologic mapping of the Lake Beds succession was performed using topographic maps and the Mbeya 244 quarter-degree sheet map of Grantham et al. (1958) as base map, with GPS set to the Arc 1960 datum. A Jacob's staff and Brunton compass were used for measurement of stratigraphic sections. Sedimentologic analysis of the middle Lake Beds, including palaeocurrent measurements, facies and architectural element analysis followed techniques and methodology outlined in Mtelela et al. (2016). Lithofacies were identified primarily based on textural, composition, and sedimentary structures. Facies codes and nomenclature follows Miall (1996), with minor modifications to illuminate distinctive characteristics of the middle Lake Beds. Assemblages of genetically related facies were grouped into distinctive facies associations. Facies and facies association were analysed and interpreted in terms of depositional processes and environments based on sedimentologic depositional features, including textural attributes (grain size, shape, sorting) and architectural elements. Lithologic compositions and variation across the study, along with limited age constrains, were used to characterize the middle Lake Beds stratigraphy into distinctive informal members.

RESULTS

Distribution of the middle Lake Beds strata

The middle Lake Beds forms the last portion of the Lake Beds stratigraphy to be identified in the Rukwa Rift Basin, following a renewed geologic mapping conducted between 2012 and 2016. The middle Lake Beds succession appears to be limited to a series of isolated, typically fault-bounded units that show considerable lithological variability. Middle Lake Beds exposures are currently recognized in the following areas.

Magogo Area

Along a tributary to the Zira River (Fig. 1), an ~ 60 m thick, steeply dipping middle Lake Beds section crops out around Magogo area, which is overlain by horizontally bedded upper Lake Beds deposits. Here, two lithostratigraphic units are recognized and assigned to the middle Lake Beds: (1) a lower limestone unit and (2) an upper volcanoclastic sandstone and mudstone dominated unit. No lower contact is observed, but both units are dipping and appear to represent a continuous stratigraphic sequence with a sharp, unconformable contact between the two units.

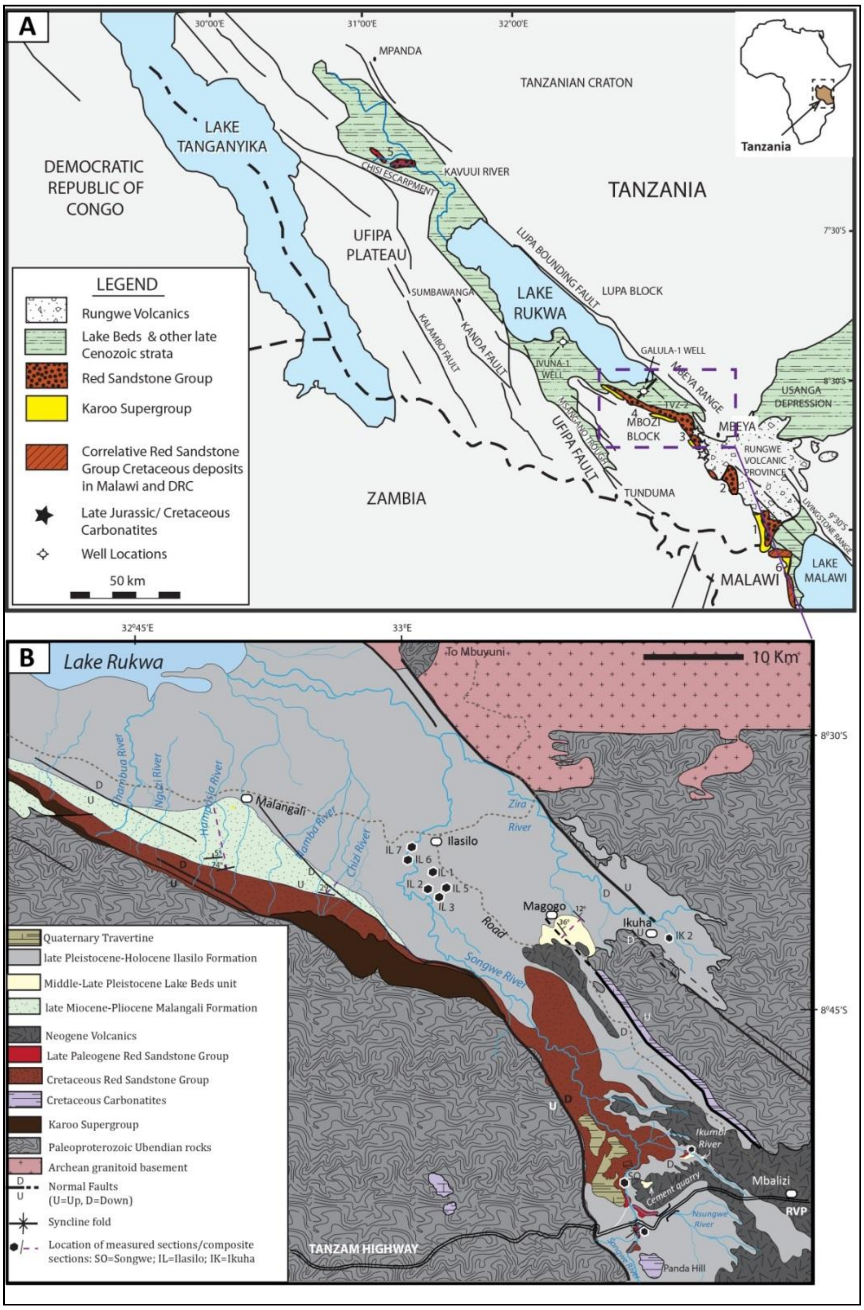

Figure 1: **A)** Geologic map of the Rukwa Rift Basin showing tectonic elements, distribution of rock units and location of the study area (insert box). **B)** Geologic map of the southern Rukwa Rift Basin (study area), showing the distribution and location of measured section through the lower, middle and upper Lake Beds in the following key areas: (1) Along the Songwe River (Songwe and Ilasilo areas), (2) to the east of

the main Songwe River (Cement Quarry and Ikumbi areas); (3) along the Hamposia and Chizi rivers (Malangali area); and (3) in the headwaters and tributaries of the Zira River (Magogo and Ikuha areas) (after Grantham et al. 1958 and Roberts et al. 2010), and the geologic map in part B is modified from Mtelela et al. (2016).

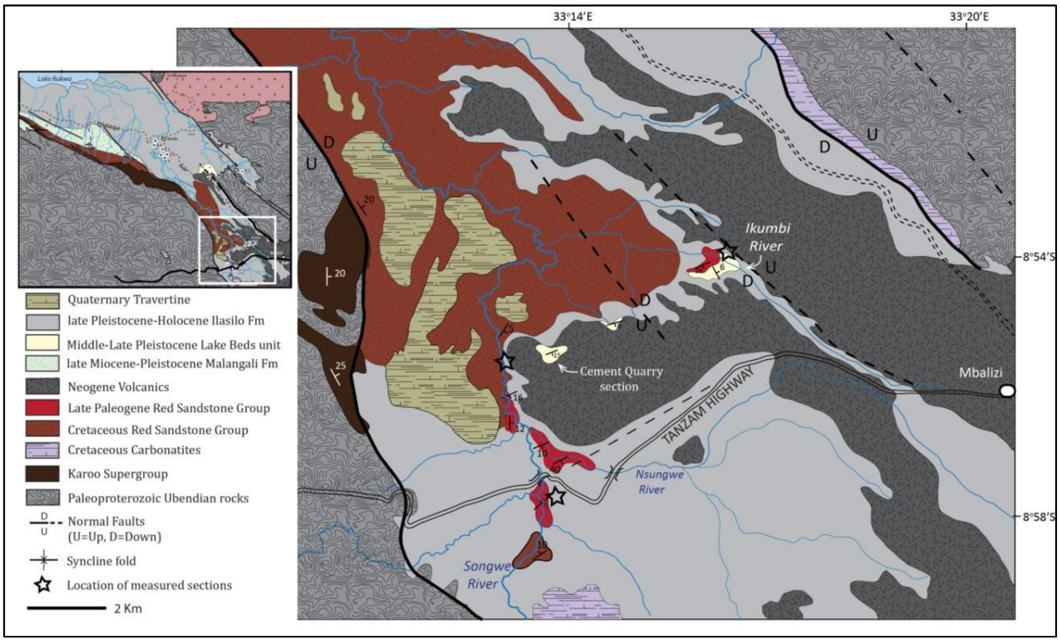

Figure 2: Geologic reference map of the study area (upper-left), and a close-up of the south-eastern part of the study (insert box in the reference map), showing middle Lake Beds exposures along the Songwe Valley and Ikumbi River. Note that the Tukuyu middle Lake Beds exposure is located ~ 80 km southeast of Mbalizi town, below Kaparogwe Falls.

Songwe Valley- Mbeya Cement Quarry

The middle Lake Beds also occur in the Songwe Valley, to the east of the Songwe River within the Mbeya Cement quarry and exposures in the valley directly to the east of the quarry (Fig. 2). In the Mbeya Cement quarry, the Lake Beds are characterized by reddish coloured siliciclastic-dominated sandstones that unconformably overlie a purple and whitish coloured sandstone unit. It is not clear yet whether the latter purple and white sandstone represents the late Oligocene Nsungwe Formation or Cretaceous Galula Formation of the Red Sandstone Group. Indeed around the quarry, the Lake Beds strata resemble the Red Sandstone Group in colour and sedimentologic characteristics. However, two detrital zircon (U-Pb) samples obtained from this section revealed early Pleistocene maximum depositional ages (~ 2 Ma and ~1 Ma grain ages; Hilbert-Wolf, H. pers. com). This is the only time in which detrital zircons of this age have been found in the Rukwa Rift (Hilbert-Wolf et al. in press), and this strongly suggests that these strata are post-lower Lake Beds; and hence, belong to the enigmatic middle Lake Beds. Much of the sandstone strata across the quarry are affected by normal faulting. The middle

Lake Beds unit around the Mbeya Cement quarry are overlain by Quaternary Travertine and horizontally bedded volcaniclastic upper Lake Beds Strata.

Ikumbi River

An exposure of possible middle Lake Beds strata is also mapped on the far east side of the Songwe Valley, along the Ikumbi River (Figs. 1 and 2). At the Ikumbi section, the middle Lake Beds strata are at least 20 m thick, and comprise volcanic ash-rich siliciclastic sandstone and conglomerate deposits that unconformably overlie a newly dated exposure of the late Oligocene Nsungwe Formation (Spandler et al. 2016). Both the middle Lake Beds succession and Nsungwe Formation strata are bounded by the Mbeya Fault to the northeast. The middle Lake Beds succession is stratigraphically overlain by distinctive, volcanic-ash rich upper Lake Beds strata along the Ikumbi River.

Kaparogwe Falls

Abundant sedimentary exposures exist south of the town of Tukuyu, many of which may represent middle Lake Beds deposits. However, to date, only a single locality has been studied in sufficient detail to report here. This locality is found below the lip of the popular tourist locality known as Kaparogwe Falls (~14 km south of Tukuyu town), which is characterised by a single ~3 m thick intra-basalt flow siltstone and sandstone sequence (Figs. 3 and 7). The southern-most middle Lake Beds deposits at Kaparogwe Falls overlie the Cretaceous Galula Formation and a basaltic flow laterally along the strike, and also capped by a basalt flow, which is dated at ~500 ka (A. Deino, pers. comm.). The Lake Beds strata form concave-up pod-like geometry, encased between the two basaltic flows. It is suspected that other middle Lake Beds equivalent deposits exist in the area; however, only a single "tourist" visit was made to this area during the course of this project, hence excellent potential exists for future work in the far southern portion of the basin.

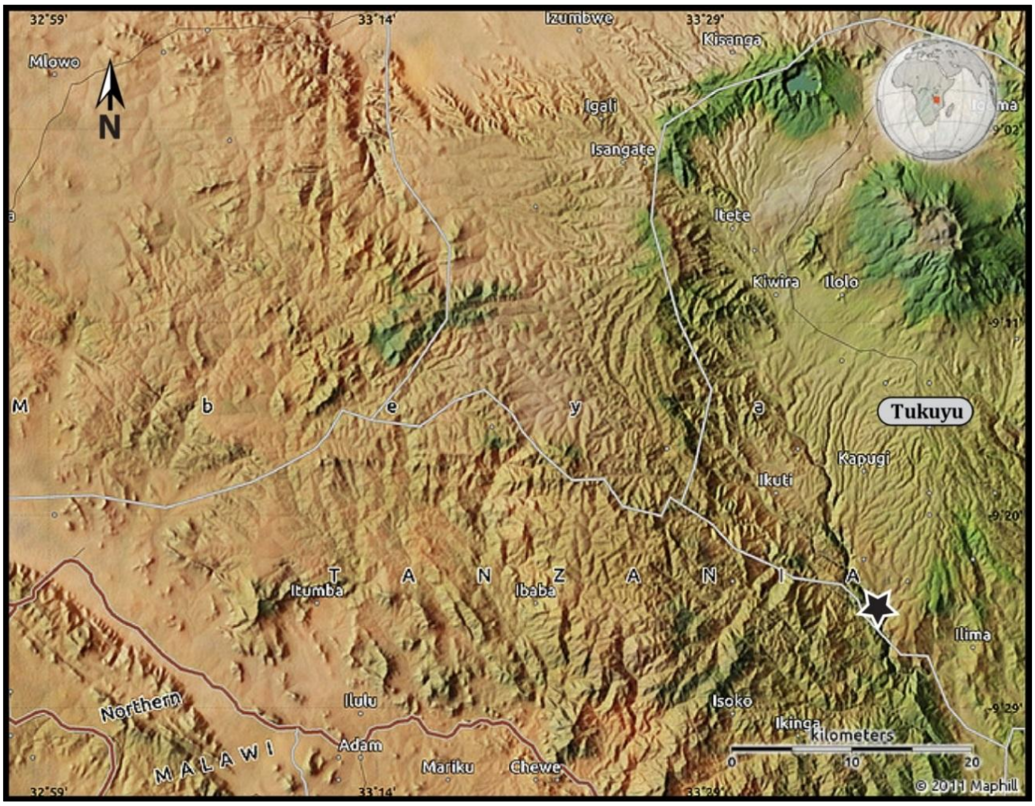

Figure 3: Satellite map of Tukuyu in the southwestern Tanzania, showing location of the mapped middle Lake Beds unit (insert star) below Kaparogwe Falls, ~ 80 km southeast Mbalizi (Figs. 1 and 2) and ~ 14 km south-southwest of Tukuyu town.

Sedimentology

Facies and architectural analysis was conducted at each of the outcrop sections. A total of 11 lithofacies were identified (Table 1), and were organised into four genetically-related facies associations (FAs), (Table 2). These FAs are described and interpreted herein, along with the contextualized depositional processes and environments.

Table 1: Sedimentary facies of the middle Lake Beds.

Facies	Texture	Structures and Features	Colour	Interpretations
Gcm: clast-supported conglomerate	Clasts: pebble- to cobble-sized; dominated by vein quartz and meta-granitoids; moderately sorted; sub-round to rounded	Massive; ungraded to weak normal graded	Yellowish gray (5Y 8/1) to white (N9)	Unidirectional high-energy flow regime deposits

	Matrix: tuffaceous medium- to coarse-grained sandstone			
Smvp: volcanic pebbly sandstone	Tuffaceous pebble-sized sandstone; comprised of volcanic (chiefly pumice), and meta-volcanics; moderately sorted; sub-angular to rounded	Massive, crudely fine upward	Very light gray (N8) to medium gray (N5)	Rapid (high-energy) pyrocla-stic flow deposits
Smv: massive sandstone	Medium- to coarse-grained, tuffaceous sand-sized, locally pebbly at base; comprises mainly quartz and feldspars; moderate- to poorly sorted; sub-angular to rounded;	Massive, crudely stratified; crudely fining upward	Pale olive (10Y 6/2) to yellowish gray (5Y 7/2)	Rapid (high energy) sedimentation deposits
Sm: massive sandstone	Fine- to medium-grained sandstone, quartzo-feldspathic in composition; moderate-well-sorted; sub-angular to rounded;	Massive, crudely stratified; crudely fining upward	Pale reddish brown (10R 5/4),moderate red (5R 4/6)	Rapid (low-medium energy) flow regime deposits
Sh: horizontally-stratified sandstone	Fine- to medium-grained sand; well-sorted; sub-round to rounded; quartzo-feldspathic	Horizontally-stratified, fine upward	Pale reddish brown (10R 5/4), moderate red (5R 4/6)	Unidirectional low- to medium-energy deposits
St: trough cross-stratified sandstone	Medium- to coarse-grained sand; composed of dominantly quartz and feldspar; moderate-well-sorted; sub-angular to rounded	Trough cross-stratified; fine upward	Pale olive (10Y 6/2), Pale reddish brown (10R 5/4),	Unidirection high-energy flow regime deposits
Fmv: massive volcanic siltstone	Ash and silt-sized grains	Typically massive; crudely bedded in places	light olive gray (5Y 5/2), medium gray (N5), light brownish gray (5YR 6/1), brownish gray (5YR 4/1),	Rapid (low-energy) subaqueous pyroclastic fallout deposits
Fhv:	Ash and silt-sized	Planar	light olive	Subaqueous

horizontally stratified volcanic siltstone	grains	stratification	gray (5Y 6/1), pinkish gray (5YR 8/1), medium gray (N5), light brownish gray (5YR 6/1), brownish gray (5YR 4/1),	pyroclastic flow/ fallout deposits
Fb: bentonitic sandy mudstone	Sandy ash, with isolated granules; comprises devitrified ash (bentonized) and pumice	Massive, crudely stratified	Pinkish gray (5YR 8/1), Very light gray (N8)	Rapid, subaqueous low-energy water-lain or air fall pyroclastic deposits
Fcf: massive fines	Silty mud and clay; moderate-well-sorted	Massive, horizontally-stratified	Pale reddish brown (10R 5/4), medium dark gray (N4)	Low-enegy suspension fallout deposits
Lst: limestone	Crystalline; composed mostly calcium carbonate ($CaCo_3$)	Massive, horizontally-stratified	Very light gray (N8), Pinkish gray(5YR 8/1)	Shallow saline lake precipitation (from solution) deposits

Table 2: .Facies associations (FAs), depositional process and environments of the middle Lake Beds.

FA	Facies	Diagnostic Features	Architectural Elements	Depositional Process	Macrofossil	Depositional Environment
FA 1: Fluvial channel deposits:						
FA 1A	Gcm, Sm	Coarse-grained nature; poor sorting; massive or crudely-stratified; ungraded- to weakly normal-grading; erosive lower bounding surface	SG, CH	Fluvial channel fill, sediment gravity fallout	-	Channel lags
FA 1B	Smvp, Smv, Fb	High degree of sediment rounding;	CH, SG	Pyroclastic reworking by sheet floods,	-	Fluvial channels.

		reverse grading; moderately-poorly-sorted; erosional or sharp basal surfaces		fluvial channels		
FA 1C	Sm, Sh, St	High degree of sediment rounding; upward fining; erosive (lower bounding) surfaces	SG, CH	Fluvial channel-fill, sediment-gravity fallout	Isolated fish bones	Fluvial channels
FA 2: *Lacustrine deposits:*						
FA 2A	Fb, Fmv, Fhv, Fcf	Fine-grained sediments; tabular; finely laminated or massive	FF, SH	subaqueous currents, suspension fallouts	Terrestrial plant trace fossils	Lacustrine (small lakes), ponds
FA 2B	Lst	Crystalline $CaCO_3$composition	-	Precipitation of $CaCO_3$	-	Lacustrine

FA1: Fluvial Channel deposits

Facies Association 1A

Facies Association 1A comprises 1-2 m thick tabular to lenticular clast-supported massive conglomerate (Gcm), embedded with thin (<40 cm thick) sandstone beds (Sm, Sh facies) (Table 1, 2). FA 1A is characterized by erosional, 5th order basal surfaces and gradational or sharp tops. This FA occurs repetitively in the upper portion of the Ikumbi section (Figs. 1, 2 and 4), where it is intercalated with lenticular sandstone deposits of FA 1C. FA 1A also occurs around Tukuyu area, interbedded with volcanic siltstone and ash deposits of Facies 2A (Figs. 3 and 7). Conglomerates are pebble- to cobble-sized (up to 90 mm in diameter), dominated by vein quartz and meta-granitoids clasts or basalts. Lithoclasts are sub-rounded to rounded, moderately sorted, exhibiting weak normal grading. The conglomerate consists of a tuffaceous medium- to coarse-grained sandy matrix. Subordinate sandstone facies are massive or horizontally stratified, fine- to medium-grained. Deposits of FA 1A are yellowish gray (5Y 8/1) to white (N9) coloured.

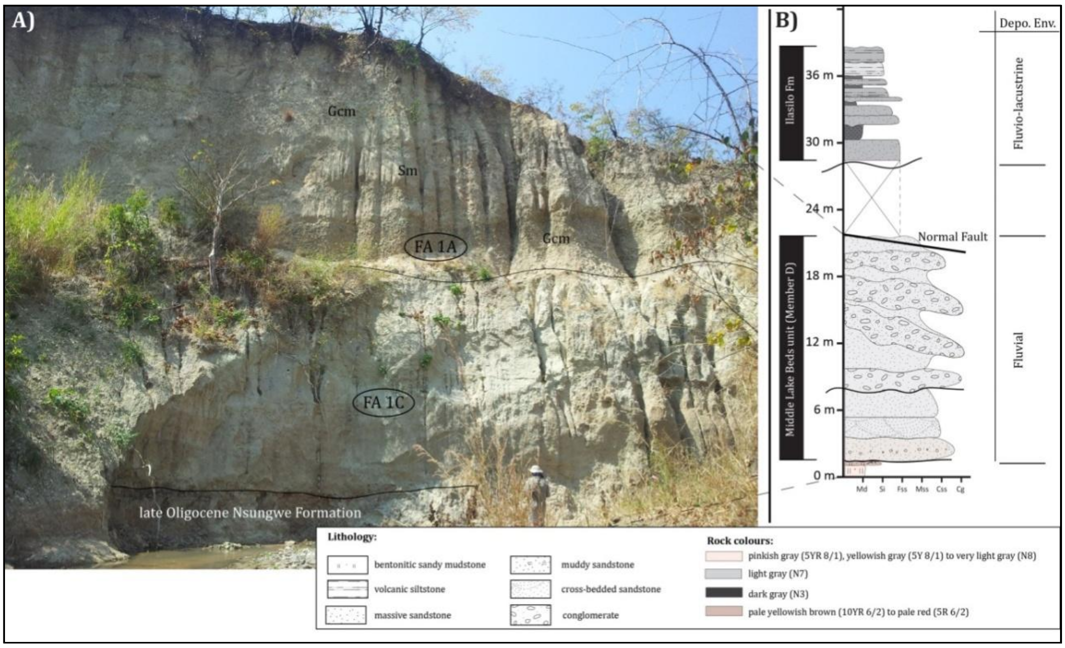

Figure 4: **A)** Middle Lake Beds exposure along the Ikumbi River, showing lithology and stratigraphic relationship of the late Oligocene Nsungwe Formation, and an informal Member D of middle Lake Beds unit. **B)** Measured stratigraphic section showing constituent facies of the middle Lake Beds informal Member D.

Interpretation
Facies Association 1A is interpreted to represent high-energy fluvial channel lag deposits, based on its coarse-grained sediment character, structureless (massive), and erosive 5th-order basal surfaces. The typical lenticular bed geometry of FA 1A, vertical and lateral alternation with lenticular sandstone beds of FA 1C suggests deposition by braided fluvial channels, and associated hydrodynamic changes within braid plain environments (cf. Miall 1996; Bride et al. 2000; Mtelela et al. 2017). The recurrence of this facies across the stratigraphic section is interpreted to probably indicate repeated channel reactivation.

Facies Association 1B
Facies Association 1B occurs in the upper portion of the Magogo section (Figs. 1, 2 and 5), and in the Kaparogwe section near Tukuyu (Figs. 3 and 7). Facies 1B consists of 0.4 to 1.5 m thick, tabular-lenticular, massive tuffaceous pebbly sandstone facies (Smvp: Table 1, 2) and minor medium- to coarse-grained tuffaceous sandstone (Smv) and bentonitic mudstone (Fb). Facies 1B extends laterally for 60 to 80 meters, and appears to have been eroded beyond this exposure. The upper and lower contacts of FA 1B are typically erosional or sharp. Tuffaceous pebbly sandstone (lapilli tuff) is typically massive, well-indurated and moderately sorted, exhibiting crudely upward fining. It is composed of sub-angular to rounded pumice particles and mafic volcanic grains that range in size from coarse sand to pebbles, and cemented by fine ash. Facies 1B is very light gray (N8) to medium gray (N5).

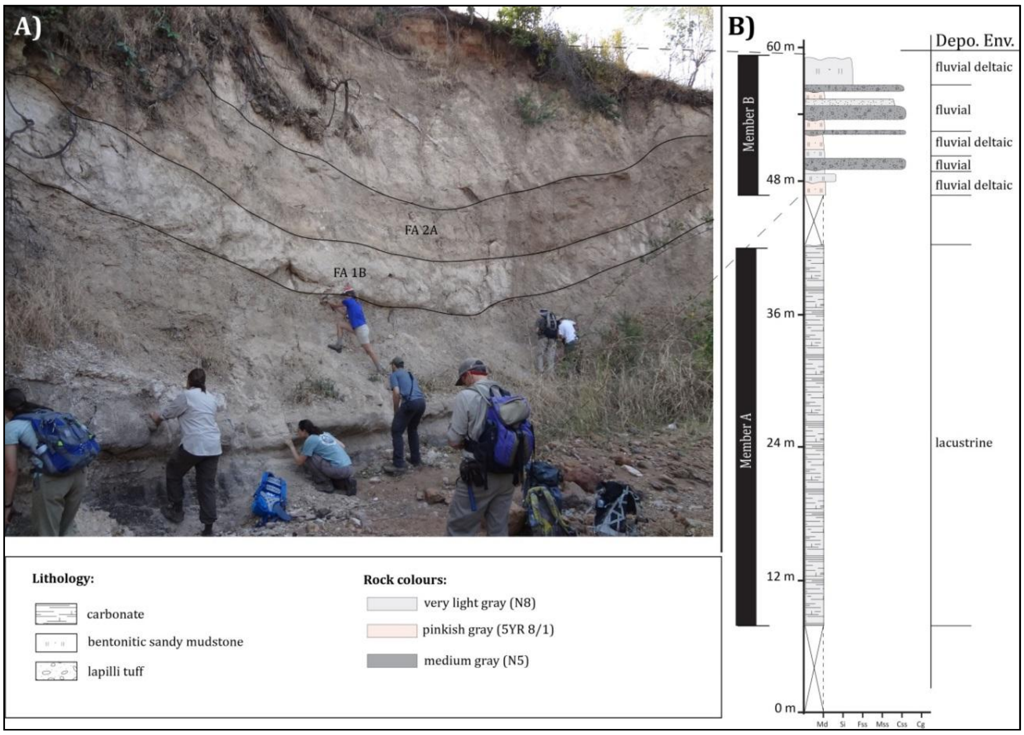

Figure 5: **A)** Exposed upper portion of the Magogo middle Lake Beds unit showing tuffaceous sandstone facies (Smvp: FA 1B) interbedded with bentonitic mudstone of FA 2A, and **B)** Measured stratigraphic section.

Interpretation

Based on high degree of sediment rounding, erosive 5th-order bases, and upward fining, FA 1B is interpreted as high-energy fluvially reworked pyroclastic flow deposits (cf. Bhat et al. 2008). The massive nature of FA 1B is interpreted to indicate rapid deposition by sediment gravity-fallout processes during wanning fluvial flows. Alternatively, the massive nature, along with ashy matrix of this facies, may also reflect the rapid production of volcanic sediment during and immediately after explosive volcanic events, most likely from the nearby Rungwe Volcanic Province.

Facies Association 1C

Facies Association 1C occurs in the Ikumbi section, cement quarry section as well as in a small exposure at the water-falls section east of cement quarry (Figs. 1, 2, 3C, 4). FA 1C comprises single or multiple tabular sandstone bedsets of St, Sh and Sm facies (Table 1, 2). FA 1C reaches up to 6 m thick unit, with individual beds ranging between few tens of cm to 1.5 m thick, and the cosets extending laterally to about 50 m. The basal surface of this FA is typically erosional (5th-order surfaces), locally containing isolated pebbles. Top contacts are either sharp or gradational fourth-order surfaces. Sandstone beds are tabular or lenticular, locally truncated by conglomerate bodies of FA 1C. They are commonly moderately well-sorted or poorly sorted in places, and comprises sub-rounded to rounded grains. FA 1C are dominantly quartzo-feldspathic in composition, varying in colour from pale reddish brown (10R 5/4), pale olive (10Y 6/2) to yellowish gray (5Y 7/2). In places, Facies IC is fossiliferous, preserving mostly fish remains.

Figure 6: Exposed section of the middle Lake Beds inside the Songwe cement quarry, showing lithologic composition of an informal Member C (FA 1C), and its relationship with underlying late Oligocene Nsungwe Formation.

Interpretation

Based on erosive basal surfaces, sedimentary structures and textural features such as sediment (grain) rounding and upward-fining, FA IC is interpreted as fluvial channel deposits. This interpretation is also supported by the presence of fish remains. Horizontally- and trough cross-stratified intervals of this FA are interpreted to record bedload tractive current sedimentation of a normal fluvial flow, whereas massive intervals are interpreted to have resulted from flood-related gravitational collapse processes (Miall 1996; Leleu et al. 2009).

FA2: Lacustrine deposits

Facies Association 2A

Facies Association 2A consists of tabular bentonitic sandy mudstone and minor siliciclastic mudstone beds (facies Fcf, Fb), or in places, volcanic siltstone beds, facies Fmv and Fhv (Tables 1 ad 2). This FA is well-developed in the Magogo section as well as in Tukuyu Lake Beds exposure. Mudstone beds comprise silt to clay-sized sediments, and are massive (structure-less) or crudely stratified. They are pale reddish brown (10R 5/4), pale olive (10Y 6/2) coloured. Bentonitic sandy mudstone is also massive, composed of pumice sand-sized grains and isolated granules and devitrified ash. They range in colour from pinkish gray (5YR 8/1) to very light gray (N8). Volcanic siltstone facies of this FA are typically tabular, light olive gray (5Y 5/2) or pinkish gray (5YR 8/1) coloured. They are massive or horizontally stratified. In the Kaparogwe section, Facies 2A is fossiliferous; preserving plant remains and trace fossils (Fig. 7C). Here, FA 2A forms part of a lenticular, concave-up middle Lake Beds strata that pinches out tens or few hundreds of meters laterally, and encased by two basaltic flows.

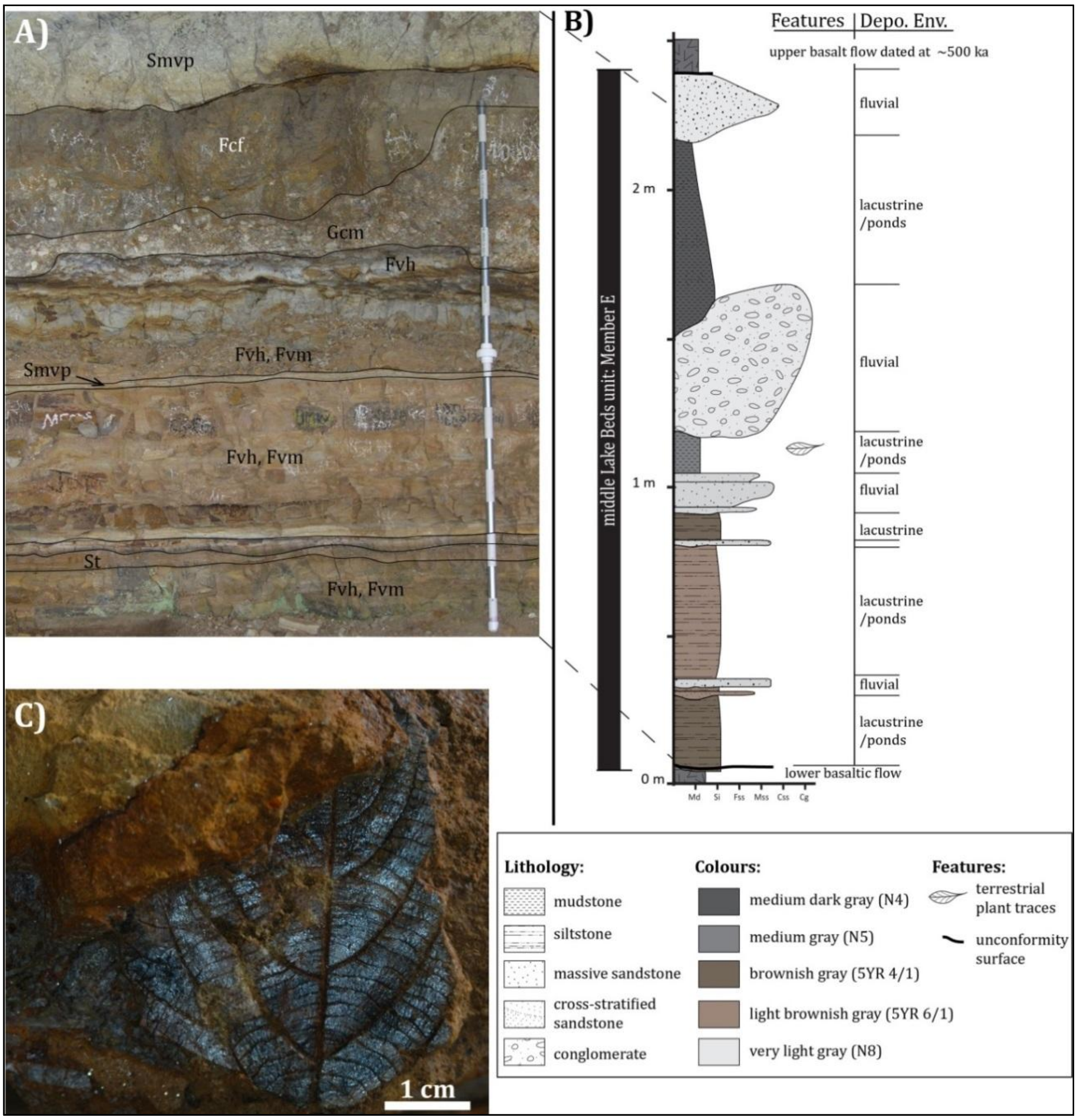

Figure 7: **A**) Exposed middle Lake Beds unit along the cliff-face of Kaparogwe Falls ~14 km south of Tukuyu town (See Fig. 3 for location), showing massive and horizontally-stratified volcanic siltstone (Fvm, Fvh) facies of Facies 2A, interbedded with tuffaceous sandstone and conglomerate deposits of FA1. **B)** a measured stratigraphic

section. **C)** A close-up photo of a leaf impression observed mid-way (at ~1.1 m from the base) across the stratigraphic section in A.

Interpretation

Fine-grained nature of FA 2A is interpreted to indicate low-energy deposition by suspension fallout of very fine (ash and clay-sized) sediments. Typical lenticular nature of this facies in the Kaparogwe section suggests deposition in small lakes or ponds that developed between lavas (basaltic flows). The common alternation of this facies with FA 1B may suggest periodic base-level fluctuations and transition between lacustrine/ponds and fluvial channel systems. Alternatively, interbedded fluvial conglomerate deposits of FA 1B might have resulted from periodic flash flooding events, which deposited more coarser grained units into small lakes and ponds, from rapidly uplifted and eroded rift flanks (cf. Mtelela et al. 2016). This interpretation is also supported by the presence of traces of plant macrofossils (Fig. 7C).

Facies Association 2B

Facies Association2B is a 50-100 m thick massive and horizontally stratified limestone and travertine (facies Lst) exposed in the lower part of the Magogo section (Table 1, 2). This facies association extends laterally to about 160 meters. The beds are dipping to the east; however, the original horizontal bedding is clear. This locality was visited briefly and prior to our recognition of the middle Lake Beds stratigraphy, so a complete measured section and detailed stratigraphic log was not completed at the time. However, preliminary description of the site and partial measured section permits a reasonable first-order (overview) description. Facies Association 2B (comprising facies Lst) is typically crystalline, composed of mainly calcium carbonate ($CaCO_3$), is very light gray (N8) or pinkish gray (5YR 8/1) coloured. Evidence of horizontal bedding (and bands, for travertine) is present, along with vertical root or burrow traces in some horizons. Although only a limited time was spent investigating for fossils, none were found.

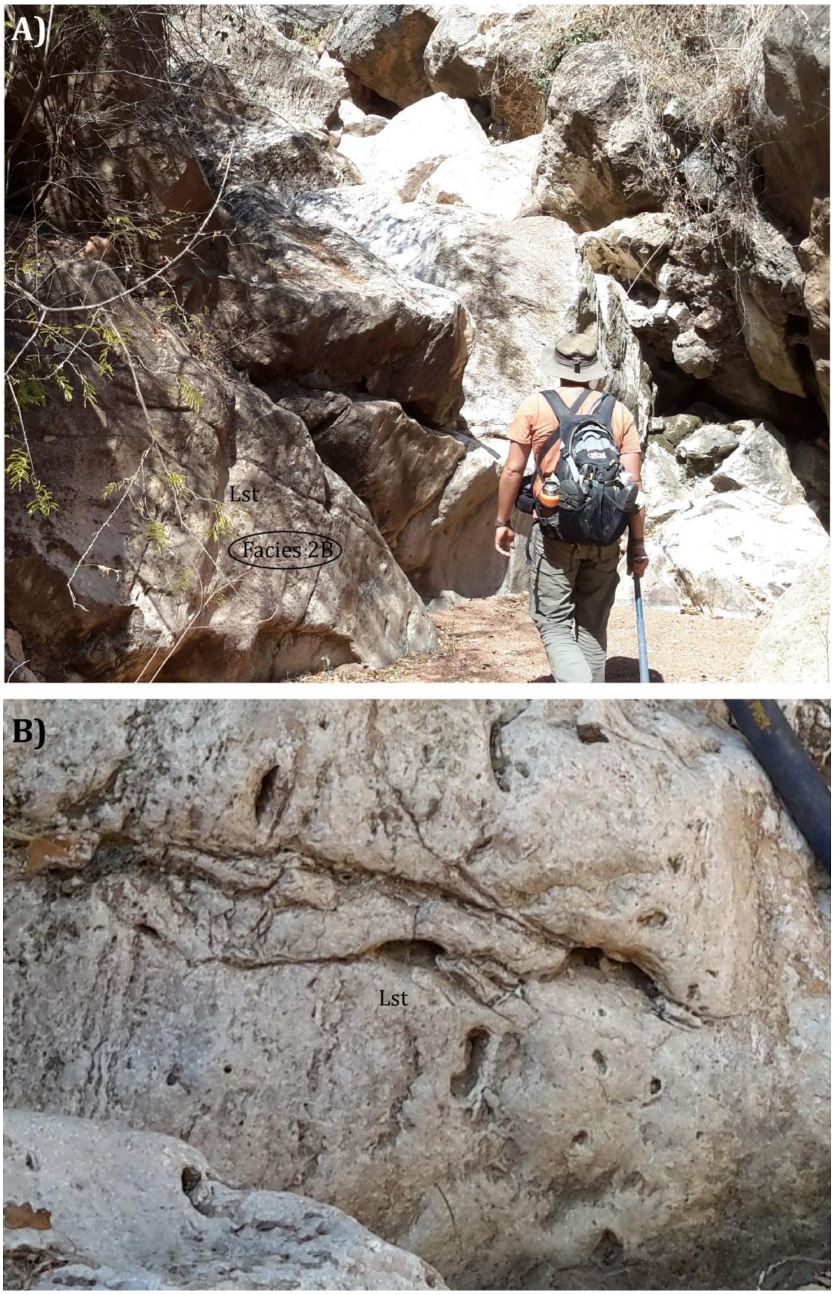

Figure 8: **A)** Outcrop photo showing a portion of the thick carbonate unit -Limestone (Lst) facies (FA 2B) exposed along the dry tributary river-cuts to the Zira River in the north-eastern portion of the study area, around Magogo Village. **B)** A close- up of the massive, crystalline limestone.

Interpretation

Based on composition, Facies 2B is interpreted to have resulted from precipitation of calcium carbonate from water in shallow lacustrine conditions. The travertine and limestone deposits of FA 2B are similar to the Quaternary travertine deposits observed in the Songwe Valley; however, it has a much more uniform horizontally bedding and contains burrows/roots in some intervals, suggesting that it was primarily deposited in a lacustrine setting, rather than a hydrothermal setting. However, a hydrothermal origin or perhaps combined hydrothermal-lacustrine origin cannot be completely ruled out (Porta, 2015). FA 2B is overlain by a distinctive succession of volcaniclastic mudstones and sandstones, and both units are tectonically tilted, and have been subsequently overlain by diagnostic deposits of the upper Lake Beds. Hence, this unit appears to be both temporally and stratigraphically distinct from the late Quaternary travertine deposits found in the Songwe Valley. The deposition of FA 2B is envisaged to have probably occurred during relatively dry climatic condition, which could have led to prolonged precipitation of this thick carbonate unit. The greater thickness and massive nature of large portion of FA 2B is interpreted to indicate formation of a local lake basin associated with the deposition of this FA.

Lithostratigraphy

Lithostratigraphic relationships between the middle Lake Beds sections are complex and remain cryptic. However, sedimentary facies and lithologic variations between and across these middle Lake Beds stratigraphic sections suggest the presence of at least five distinctive lithologic units. These distinctive units are referred to here as informal members (member A-E) of the middle Lake Beds unit, and are described below.

Member A

Informal member A is defined as the 36 m thick (minimally, but probably much greater) limestone unit (FA 2B) that crops out in the lower part of the Magogo section (Fig. 5B, 8). This thick-bedded limestone unit is not observed elsewhere within the Lake Beds succession in the study area, and is distinct from late Quaternary travertines documented in the Songwe Valley. The basal contact of this unit is not exposed, and the upper contact is sharp, and likely unconformable, Based on differences in attitude (bedding) of the strata between this unit and the overlying succession of the informal Member B. The unit is gently to steeply inclined towards northeast; exhibiting changes dip angles due to post-depositional tectonics movements (faulting) from 12° near the base, to 36° at the upper portion (Fig. 1B).

Member B

Overlying member A in the Magogo Lake beds exposure is ~12 m thick succession of volcaniclastic deposits identified here as informal member B of the middle lake beds unit (Fig. 5A-B). Member B is characterized by alternating tuffaceous sandstones, bentonitic mudstone and massive volcaniclastic conglomerates (FAs 1A, 1B). Tuffaceous sandstones are coarse-grained sand sized and pebbly, ranging in thickness between 0.4 and 1.5 m, and are typically massive or crudely stratified. They are very light gray (N8) or medium gray (N5) coloured. The tuffaceous pebbly sandstone and conglomerate beds are composed of sub-angular to rounded pumice particles and mafic volcanic grains/pebbles, moderately sorted and cemented by fine ash. The basal surfaces are typically erosive 5th order contacts, cutting and filling the bentonitic mudstone beds. The top contacts are either sharp or gradational. Volcanic mudstone is also massive, tabular bedded, up to 80 cm thick, and extends laterally to ~80 meters.

They are pinkish gray (5YR 8/1) or very light gray (N8) coloured, comprising bentonized ash and isolated sandy pumice grains. .

Member C

Informal member C of the middle lake beds is identified at the cement quarry section, where lake beds crops out as pale reddish brown (10R 5/4) to moderate red (5R 4/6) coloured, medium-coarse grained sandstone and siltstone (FA IC), dipping 15° towards southeast (Fig. 6).Member C is characterized by well-sorted, massive and horizontally stratified siliciclastic sandstones and massive or crudely stratified siltstones and mudstones. Sandstone bodies are composed of sub-rounded to rounded grains of dominantly quartz and feldspars. Individual beds have erosional 5^{th} order basal surfaces, and exhibits upward fining.

Member D

Member D occurs along the Ikumbi River, and is informally defined as a ~20 m thick and 50-70 m long succession of volcanic ash-rich siliciclastic sandstones (FA IC) and conglomerates (FA 1A) unconformably overlying the Oligocene Nsungwe Formation (Fig. 4). Both sandstones and conglomerate deposits of member D are Pale olive (10Y 6/2) to yellowish gray (5Y 7/2) coloured, albeit due to volcanic ash content in the matrix. The basal portion of member D comprises 6° northeast-dipping bedset of massive and trough cross-bedded sandstones. This basal succession is overlain by repetitive tabular and lenticular, massive, pebble-cobble conglomerate beds that are interbedded and intercalated with lenticular sandstones. High-relief erosional scours separates the lower part and upper portion of this unit. The lower sandstone bedset is moderate- to well-sorted, showing generally upward fining trend from pebbly sandstone basal bed to medium-/fine-grained sandstone.

Member E

Informal member E is identified as a volcaniclastic dominated unit exposed near Tukuyu (Fig. 3), unconformably overlying the Cretaceous Galula Formation and capped by a basaltic flow. Member E is dominated by tabular-lenticular volcanic siltstone, mudstone and claystone deposits (FA 2A) that are interbedded with tuffaceous sandstone (lapilli tuff) and conglomerates (Fig. 7). Volcanic siltstone and mudstone/claystone is massive or horizontally stratified, comprised of dominantly silty to clay-sized pumice and ash. They are locally fossiliferous, preserving traces of terrestrial plant macrofossils (Fig. 7C), and varies in colour between brownish gray (5YR 4/1), light brownish gray (5YR 6/1), medium gray (N5) and medium dark gray (N4). The interbedded tuffaceous sandstone and conglomerate are typically massive, with erosion bases, and are very light gray coloured. They are commonly lenticular, and pinch out few meters laterally.

DISCUSSION

The Lake Beds succession was mapped by Grantham et al. (1958) and subsequent workers, revealing that they cover much of the Rukwa Rift Basin (RRB). Recent work by Cohen et al. (2013) and Mtelela et al. (2016) are largely in agreement with Grantham et al. (1958) that the vast majority of the mapped Lake Beds deposits are late Quaternary, and corresponds to what is termed in Mtelela et al. (2016) as the upper Lake Beds. In contrast, the Miocene to Pliocene (and possible Pleistocene) lower Lake Beds is extremely limited in outcrop distribution (Mtelela et al. 2017), with only two well-exposed outcrop areas (along Chizi and Hamposia River drainages) along the southwestern margin of the rift. The current study provides insights to a broader understanding of the Lake Beds sedimentology and stratigraphic setting in the RRB, providing an overview of a third depositional unit within the strata that was previously unrecognized. This newly identified unit occurs in a suite of isolated, fault-bounded sections across the southern RRB, unconformably overlying older Red Sandstone Group strata (Roberts et al. 2010), and overlain by the upper Lake Beds succession (Mtelela et al., 2016). Based on pilot U-Pb dating (H. Hilbert-Wolf pers. comm.), Ar/Ar dating of basalts (A. Deino, pers. comm.), and cross-cutting relationships, this newly identified series of deposits in the RRB is interpreted to represent an early to middle Pleistocene middle Lake Beds unit, deposited between ~ 2 Ma and 200 ka. However, these radiometric age assignments are considered as preliminary until further dating of the strata can be conducted to improve the geochronology.

This sedimentologic investigation reveals remarkable lateral and vertical depositional facies variation across the middle Lake Beds strata, ranging from highly siliciclastics units, volcaniclastics units to carbonates. Similar facies changes between volcaniclastics and siliciclastics units were also observed in the upper Lake Beds succession (see Mtelela et al. 2016). However, sedimentologic features such as degree of compaction, textural and compositional variations in addition to stratigraphic positions, suggests that these units may not represent time-equivalent strata. Most of the middle Lake Beds exposures appear to be fault-bounded, which may suggest that deposition occurred during more tectonically active episode. Rift tectonics (faulting) may also be linked to the observed lateral variability in depositional facies and environments, and provenance in a number of possible ways, probably leading to: 1) tectonic subsidence proximal to the paleo-lake Rukwa around Magogo area, where localized lacustrine carbonates were deposited in a small, possibly saline lake; 2) likely simultaneous tectonic uplift of the rift flanks in the hinterland, leading to siliciclastic fluvial deposition around Songwe and Ikumbi areas; and 3) contemporaneously volcanism in the nearby Rungwe Volcanic Province that resulted in primary and fluvial reworked volcaniclastic deposition in the Kaparogwe area (near Tukuyu), and upper part of the Magogo section, as well as volcanic ash-rich siliciclastic deposition in the upper portion of the Ikumbi section.

The identification of this new stratigraphic unit, the middle Lake Beds, provides an important insight into revising the Lake Beds stratigraphy, and establishing a formal nomenclature for this academically and economic important strata in the basin. The Lake Beds have recently produced the whole new suite of vertebrate fossil record from the RRB (cf. Mtelela et al. 2017). Indeed, the late Cenozoic Lake Beds succession is also important hydrocarbon exploration target of the Tanzania Petroleum Development Corporation and Heritage Oil Plc in the basin. Thus, findings from this study serve as an important geologic background towards understanding full tectono-sedimentary history of the RRB, building upon recent efforts by the members of the Rukwa Rift Basin project (e.g. Roberts et al. 2004, 2010, 2012; Hilbert-Wolf et al. 2017). However, further work should be done to map-out and date the middle Lake Beds throughout the basin, to determine the full extent of the unit and age.

CONCLUSIONS

Sedimentologic and stratigraphic studies were conducted on a previously unrecognized Lake Beds unit in the Rukwa Rift Basin, termed herein as the middle Lake Beds. The results indicate that the middle Lake Beds were deposited in a series of local depocenters during the early to mid-Pleistocene. Eleven sedimentary facies were identified across a series of faulted-bounded exposures, which were recognized into five genetically-related facies associations, including: clast-supported conglomerate (Facies 1A), volcaniclastic sandstones (Facies 1B), and single and multi-story siliciclastic sandstone bodies (Facies 1C), which are associated with fluvial channel and fluvially reworked pyroclastic flows; and lacustrine deposits of tabular volcanic siltstone and mudstone (Facies 2A), and massive and horizontally stratified limestone (Facies 2B).

Lithostratigraphic relationships between the discrete middle Lake Beds units is complex and poorly understood due to complex faulting system associated with these small and isolated exposures, and requires a follow-up mapping. However, lithologic variations between the mapped sections suggest the presence of five distinctive units, herein referred to as informal members (A-E) of the middle Lake Beds succession. The discovery of this new stratigraphic unit in the Rukwa Rift Basin further highlights the need to extend geochronologic investigation into this unit, and to establish a revised, formal stratigraphy of the Lake Beds succession.

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