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Sedimentology and depositional environments of the Red Sandstone Group, Rukwa Rift Basin, southwestern Tanzania: New insight into Cretaceous and Paleogene terrestrial ecosystems and tectonics in sub-equatorial Africa

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ABSTRACT

The Red Sandstone Group (RSG) in the Rukwa Rift Basin of southwestern Tanzania represents one of the only well-exposed, fossiliferous Cretaceous–Paleogene continental sedimentary sequences in sub-equatorial Africa. The significance of the RSG for reconstructing the paleoenvironmental and paleoclimatic history of African ecosystems during these critical time periods has been obfuscated by long-standing confusion and debate over the age of the deposits. Detailed stratigraphic, sedimentologic, and paleontologic investigations of the RSG conducted between 2002 and 2008 have produced a wealth of new fossil discoveries and data on lithofacies, alluvial architecture, sedimentary provenance, clay mineralogy and geochronology that resolve the long-standing debate over the age of these deposits. This study confirms the existence of an extensive middle Cretaceous sequence, herein named the Galula Formation, and subdivided into the Mtuka and Namba members. Moreover, we document the existence of a previously unrecognized late Paleogene continental sequence termed the Nsungwe Formation, which is divided into the Utengule and Songwe members. The Galula Formation represents a 600-3000 m thick sequence of amalgamated, braided fluvial deposits that were deposited across a large braidplain system via multiple parallel channels that had their source in the highlands of Malawi and Zambia. The middle Cretaceous Dinosaur Beds of Malawi are hypothesized to be at least partially correlative with the Galula Formation, and represent proximal deposits of this large, northwest flowing, trunk stream system. A moderately diverse terrestrial vertebrate fauna, including multiple species of dinosaurs, crocodyliforms, turtles, fishes and mammals have been recovered, along with a sparse aquatic molluscan fauna. Lithofacies and clay mineralogy indicate that Cretaceous paleoclimate ameliorated during deposition of the Galula Formation, transitioning from tropical semi-arid to tropical humid conditions.

The 400+ m-thick late Oligocene Nsungwe Formation is temporally constrained by concordant mammalian biostratigraphy, detrital zircon geochronology and a radiometrically dated volcanic tuff capping the sequence (∼24.9 Ma). A significant change in depositional environments occurs between the lower alluvial fan-dominated Utengule Member and the upper fluvial and lacustrine-dominated Songwe Member. The Songwe Member preserves a diverse terrestrial and aquatic vertebrate and invertebrate fauna, with abundant ashfall and ashflow volcanic tuffs that were deposited in a semi-arid wetland landscape during the late Oligocene. The Nsungwe Formation provides a new window into the early tectonics and faunal transitions associated with initiation of the "modern" East African Rift System.

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1. Introduction

Late Mesozoic and early Cenozoic sedimentary strata are scarce and poorly exposed in Southern and Central Africa (Mateer et al., 1992). In contrast, they are extensively exposed across much of North and West Africa, and a comparative wealth of data have been obtained from various basins in the circum-Saharan region, in large part due to their prospective hydrocarbon potential (e.g., Bosworth, 1992; Guiraud et al., 1992, 2005; Burke et al., 2003). Intensive paleontological exploration in many of these deposits has facilitated reconstruction of paleoenvironments, paleoclimate, and paleoecology for much of supra-equatorial Africa during the Cretaceous–Paleogene interval (e.g., Osborn, 1908; Lavocat, 1954; Lapparent, 1960; Taquet, 1976, 1982; Jacobs et al., 1988, 1989; Brunet et al., 1990; Sereno et al., 1994, 1996, 1998; Simons et al., 1994; Rauhut and Werner, 1995, 1997; Simons and Rasmussen, 1995; Russell, 1996; Nessov et al., 1998; Sigogneau-Russell et al., 1998; Goodwin et al., 1999; Smith et al., 2001; Rage and Cappetta, 2002; O'Leary et al., 2004, 2007).

In contrast, similarly aged continental sedimentary sequences in sub-equatorial Africa remain very poorly studied and understood, partially as a consequence of vegetative cover and inaccessibility (Mateer et al., 1992). Limited economic resources and poor fossil preservation in many sub-equatorial basins have also minimized geological and paleontological investigations. Basin studies in southern Africa have instead been heavily focused on the extensive network of coal and fossil-bearing Karoo-aged sedimentary sequences (e.g., Haughton, 1963; Kitching, 1977; Falcon, 1986; Catuneanu et al. 2005; Rubidge, 2005) and hominid-bearing late Neogene to Pleistocene deposits (e.g., Dart, 1925; Broom, 1938; Tobias, 1981; Brain et al., 1988).

Continental faunas, floras, paleoenvironments and paleoclimates of sub-equatorial Africa during the Cretaceous–Paleogene remain poorly understood with few exceptions (see Stevens et al., 2008 and references therein). O'Connor et al. (2006) referred to this problem as the 'African Gap'. As a result, large-scale studies that focus on the geological and biological relationships of sub-equatorial Africa with other regions of Africa, and other parts of

Gondwana, have been greatly hampered by the lack of critical data resulting from this gap in our knowledge.

The best combined stratigraphic and paleontologic record for the interval in question comes from the earliest Cretaceous in the Eastern Cape region of South Africa. Extensive research on the faunas, floras, and depositional environments of alluvial to coastal plain deposits of the Enon, Kirkwood and Sundays River Formations has produced an excellent record for this region (Broom, 1904; McLachlan and McMillian, 1976; Shone, 1978; Galton and Coombs, 1981; Rich et al., 1983; McMillan, 1999; Ross et al., 1999; De Klerk et al., 2000; Gomez et al., 2002a,b). The ?Aptian Dinosaur Beds of Malawi have also been well studied with regard to vertebrate paleontology, yet the necessary stratigraphic and sedimentologic data on these deposits remain limited (e.g., Dixey, 1928; Haughton, 1928; Colin and Jacobs, 1990; Jacobs et al., 1990, 1992, 1993; Gomani, 1997, 1999; Winkler et al., 2000). In contrast, detailed sedimentological studies by Mountney et al. (1998, 1999) and others have obtained important paleoenvironmental and paleoclimatic data on the earliest Cretaceous depo-

sitional systems in the Huab Basin of Namibia, but no body fossils have yet been recovered from these deposits, hampering terrestrial ecosystem reconstruction. The majority of studies on Early Cretaceous continental deposits in Zimbabwe, Zambia, Mozambique, Malawi, Tanzania, Democratic Republic of Congo (DRC), Angola, Central African Republic and Gabon were conducted by colonial geological surveys (e.g., Dixey, 1928; Cahen, 1954; Spence, 1954; Spurr, 1954; Harkin and Harpum, 1957; Grantham et al., 1958), along with limited recent studies primarily focused on regional tectonics and hydrocarbon potential (Barber, 1987; Censier and Lang, 1999; Hancox et al., 2002; Mounguengui et al., 2003). Significantly, these early sedimentological and paleontological reports on Cretaceous–Paleogene age deposits in Central Africa provide an excellent regional stratigraphic framework and have resulted in a series of isolated fossil discoveries, dominated by microfossil assemblages, fish remains and scattered terrestrial vertebrate finds, including dinosaurs. For example, Raath and McIntosh (1987) discovered sauropod dinosaur remains from the putative Lower Cretaceous Kadzi Formation in the Zambezi Valley,

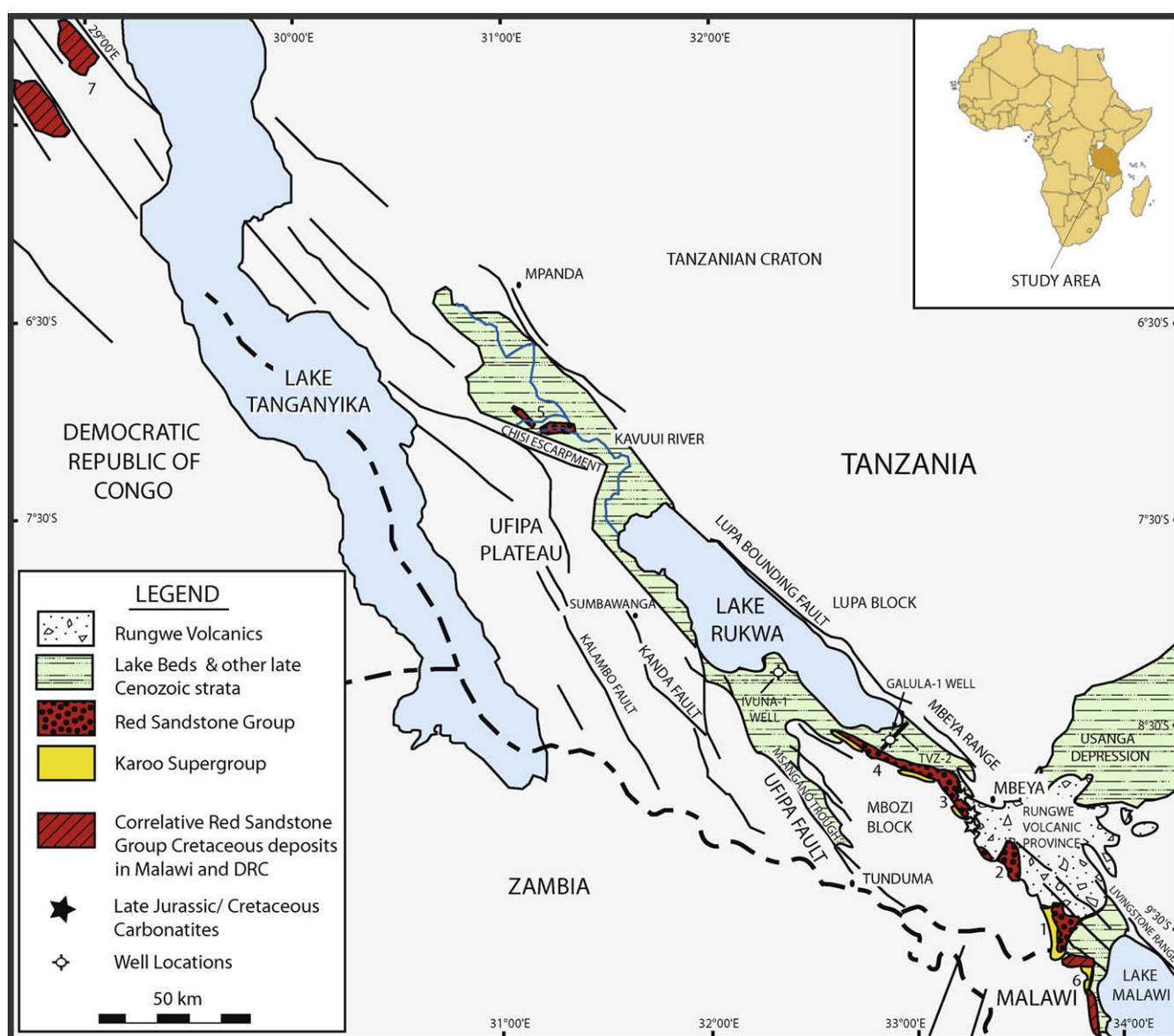**Fig. 1.** Geological map of the Rukwa Rift Basin showing major tectonic elements and distribution of Phanerozoic sedimentary deposits. Field localities are numbered: 1 – Tukuyu; 2 – Kipande; 3 – Songwe; 4 – Galula; 5 – Usevia; 6 – Dinosaur Beds of Malawi; and 7 – Luama Redbeds in DRC. See Van Straaten (1989) for details on the Late Jurassic/Cretaceous carbonatites, which are marked on the map as stars.
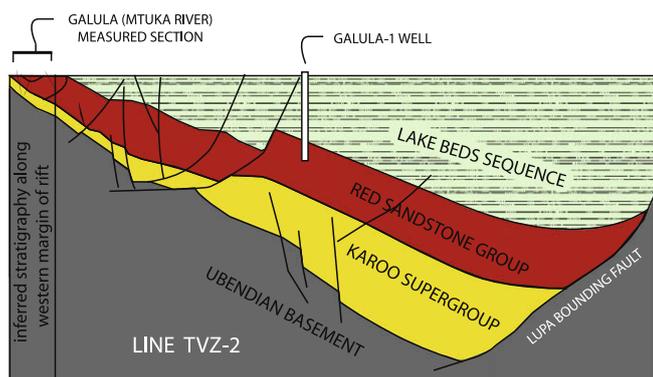
Fig. 2. Schematic seismic section through the Rukwa Rift Basin in the vicinity of the Galula-1 well, oriented perpendicular to the rift axis (SW to NE). The inferred structure and stratigraphy along the western margin of the basin is shown on the left (based on seismic line TVZ-2, shown in Fig. 1; Tanzanian Petroleum Development Corporation, Dar es Saalam).

Zimbabwe. Dixey and Smith (1929) reported isolated dinosaur material of similar age from western Mozambique. Cahen (1954, 1983a,b) and others (e.g., Cahen and Lepersonne, 1978; Pereira et al., 2003; Giresse, 2005; Jelsma, 2006; Hanson, 2007) have investigated isolated Lower Cretaceous exposures and drill cores from portions of the Congo Basin in DRC and Angola, documenting microfossils and basic sedimentological characteristics of these deposits. Such studies provide a rare glimpse into ancient ecosystems locally, but considerably more research is needed to obtain a fuller understanding of Mesozoic terrestrial ecosystems of sub-equatorial Africa.

Late Cretaceous–Paleogene continental systems in sub-equatorial Africa are rarer still and far less documented. Investigations of three deep cores drilled though the Kwango sequence in the Congo Basin, along with patchy outcrop exposures in the DRC and Angola, provide only a limited view of Late Cretaceous terrestrial systems of Central Africa (Cahen, 1954, 1983a,b). Jacobs et al. (2006) also recently noted the rare occurrence of Late Cretaceous continental vertebrates preserved in shallow marine deposits along the Angolan coastline.

Putative Upper Cretaceous beds (the Malonga Formation, 'Formaçao de Sena', 'Formaçao de Singuédeze/Elefantes' and Gona-re-Zhou Plateau Beds) in southeastern Zimbabwe and western Mozambique were studied by Botha and deWit (1996) and permit some basic paleoenvironmental and paleoclimatic insights. Unfortunately, these deposits are unfossiliferous and their age is too poorly constrained to provide much resolution. The best records for the Late Cretaceous and Paleogene come from isolated kimberlite crater lake deposits containing important floral and faunal remains, located in South Africa, Botswana, Namibia and Tanzania (e.g., McKay and Rayner, 1986; Smith, 1986; Rayner, 1987; Bamford, 1990; Rayner et al., 1991, 1997; Harrison et al., 2001; Gunnell et al., 2003). Aside from these examples, no other unequivocal continental Paleogene deposits are known from anywhere in sub-equatorial Africa prior to this report, with the exception of mostly unfossiliferous and poorly age-constrained silcretes across DRC and Angola (gres polymorphs; Cahen, 1954) and southern Africa (Kalahari Group; Haddon and McCarthy, 2005).

The study presented here aims to highlight recent exploratory efforts that expand the record of Cretaceous and Paleogene terrestrial ecosystems in sub-equatorial Africa. Towards this end, our team has conducted eight field seasons investigating the sedimentary geology and paleontology of the Rukwa Rift Basin in southwestern Tanzania, confirming the existence of Cretaceous continental deposits in the basin, as well as discovering a previously unrecognized Paleogene depositional sequence (Roberts

et al., 2004; O'Connor et al., 2006; Stevens et al., 2008). Both sequences are assigned to the Red Sandstone Group (RSG) and are notable for preservation of abundant and diverse vertebrate and invertebrate fossils (Krause et al., 2003; Gottfried et al., 2004; Stevens et al., 2005, 2006, 2008, 2009a,b; O'Connor et al., 2006; Feldmann et al., 2007). The purpose of this paper is to: (1) formalize the stratigraphic nomenclature of the RSG; (2) establish radiometric and biostratigraphic age constraints for the RSG; and (3) interpret the depositional environments and paleoclimate of the RSG.

2. Regional geology and background

The Rukwa Rift is a roughly 300 km long by 50 km wide northwest-southeast trending segment of the Western Branch of the East African Rift System, located in southwestern Tanzania between Lakes Tanganyika and Malawi (Nyasa) (Fig. 1; Chorowicz, 2005). The middle third of the basin is currently occupied by Lake Rukwa, a shallow (<15 m deep) lake. Structurally, the Rukwa Rift displays classic half-graben architecture, flanked by uplifted Paleoproterozoic metamorphic rocks of the Ubendian shear belt (Kilembe and Rosendahl, 1992). The exact timing, direction and structural regime associated with rifting have been the subject of considerable debate (Tiercelin et al., 1988; Ebinger et al., 1989; Kilembe and Rosendahl, 1992; Mbede, 1993; Milga, 1994; Wheeler and Karson, 1994; Morley et al., 1999). Delvaux et al. (1998) and others have clarified the debate by noting that numerous changes in stress regime and kinematics have occurred throughout the poly-phase rift history.

The basin is bounded by the Ufipa fault and plateau to the southwest, the Lupa fault to the northeast, the Ubende plateau to the north, and the Mbozi Block and Rungwe Volcanics to the southwest and south, respectively (Fig. 1; Ebinger et al., 1989; Kilembe and Rosendahl, 1992). An important feature of the Rukwa Rift Basin is its location along the trend of the late Ubendian shear belt. The Ubendian belt is located on the west side of the Archean Tanzanian Craton and is a well-documented zone of crustal structural weakness composed of different terrains organized in a NW–SE lateral shear pattern (Boven et al., 1999). Multiple phases of tectonic reactivation along the Paleoproterozoic Ubendian belt have been identified and associated with various tectonic events throughout the Precambrian and Phanerozoic (McConnell, 1950, 1972; Tiercelin et al., 1988; Ebinger et al., 1989; Lenoir et al., 1994; Theunissen et al., 1996; Delvaux et al., 1998).

2.1. Stratigraphy of the Rukwa Rift Basin

Seismic profiles of the basin have revealed up to 11 km of sedimentary fill, making this one of the thickest continental rift–fill sequences in all of Africa (Figs. 2 and 3) (Kilembe and Rosendahl, 1992). In addition to extensive multi-fold seismic reflection data (see Kilembe and Rosendahl, 1992; Milga, 1994; Morley et al., 1999) and gravity profiles (Peirce and Lipkov, 1988), two hydrocarbon exploration wells (Galula-1, Ivuna-1) were drilled by the Amoco Production Company (Wescott et al., 1991). Both wells were dry and neither penetrated the basin depocenter, and only one (the Ivuna-1 well) reached basement (Wescott et al., 1991). This work was conducted in the 1980s and 1990s, contemporaneous with widespread seismic and drilling programs throughout Southern and Central Africa aimed at assessing the hydrocarbon potential of numerous continental interior rift basins (e.g., Barber, 1987; Shull, 1988; Genik, 1992; Kilembe and Rosendahl, 1992; Bosworth and Morley, 1994; Banks et al., 1995; and others).

Three depositional megasequences are preserved within the Rukwa Rift, as demonstrated by seismic profiles, well data and surface geology (Fig. 2; Kilembe and Rosendahl, 1992). The lowest unit represents deposition of continental strata during the Pangaean
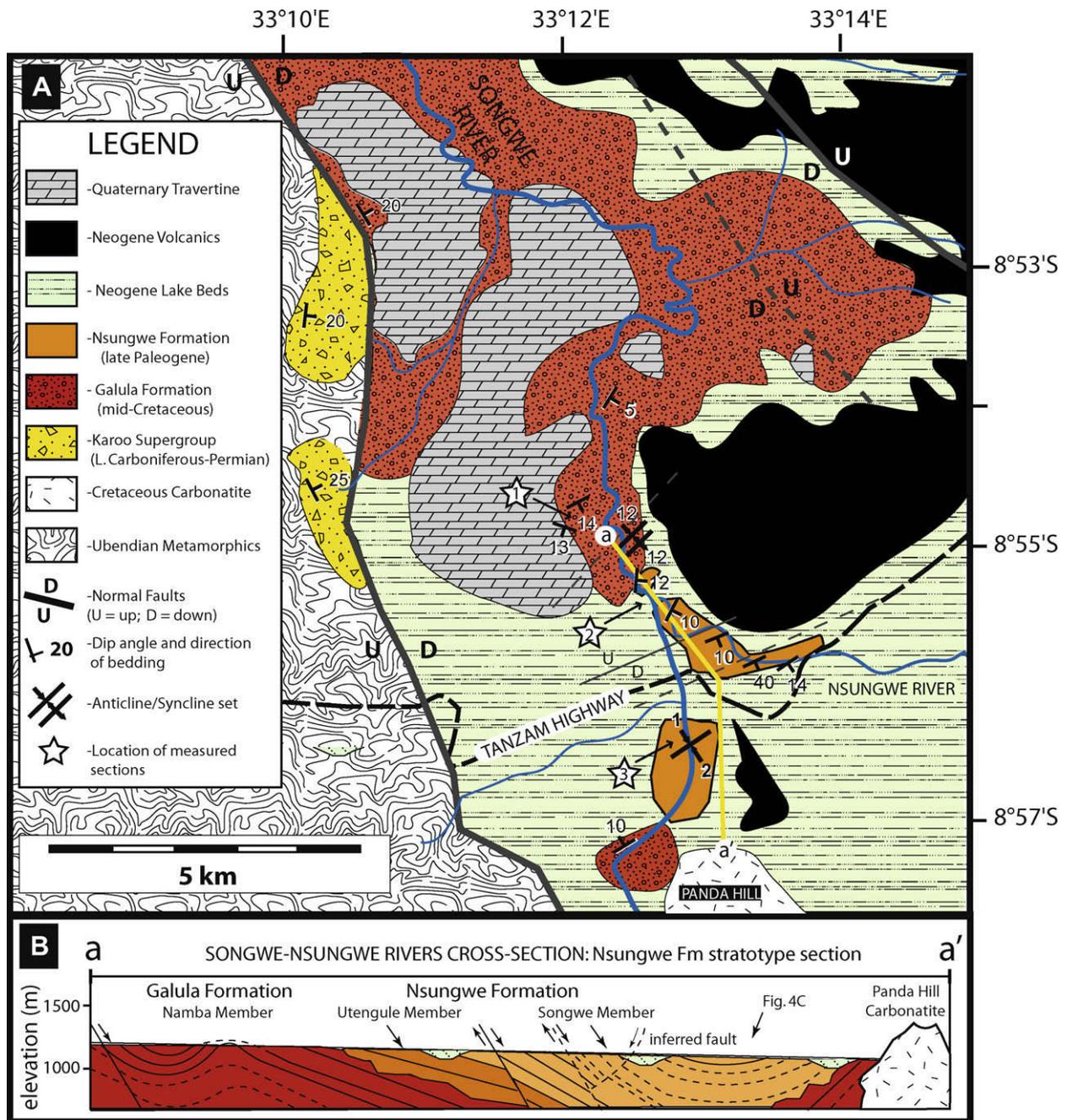
Fig. 3. (A) Detailed geological map of the Songwe Sub-basin, showing the location of newly described Galula and Nsungwe Formations of the Red Sandstone Group. Other lithologic units and key structural features are also mapped in the field area (modified from Grantham et al., 1958; Ebinger et al., 1989). Measured sections: 1 = Upper Galula Formation; 2 = Galula Formation/Nsungwe Formation contact; 3 = Upper Songwe Member (Fig. 22). (B) Cross-section through line a–a′, showing the stratigraphic and structural relationships between the Galula Formation and the Utengule and Songwe Members of the Nsungwe Formation.

megasequence and is part of the Karoo Supergroup (see Wopfner, 2002 and references therein). The upper megasequence is generally referred to as the Lake Beds (sensu Quenell et al., 1956) and records Neogene to Holocene rift-filling associated with development of the modern East African Rift System. The middle megasequence is represented by a thick package of continental sandstones and subordinate mudstones of controversial age, historically referred to as the Red Sandstone Group.

2.2. Karoo depositional megasequence

Karoo basins exist throughout much of central and eastern Africa, with particularly extensive surficial and subsurface sequences in the Luangwa rift in Zambia, the Mid-Zambezi rift in Zimbabwe and throughout much of the greater Congo Basin in the DRC (Semkiwa et al., 1998; Wopfner, 2002). Tanzania and Mozambique also preserve large northeast–southwest trending Karoo rifts, including the Metangula, Ruhuhu and Selous basins. Additional Tanzanian (and Malawian) deposits of Karoo-age sporadically crop out along a northwest–southeast corridor between Lake Rukwa and Lake Nyasa within the Rukwa Rift Basin (McConnell, 1950; Semkiwa et al., 1998). Compared to the Selous and Ruhuhu basins in Tanzania and most other Karoo successions across sub-equatorial Africa, Karoo strata in the Rukwa Rift are poorly exposed and studied.

Karoo exposures in the Rukwa Rift are isolated, extending from the Songwe-Kiwira area near the Malawi border in the south to a

patchwork of isolated outcrops in the vicinity of Songwe, Galula, Muze, Namwele, and Usevia, areas and across Lake Tanganyika in the Luama Basin in DRC (Fig. 1). The Karoo Supergroup in the Rukwa Rift is composed of a series of glacial, lacustrine, and fluvial deposits, assigned a latest Carboniferous to Late Permian age based primarily on palynology (Semkiwa et al., 1998). These units are dominated by thin diamictites, thick oxidized mudstones and sandstones, and extensive coal deposits (Dypvik et al., 1990).

2.3. Lake Beds depositional megasequence

The "Lake Beds" represent the youngest megasequence contained in the Rukwa Rift Basin, and are related to late Tertiary-Pleistocene rifting associated with the modern East African Rift System (Quenell et al., 1956; Wescott et al., 1991; Milga, 1994). Lake Beds strata are well-exposed throughout much of the basin, particularly in the Galula area. Unconsolidated alluvium, sand, silt and mud, along with intercalated volcanic ash, dominate the sedimentary succession. Whereas fluvial and alluvial deposits dominate around the periphery of the basin, the depocenter is dominated by lacustrine deposits (Milga, 1994). The wedge-shaped Lake Beds thicken dramatically from west to east, reaching a maximum thickness of 3–4 km along the Lupa bounding fault (Fig. 1) (Kilembe and Rosendahl, 1992). The majority of Lake Beds sediments are derived from uplifted metamorphic basement and volcanic detritus that is in turn derived from the late Neogene (8.6 Ma-Recent) Rungwe Volcanic province (Harkin and Harpum, 1957; Ebinger et al., 1989). The contact between the Lake Beds sequence and the underlying RSG is typically erosional (Milga, 1994). Grantham et al. (1958) subdivided the Lake Beds sequence into lower and upper units, however detailed studies of stratigraphic and facies relationships have not been conducted to date. The age of the Lake Beds is generally well-constrained based on radiometric dating of intercalated ash beds and microfloral analysis of core samples (Ebinger et al., 1989; Wescott et al., 1991).

2.4. Red Sandstone Group depositional megasequence

2.4.1. Exposures and field relations

The thickness of the RSG varies across the basin, with outcrop exposures on the western margin of the basin reaching up to 600 m. Eastward thickening of the basin was revealed by two hydrocarbon exploration wells (Galula-1 and Ivuna-1) that recorded thicknesses of up to 900 m for the RSG in the center of the basin (Wescott et al., 1991; Dypvik et al., 1990). Seismic profiles produced across much of the basin were analyzed and interpreted by Kilembe and Rosendahl (1992), Milga (1994) and Morley et al. (1999). Milga (1994) used seismic interval velocities to calculate depth profiles of the basin, indicating a maximum thickness of >3000 m. Eastward thickening of the sequence occurs towards the Lupa bounding fault along the full length of the basin (Kilembe and Rosendahl, 1992). Milga (1994) identified two primary depocenters in the southeastern portion of the basin, adjacent to the Lupa fault (see also Wheeler and Karson, 1994). This eastward thickening is consistent with persistent half-graben development, although changes in stress-field and kinematic regime have changed periodically throughout the 300 Ma history of the rift (Kilembe and Rosendahl, 1992; Delvaux et al., 1998). Seismic data were not obtained for the western margin of the basin; however, based on both seismic lines approaching the western margin and structural mapping, it is apparent that the western side of the rift is considerably more complex (Fig. 2; Spence, 1954; Grantham et al., 1958; Tiercelin et al., 1988; Ebinger et al., 1989; Dypvik et al., 1990; Kilembe and Rosendahl, 1992; Milga, 1994; Wheeler and Karson, 1994; Delvaux et al., 1998; Morley et al., 1999; Roberts et al., 2004).

Outcrop exposures of the RSG are restricted to the extreme western margin of the basin, where it variably overlies the Karoo Supergroup or high-grade metamorphic rocks of the Ubendian Belt (Dypvik et al., 1990; Morley et al., 1999). An angular unconformity separates the Karoo Supergroup from the RSG, with dip angles ranging from 4° to 30°. This can be observed in both outcrop and seismic profiles and suggests a lengthy period of erosion and uplift of the Karoo Supergroup prior to deposition of the RSG (Milga, 1994). Deposition of the RSG began roughly 130–150 million years later due to renewed tectonic activity and reactivation of Ubendian basement structures. This renewed phase of basin development is associated with continent-wide tectonism and reactivation of major fault systems, lineaments and zones of crustal weakness associated with Gondwanan break-up during the Early Cretaceous (Guiraud et al., 1992; Kilembe and Rosendahl, 1992). The most intense and regionally extensive period of basin development and tectonic reactivation appears to center around Aptian–Albian (120–100 Ma), which correlates with the separation of South America from Africa (e.g., see Guiraud et al., 1992).

The RSG crops out in isolated exposure belts throughout the western margin of the rift, from the Tanzania–Malawi border all the way to the northwestern end of the basin near Usevia (Fig. 1).
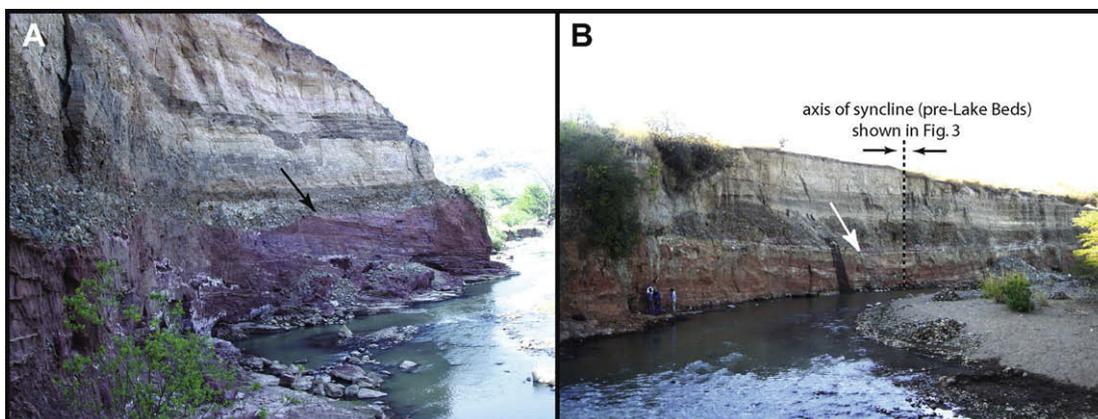
Fig. 4. Outcrop photos in the Songwe Sub-basin. (A) Angular unconformity (see arrows) between the Galula Formation below and the Plio–Pleistocene Lake Beds sequence above. Cliff is ~30 m tall by 35 m long; located along the Songwe River. (B) Unconformable contact between the Nsungwe Formation below and the Lake Beds sequence above. White arrow points to contact, whereas dashed line and black arrows shows the axis of a shallow syncline through the Nsungwe Formation (Fig. 3B). Cliff is ~12 m tall by 70 m long; located 1 km upstream of Tan-Zam Highway along the Songwe River.
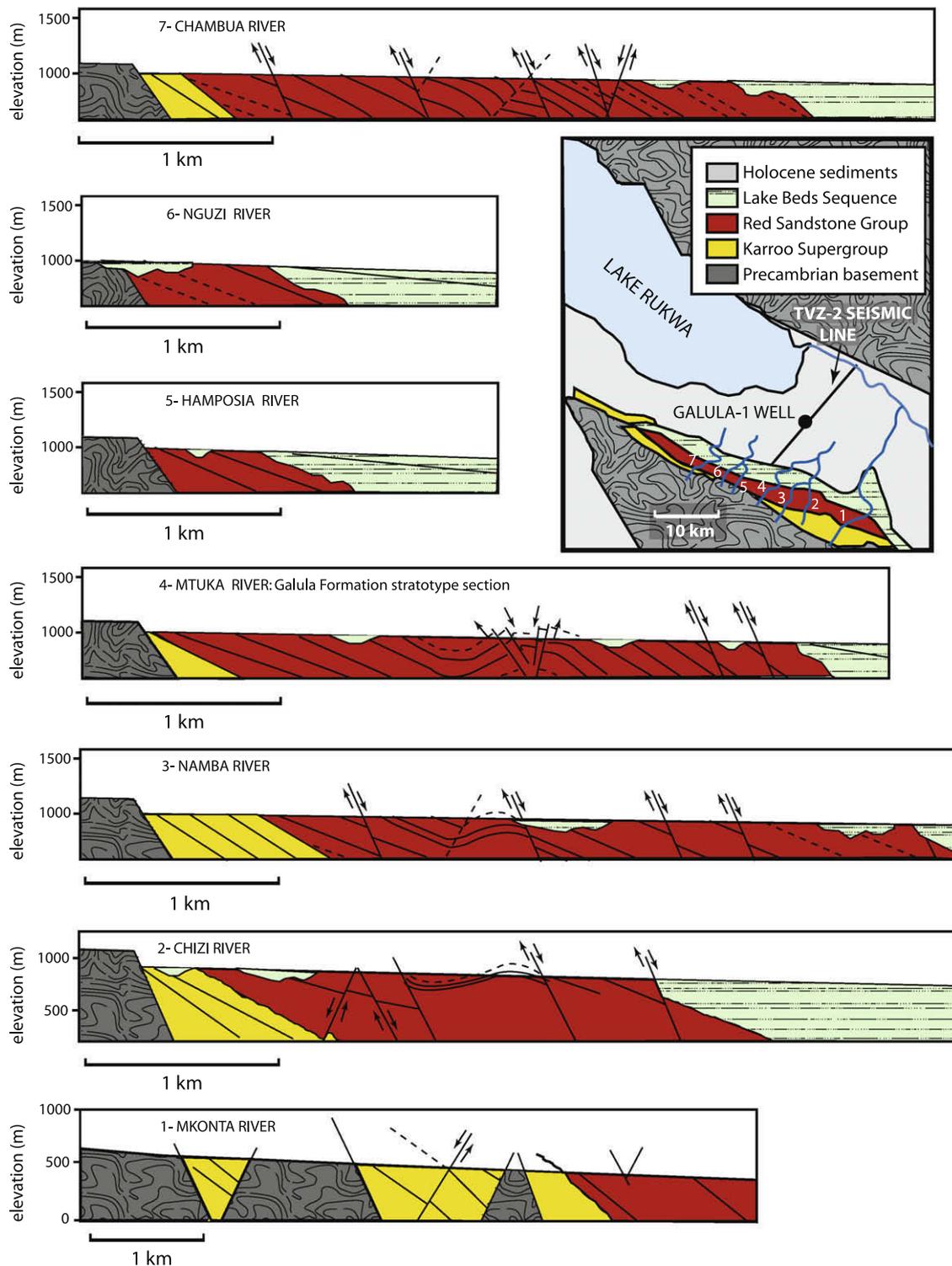
Fig. 5. Cross-sections through the main outcrop exposures of the Galula Formation of the Red Sandstone Group in the Galula area. Inset map shows location of river cross-sections. Cross-sections are based on mapping of mostly ephemeral stream channels flowing off the eastern margin of the Mbozi escarpment. The Mtuka river drainage is defined herein as the stratotype section for the Galula Formation (4). Note the Mkonta, Chizi and Chambua river cross-sections are modified after Morley et al. (1999); however, the geology of the Chambua river cross-section is more complex than previously suggested.

Potentially correlative continental strata also extend into northern Malawi, where they are called the Dinosaur Beds of Malawi (Dixey, 1928). Early work by Dixey (1928) and Haughton (1928), along with more recent work by Jacobs et al. (1990, 1993, 1996), Colin and Jacobs (1990), Gomani (1997, 1999) and Winkler et al. (2000) have

suggested a middle Cretaceous age. A number of workers have noted a strong lithological similarity between the Malawi Dinosaur Beds and the RSG. Putative Cretaceous red beds also crop out along a similar trend (following the Ubendian shear zone) in the Luama Basin on the northwestern side of Lake Tanganyika in the DRC (Tiercelin et al.,

1988; Mondeguer et al., 1989). If these strata are indeed correlative, as interpretations currently suggest, it implies coeval deposition of Cretaceous-age fluvial deposits within a 1000-km long northwest-trending corridor spanning East to Central Africa along the trend of the Paleoproterozoic Ubendian shear zone.

Exposures of the RSG have been identified in six primary locations on the western side of the Rukwa Rift Basin (Fig. 1). The southernmost exposure is located in the Songwe-Kiwara area, with scattered outcrops extending from the Malawi border along the Mwelesi Gorge northward to Ilima Hill, just east of the Kiwira coal mine. Dypvik et al. (1990) suggested that the total thickness of deposits in this area was ~400–500 m, having themselves measured a ~180 m-thick stratigraphic section near Ilima Hill. A short distance to the northwest in the Rungwe Volcanic province, the RSG crops out in an area variably referred to as Kipande or Kiwira (Dypvik et al., 1990). Exposures here are patchy due to dense vegetation and the overlying late Neogene Rungwe Volcanic deposits. Dypvik et al. (1990) also measured a section here, but they were unable to correlate it with sections to the south at Ilima Hill, or to the north along the Chizi (Shizi) River.

The most extensive exposures of the RSG occur to the west of the regional capital of Mbeya, throughout the Songwe Valley (Songwe Sub-basin; sensu Ebinger et al., 1989). We have mapped exposures in this area along both sides of the Songwe River and its tributaries, from the Panda Hill carbonatite complex in the south to just beyond the junction with Lingozi creek in the north (Fig. 3). Outcrops, ranging in size from a few square meters to 50 m tall cliffs that extend for several kilometers, are generally best exposed along river cuts, while badland-type exposures are found in areas where recent erosion has occurred (Fig. 4). Well-exposed quarry faces are observable in the Mbeya Cement plant, where the RSG is quarried for use as aggregate in concrete (Fig. 4). The most continuous RSG outcrops are located in the vicinity of the Galula coalfield, to the southwest of Lake Rukwa. In this region, a series of northeast flowing rivers draining the Mbozi Block have incised down through Lake Beds strata, exposing continuous NE dipping stratigraphic sections, many of which were mapped during this study. The best exposures here are found along the Mkonta (Khonto), Tembo, Chizi, Namba, Mtuka and Hamposia rivers (Fig. 5). Good RSG outcrops are also found near the Muassa Coalfield, along the Chambwa (Chambua) and Nguzi rivers (Fig. 5). Extensive river cuts, minor badlands and well-exposed sequences between 200 and 520 m have been identified and measured along each of rivers. Further north still, at the Namwele/Muze coalfields, Dypvik et al. (1990) suggested that red beds originally mapped as upper Karoo (McConnell, 1950) actually represent a thick sequence (~600 m) of RSG strata. This is consistent with reports by Spence (1954) and Smirnov et al. (1974), who correlated these deposits with the RSG in the Galula coalfields. The most northerly exposures in the basin crop out along the Msadya and Mongwe rivers in the Usevia area, near the village of Kiboni (Fig. 1). Here again, outcrops are restricted to river cuts with the total exposed thickness at approximately 250–300 m.

Extensive exposures of putative Cretaceous red beds overlie coal bearing Karoo strata on the western side of Lake Tanganyika, near the town of Kalemie in the DRC (Mondeguer et al., 1989). These deposits crop out along the same NW–SE trending Ubendian structures and presumably have a close stratigraphic relationship with the RSG in Tanzania (Fig. 1), however, little is known about the specific character or extent of these deposits.

2.4.2. Age

The age of the RSG has been the subject of intense controversy and debate, particularly since the drilling of hydrocarbon exploration wells in the basin in the late 1980s. Proposed age assignments have ranged from Middle Jurassic to late Miocene. Spence (1954)

and others (e.g., Spurr, 1954; Grantham et al., 1958) originally considered the RSG to be Cretaceous based upon lithological similarities with Cretaceous dinosaur-bearing beds in Malawi (Dixey, 1928; Jacobs et al., 1990). Quenell et al. (1956) and later Pentelkov (1979) suggested a Late Jurassic age based on long-range lithological correlations with well-dated red beds exposed along the southern coast of Tanzania and into eastern Mozambique. Several other workers have proposed ages between Middle Jurassic and Early Cretaceous based on unidentified reptile bone fragments near Galula (Pallister, 1963), purported fossil dinosaur eggs along the Songwe River (Swinton, 1950), "relics of mollusks and reptiles" near Usevia (Smirnov et al., 1974), and stratigraphic relationships with intrusive carbonatites near Mbeya (Fawley and James, 1955; Snelling, 1965; Cahen and Snelling, 1984; Pentelkov and Voronov-skii, 1977).

Investigation of cuttings from the two Amoco exploration wells (Ivuna-1 and Galula-1; Figs. 1 and 2) further stirred the debate concerning the age of the RSG. Wescott et al. (1991) reported a Miocene–Pliocene age for the RSG on the basis of several isolated populations of diatoms. However, Kilembe and Rosendahl (1992) also examined cuttings from the same wells and failed to document the presence of Neogene diatoms. Instead, they found rare specimens of the wind-blown pollen Classopollis classoides and Callialasporites dampieri from a limited 200 m interval near the base of the sequence, suggesting a Middle Jurassic–middle Cretaceous age for these deposits. Morley et al. (1999) favored a Neogene age for the group, suggesting that the pollen reported by Kilembe and Rosendahl (1992) may have been a contaminant from the Cretaceous bentonite used as drilling mud in the two wells. Damblon et al. (1998) supported the Neogene age assessment based on the discovery of a fragment of silicified fossil wood (just north of the Malawi border) diagnosed as Pahudioxylon, a taxon with an early Eocene to Pleistocene range. Milga (1994) studied seismic profiles across the basin and recognized a regionally extensive unconformity in the lower portion of the RSG. He suggested that this break in deposition could account for the presence of both Cretaceous and Neogene depositional units and further suggested that the RSG be subdivided into a lower and upper sequence.

Extensive paleontological and geological work conducted by our team (Gottfried et al., 2004; Roberts et al., 2004; Stevens et al., 2005, 2006, 2008, 2009a,b; O'Connor et al., 2006; Sokhela, 2006; Choh, 2007; Simons, 2008) coupled with new radiometric age data presented herein, helps to resolve the controversy concerning the age of the RSG. Our work agrees in principle with Milga (1994) in that there is a poly-phase tectonic history for the Rukwa Rift Basin; however a Neogene-aged unit of the RSG has yet to be confirmed.

2.4.3. Previous stratigraphy and nomenclature

The name "Red Sandstones" was originally used by Spence (1954) to describe the series of red sandstones and mudstones exposed near the Galula coalfields, although a formal type section with a detailed description was never presented. Numerous names have been applied to this sedimentary succession since Spence's (1954) work, including: the "Red Beds" (Pentelkov, 1979), the "Red Bed Sandstone Sequence" or the "Red Bed Sandstone Formation" (Kilembe and Rosendahl, 1992), and the "Red Sandstone Formation" (Wescott et al., 1991). Recently however, the term Red Sandstone Group, as defined by Dypvik et al. (1990), has found common usage for defining all exposures of red sandstones and mudstones that are stratigraphically interposed between the Karoo Supergroup and the Lake Beds strata in the Rukwa Rift Basin (Damblon et al., 1998; Morley et al., 1999; Roberts et al., 2004).

Roberts et al. (2004) proposed an informal, twofold subdivision for the RSG based on preliminary sedimentological and paleontological data indicating the presence of two temporally distinct

depositional sequences. The older was termed "Unit I" and assigned a Cretaceous-age, while the younger was called "Unit II" and interpreted as Paleogene in age. Preliminary vertebrate and invertebrate biostratigraphy, coupled with lithological analysis, were used to define the two informal units until more detailed investigations could be completed to confirm these age assignments and establish a firm basis for formal stratigraphic subdivisions (Fig. 6).

3. Methods

Remote sensing applications were utilized to identify and map previously unknown outcrop areas from satellite imagery (Stevens et al., 2008). Geological mapping was conducted at both new and previously known localities and twelve stratigraphic sections through the RSG were measured at various outcrop localities along the western margin of the 300 km long basin. Lithofacies, facies associations and architectural elements were diagnosed and interpreted following a modified version of Miall's (1990, 1992) classification system. Paleocurrent data were measured in the field using clearly exposed planar-cross-beds and down the axes of three-dimensionally exposed trough cross-beds, and on (rare) sole structures. Provenance analysis of fluvial channel sandstone samples was conducted on framework minerals (quartz, feldspar, lithics [QFL]), heavy minerals and detrital zircons. Medium-grained channel sandstones from all levels of the RSG were sampled and point counted (350 counts per sample) via the Gazzi–Dickinson method (Ingersoll et al., 1984). Framework grain (QFL) analysis was used by Sokhela (2006) to investigate sedimentary provenance and classify sandstones in the RSG. Pebble counts were also performed to supplement the sandstone provenance analysis. Investigation of paleosols was conducted for the RSG by Choh (2007), including

decimeter scale profile measurements and sampling. Samples were analyzed using XRD and XRF at the University of the Witwatersrand School of Geosciences Earth Lab to determine clay mineralogy and trace and major element geochemistry.

One tuff sample was collected and analyzed using XRF, XRD, and microprobe for mineralogy and trace and major element geochemistry. The sample was dated via U–Pb geochronology on pyrochlore. Pyrochlore phenocrysts for sample 72504-4 were separated at the University of the Witwatersrand Earth Lab using a Wilfley Table, a Frantz Isodynamic Magnetic Separator, and heavy liquids. Pyrochlore was verified using multiple methods, including, microprobe, XRD, and XRF analysis. U–Pb analyses were performed on the SHRIMP ion microprobe at the Australian National University, Canberra. The SHRIMP analytical procedure used in this study is similar to that described by Claoué-Long et al. (1995). Age calculations and plotting were done using Isoplot/Ex (Ludwig, 2000).

4. Subdivision and proposed nomenclature for the Red Sandstone Group

We propose that the RSG be formally subdivided into two new formations with two members each, and we present detailed descriptions and stratotype sections for each. Subdivision is strongly warranted based on temporal differences and diagnostic lithological, petrographic, and depositional variations between the two units. Moreover, formal subdivision of the RSG is necessary to clarify the confusing nomenclatural issues and long-standing age controversy associated with this sequence.

4.1. Galula Formation

The name Galula Formation is proposed for the Cretaceous-age, lower sequence of the RSG (Unit I of Roberts et al., 2004). Spence (1954) originally described the RSG deposits in the Galula coalfields. The name 'Galula' refers to the small village located a short distance to the east of the proposed type locality in the Galula Coalfields (Figs. 5 and 7). The Galula Formation is defined herein as the sequence of red, pink, purple and occasionally white colored sandstones, conglomerates, and mudstones located between the Permo-Carboniferous Karoo Supergroup, or Precambrian crystalline basement, and the base of the overlying Paleogene Nsungwe Formation (defined below).

The basal contact of the Galula Formation is variable due to post-depositional erosion and uneven distribution of the underlying Karoo Supergroup. In some areas along the western margin of the rift, the Galula Formation is observed to rest directly on top of gneissic Ubendian basement rocks, whereas in other areas, and in seismic profiles, the Galula Formation directly overlies the Karoo Supergroup with angular unconformity between 4° and 30° (Figs. 2, 3 and 5). The upper contact of the Galula Formation is an almost imperceptible, low-angle unconformity between 1° and 2°. In outcrop, this upper contact is defined as an erosion surface at the base of a distinctive bed of white colored, medium-coarse-grained, pebbly sandstone to pebble conglomerate that forms the base of the overlying Nsungwe Formation (defined below; Figs. 3, 4 and 8).

4.1.1. Type locality and stratotype section

The type section begins ~200 m due south of a big bend in the Mtuka River where the base of the Galula Formation rests on top of a 1 m thick remnant of the Karoo Supergroup (which itself overlies Ubendian metamorphic basement). The section is ~1000 m above sea level and begins at GPS coordinates (WGS 84; UTM zone 36) 8°40′55.6″S/32°53′33.5″E. The upper contact of the Galula Formation cannot be observed in the type area, however it is well-ex-
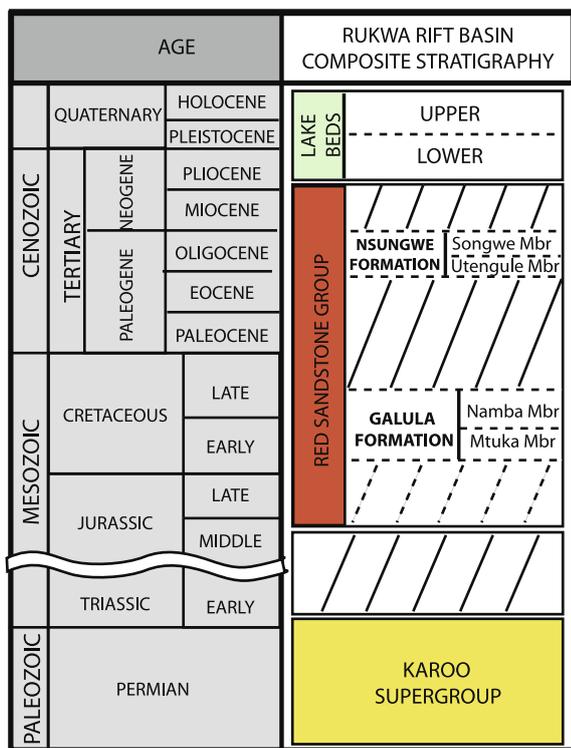

Fig. 6. Revised stratigraphy and nomenclature for the Red Sandstone Group and other stratigraphic sequences in the Rukwa Rift Basin (note: stripes indicate stratigraphic gap; modified from Roberts et al., 2004).
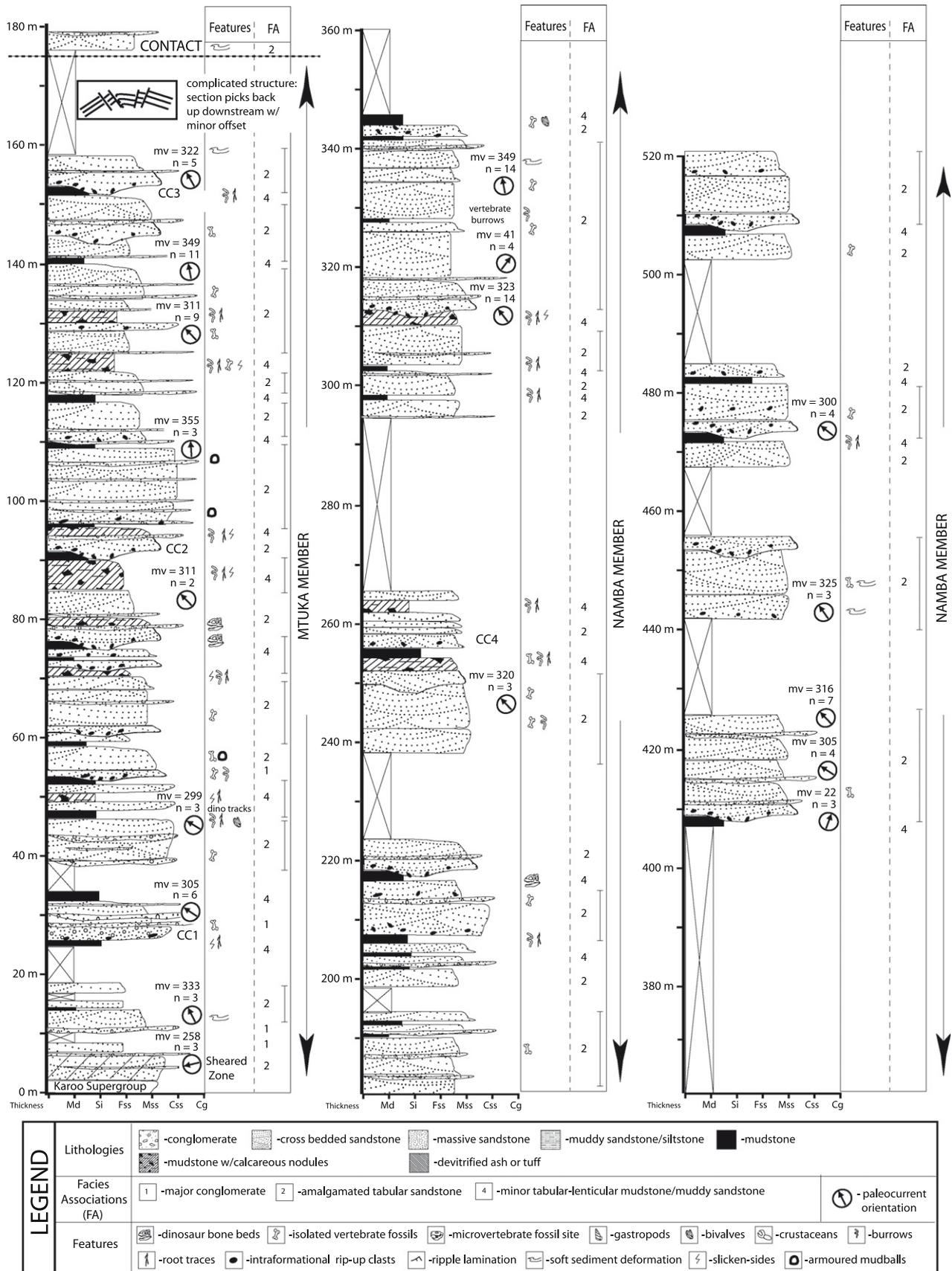
Fig. 7. Stratotype section for the Galula Formation along the Mtuka (Mtuha) River, in the Galula coalfield (Fig. 5 for exact location).
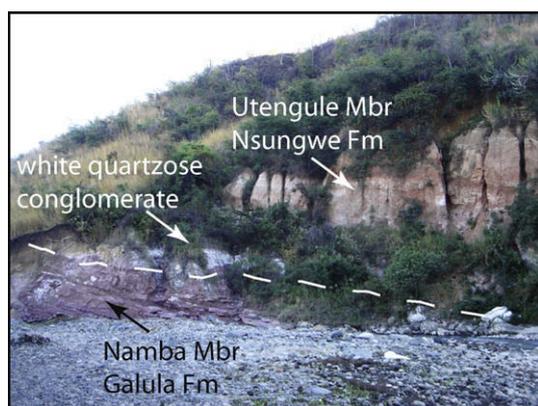
Fig. 8. Contact between the Galula and Nsungwe Formations along the Songwe River in the Nsungwe stratotype section. Note basal white conglomeratic sandstone of the Utengule Member incised into the Galula Formation and slight angular relationship. Cliff is ~18 m tall by 30 m long; located along the Songwe River 2–3 km south of the Tan-Zam Highway bridge.

posed at an auxiliary section located to the southeast along the Songwe River, ~1.5 km north of the main Mbeya–Tunduma road, on the east side of the river (Fig. 3 cross-section; WGS 84; 8°54′45.2″S/32°12′10.5″E). A complete outcrop section of the RSG has not been observed, however complete sequences for each unit are recorded in well and seismic logs (Wescott et al., 1991; also see Milga, 1994). Five reference sections for the Galula Formation have been identified (Figs. 1 and 5), including: (a) the Chizi (Shizi); (b) Namba river sections within the Galula Coalfield; (c) a section adjacent to the Songwe River in a large, artificial badland created by the Mbeya Cement Company (see Roberts et al., 2004, Fig. 5); (d) the Mwelesi Gorge section in the southern extent of the basin, near the Songwe-Kiwira Coalfields (based on Dypvik et al., 1990; Fig. 5); and (e) a final section at the far northern extent of the basin, near the village of Kiboni in the Usevia area along the Msadya River (Fig. 1). In addition, the two borehole logs drilled by Amoco and published by Wescott et al. (1991) are considered additional reference sections. These borehole logs and well cuttings from both boreholes are permanently stored in Dar es Salaam at the Tanzania Petroleum Development Corporation office (E. Kilembe, pers. comm.).

4.1.2. Mtuka and Namba Members

The Galula Formation exhibits variations in grain size, lithofacies and alluvial architecture between the lower and upper portions of the formation. Although the variation between the lower and upper sequences is subtle and a diagnostic contact cannot be unambiguously defined throughout the field area, enough variation exists to warrant the subdivision of the Galula Formation into formalized lower and upper members, defined herein as the Mtuka and Namba Members, respectively. Both members are well-exposed in the type section, along many of the river drainages in the Galula area, and in the Tukuyu and Usevia areas. Additionally, the Namba Member is exposed in the Songwe area. The observed variations in alluvial architecture, facies, and grain size differences demonstrate changes in depositional regime between the accumulation of the lower Mtuka Member and the Namba Member above (Figs. 6 and 7). The Mtuka Member comprises the basal 160–180 m of the formation, and is characterized by coarser sandstones, more abundant conglomerates, slightly higher proportions of extraformational clasts, more pronounced fluvial disconformities, thicker and more abundant overbank siltstone and mudstone lenses, and a higher proportion of paleosols. The Namba Member is between 340 and 360 m thick in outcrop, extending from the top contact

of the Mtuka Member (~180 m level) to the top of the formation and is more homogeneous throughout, dominated by very fine-to medium-grained sandstones with fewer overbank mudstone and siltstone lenses.

4.2. Nsungwe Formation

We propose the name Nsungwe Formation for the Paleogene sequence (Unit II of Roberts et al., 2004) of the RSG. This name is in reference to the Nsungwe River, a small tributary of the Songwe River, along which this unit is best exposed. The Nsungwe Formation is defined here as the sequence of red, maroon, orange, white and tan sandstones, siltstones, claystones, tuffs, and conglomerates that are exposed in the Songwe area between the Galula Formation and the Lake Beds sequence (Figs. 3, 6 and 8). The Nsungwe Formation varies considerably between its basal and upper portions, necessitating further subdivision of the formation into two members, the lower Utengule Member and upper Songwe Member.

4.2.1. Type locality and stratotype section

The type locality for the Nsungwe Formation is located in the Songwe sub-basin of the Rukwa Rift Basin ~20 km west of Mbeya Town along the Songwe and Nsungwe rivers in the vicinity of the Tan-zam Highway bridge over the Songwe River (Fig. 3). The type section is a composite section pieced together from several sections separated by intervening covered intervals (Fig. 9). The section begins along the Songwe River ~2 km north of the Tan-zam Highway bridge on the east side of the Songwe River, immediately above the contact with the Galula Formation. The beds strike in a NE–SW direction, however both dip direction and dip angle changes throughout the section due to a number of folds and small offset normal faults that affect the sequence (Fig. 3). From the contact with the Galula Formation, the section continues upstream parallel to dip until it goes into covered interval. The section reemerges several hundred meters southeast, near the confluence of the Songwe and Nsungwe rivers, and continues along the Nsungwe River for ~300 m down dip. The section pinches out here, and the top of the formation can then be observed 500 m to the south of the Tan-zam Highway along the Songwe River in the axis of a broad syncline. The top of the Nsungwe Formation is overlain with angular unconformity by poorly consolidated gravels, silts and ash of the Lake Beds sequence. In the southern limb of the syncline, beds are mostly covered except near Panda Hill where the top of the Galula Formation is exposed.

4.2.2. Utengule and Songwe Members

The Nsungwe Formation exhibits marked variations in facies, facies associations and alluvial architecture between the lower and upper portions of the formation. The observed variations in sedimentology (detailed below) provide clear evidence for changing depositional environments through the section and clearly indicate that the Nsungwe Formation should be subdivided into two formal members. We therefore propose the lower Utengule Member and the overlying Songwe Member (Fig. 6).

The Utengule Member is ~80–85 m thick, coarse-grained and composed of a completely different suite of facies than the overlying Songwe Member. The type section is the only place where relatively good exposures of either member of the Nsungwe Formation can be observed. Here, the base of the Utengule Member is easily recognized by a white sandstone/conglomerate unit with abundant well-rounded quartz pebbles, overlying purple and red sandstones of the Galula Formation (Fig. 8). The Utengule Member grades upwards from its base into a series of poorly sorted deep red to orange sandstones and matrix- to clast-supported conglomerates containing abundant metamorphic/vein quartz clasts and pedogenic calcium carbonate nodules. The upper 40 m the Uten-
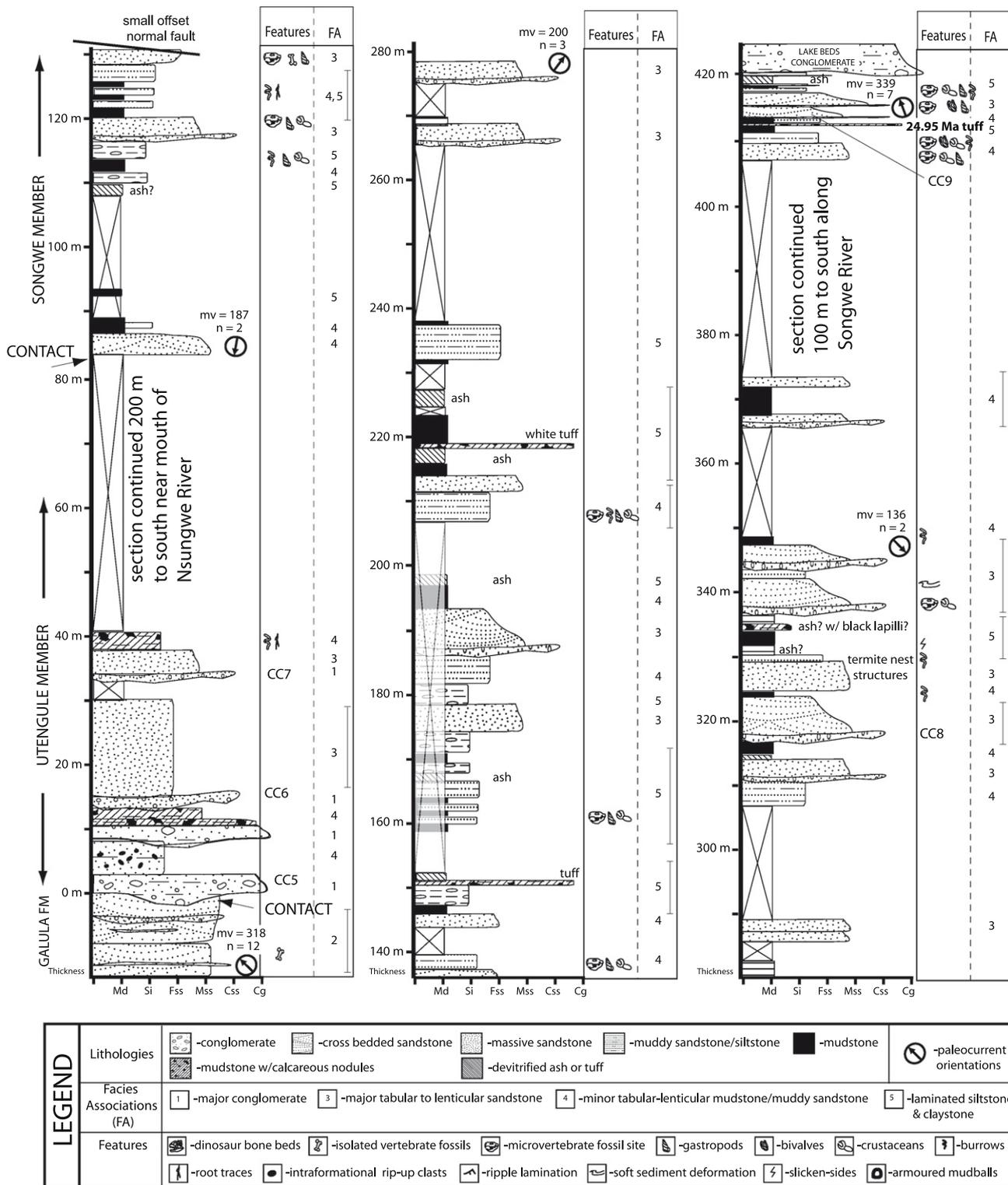
Fig. 9. Stratotype section of the Nsungwe Formation along the Songwe and Nsungwe rivers (Fig. 3 – Section 3 for exact location).

gule Member is almost entirely covered by heavy vegetation and its contact with the overlying Songwe Member is not visible anywhere.

The finer-grained Songwe Member is ~twice as thick as the underlying Utengule Member. The lower part of the Songwe Member is exposed along the Nsungwe River, whereas the top is exposed along the Songwe River (Fig. 4). The lower part of the Songwe Member transitions from a thin, green cross-bedded/ripple-laminated sandstone to a series of richly fossiliferous red, orange, and gray–green siltstones, mudstones, laminated claystones, lenticular sandstones, and devitrified bentonitic tuffs. The Songwe Member is overlain with angular unconformity by poorly consolidated gravel, silt and ash of the Lake Beds sequence. The type section of the Songwe Member is minimally 310–320 m

Table 1
Coarse-grained lithofacies in the Red Sandstone Group.

Code	Lithofacies	Texture	Structures and features	Color	Interpretation
Gmm	Matrix-supported conglomerate	Matrix: unsorted medium to coarse sand with varying proportions of silt and clay. *Clasts:* typically granule to pebble-sized; up to cobble-sized; poorly sorted; sub-angular-rounded; dominantly extraformational quartz and metamorphic basement clasts; intraformational pedogenic carbonate clasts common	Structures: typically massive, sometimes laminated, rare clast orientation; no grading to weak normal grading	Deep red (5R 2/6), orange–red (10R 6/6), reddish brown (10R 4/6)	Debris flows
Gcmi	Clast-supported intraformational conglomerate	Matrix: mostly absent; medium-coarse sand if *present*; *Clasts:* typically granule to pebble-sized, up to boulder-sized; poorly sorted; subangular-rounded; dominantly intraformational mudstone and siltstone; minor pedogenic carbonate nodules; rare extraformational clasts	Typically structureless, rare trough and tabular cross-beds; rare clast imbrication	Deep red (5R 2/6), pale red–purple (5RP 6/2), orange–red (10R 6/6) to reddish brown (10R 4/6)	Initial rapid deposition after channel downcutting, lobe switching event or scouring; or thalweg
Gcme	Clast-supported extraformational conglomerate	Matrix: mostly absent; medium-coarse sand if *present*; *Clasts:* typically granule to pebble-sized, up to cobble-sized; poorly sorted; subangular-rounded; dominantly extraformational quartz and metamorphic basement derived clasts; less common intraformational clasts	Trough and tabular cross-beds or structureless; clast imbrication; weak normal grading	Deep red (5R 2/6), pale red–purple (5RP 6/2), orange–red (10R 6/6) to reddish brown (10R 4/6); bleached zones locally common	Fluvial gravel bars or thalweg-fills
Se	Crudely stratified sandstone	Coarse- to very-coarse sand w/pebble-sized intraformational rip-up clasts and less common extraformational pebbles	Scours up to 1.5 m deep; crude stratification	Deep red (5R 2/6), pale red–purple (5RP 6/2), orange–red (10R 6/6) to reddish brown (10R 4/6)	Erosional scour-fills
Sp	Planar cross-bedded sandstone	Very fine- to medium-grained sand, sometimes coarse-grained, moderate-well-sorted	Planar tabular cross-beds; Coset thickness: ranges from 0.1 to 1.7 m	Deep red (5R 2/6) to pale red–purple (5RP 6/2)	Lower flow regime 2D dunes within channels
St	Trough cross-bedded sandstone	Very fine- to coarse-grained sand; moderate-well-sorted	Trough cross-beds; Coset thickness 0.1–2.3 m	Deep red (5R 2/6), pale red–purple (5RP 6/2), orange–red (10R 6/6) to reddish brown (10R 4/6)	Lower flow regime 3D dunes within channels
Sh	Horizontally stratified sandstone	Very fine- to medium-grained sand; well-sorted	Horizontally stratified; rare parting lineation	Deep red (5R 2/6) to pale red–purple (5RP 6/2)	May be upper (if med gr) or lower (if fine gr) flow regime
Sr	Ripple cross-laminated sandstone	Very fine- to fine-grained sand; well-sorted	Ripple cross-lamination; climbing ripples common	Deep red (5R 2/6), pale red–purple (5RP 6/2)	Lower flow regime migrating ripples
Sm	Massive sandstone	Very fine- to coarse-grained sand; moderate-well-sorted	Massive; possible crude stratification; bioturbation common	Deep red (5R 2/6), pale red–purple (5RP 6/2), orange–red (10R 6/6) to reddish brown (10R 4/6)	Rapid sedimentation with dewatering or intense bioturbation

thick, although covered interval and folding and faulting obscure the true thickness (Fig. 3). Seismic data and well logs indicate that this member may be much thicker towards the basin depocenter (see Milga, 1994).

5. Sedimentology and Geological History of the Galula Formation

5.1. Facies analysis of the Galula Formation

A suite of nine coarse-grained lithofacies (Table 1) and four fine-grained lithofacies (Table 2) were identified for the RSG. Lithofacies identification was utilized in conjunction with detailed analysis of internal and external geometry and bounding surfaces, architectural element analysis, and paleontology to subdivide both the Galula and Nsungwe Formations into distinct facies associations (FA). Three primary facies associations were identified for the Galula Formation; these include major conglomerate (FA1), amalgamated tabular sandstone (FA2), and minor tabular to lenticular mudstone/muddy sandstone (FA4) (Table 3).

5.1.1. Description: major conglomerate (FA1)

Major conglomerates in the Galula Formation are defined as thick, laterally persistent, matrix- to clast-supported conglomerate sequences. They may represent single thick units, or multiple thin-

ner, stacked beds dominated by conglomeratic lithofacies, including Gmm, Gcmi, Gcme (see Table 1). Minor components of finer-grained lithofacies, including Se, Sm and Fcf, may also be present. Isolated major conglomerates are typically several meters thick, and may form amalgamated bodies attaining composite thicknesses exceeding 10 m. Thin, interbedded lenses of lithofacies Se, Sm, Sp, and St are common. These different lithofacies are separated by third- and fourth-order bounding surfaces, whereas the bases of individual major conglomerate units are recognized by sharp to erosional fifth-order bounding surfaces (sensu Miall, 1990, 1992).

In most cases FA1 is dominated by pebble- to cobble-sized extraformational conglomerate beds (Gcme) composed of foliated and mafic metamorphic basement and metamorphic/vein quartz in clast-to-clast contact with medium-coarse-grained sandstone matrix. Units range from well-indurated to virtually unlithified. Pebble counts were conducted on conglomerates (Gmm, Gcmi, Gcme), primarily from FA1—but also from FA2, in the lower and upper Galula Formation in the Galula and Songwe areas. At each location where pebble counts were conducted, two well-spaced 50 cm² grids were mapped on vertical rock faces and all pebbles within that grid were observed and recorded. An array of lithologies were identified, and classified into seven categories, including: type 1—intraformational mudstone and sandstone; type 2—intraformational pedogenic calcrete; type 3—large weathered feldspars;

Table 2
Fine-grained lithofacies in the Red Sandstone Group.

Code	Lithofacies	Texture	Structures and features	Color	Interpretation
Fl	Finely laminated siltstone and claystone	Pure clay to silt	Very fine laminations; rare bioturbation	Deep red (5R 2/6), orange–red (10R 6/6), pale red purple (5RP 6/2)	Suspension load deposits
Fcf	Massive fines	Poorly sorted, sandy silt and clay	Massive; freshwater invertebrates and micro-vertebrates locally abundant	Deep red (5R 2/6), orange–red (10R 6/6), reddish brown (10R 4/6)	High-energy, flood stage fluvial and overbank deposits or fine-grained debris flows
Fr	Rooted fines	Clayey and silty fine sands, silt and clay	Primary structures destroyed or disturbed; mottled rootlets, rhizoconcretions, calcite nodules common; roots may be filled with overlying sediment	Deep red (5R 2/6), orange–red (10R 6/6), reddish brown (1 0R 4/6)	Paleosol
Fb	Bentonitic and tuffaceous claystone	Pure clay (dominated by vermiculite and montmorillinite) with pyrochlore, apatite, andradite and other phenocrysts and granule to pebble-sized calcite clasts	Finely laminated to massive; claystone breccia common due to swelling properites of clay	Orange–red (10R 6/6), weak red (5R 4/2), bluish white (10Y 8/1)	Pyroclastic flow or airfall ash deposit

Table 3
Facies associations identified in the Red Sandstone Group.

Formation	Code	Facies association	Facies and Architectural Elements	Diagnostic Features	Macrofossils	Interpretation
Galula Formation	FA1	Major conglomerate	Gmm, Gcme, Gcmi, Se, Sm, Fr *Arch. Elements: GB*	Massive to crudely stratified	Poorly fossiliferous	Proximal braided fluvial to transverse alluvial fans
	FA2	Amalgamated tabular sandstone	Gcmi, Gcme, Gmm, Se, Sp, St, Sh, Sr, Sm; Fl, Fm *Arch. Elements: CH, CF, DA, SB, GB, SO*	Stacked sandbodies, cut and fill structures, numerous third- to fifth-order surfaces	Isolated to articulated dinosaurs, crocodiles, turtles, mammals, fish, rare invertebrates	Low-accommodation, low-sinuosity, bed load fluvial channel complex
	FA4	Minor tabular to lenticular mudstone/sandy mudstone	Fl, Fr, Fcf, Sm, Sr, Sh, rare St	Root traces, burrows, disturbed bedding, pedogenic carbonate, pedogenic structures	Isolated, associated and articulated dinosaurs, crocodiles, fish, rare gastropods	Channel fills, overbank ponds and paleosols
Nsungwe Formation	FA1	Major conglomerate	Gmm, Gcme, Gmce, Se, St, Sm, Fr	Massive to crudely stratified, pedogenic carbonate nodules	Unfossiliferous	Proximal to distal alluvial fans
	FA3	Major Tabular to Lenticular Sandstone	Thin Gcmi and Gcme, Se, Sp, St, Sh, Sr, Sm *Arch. Elements: CH*	Upward fining, bioturbation increases upwards	Rare articulated frogs; isolated mammals, fish, crocodiles; freshwater crabs, gastropods, bivalves	Fluvial channels with cohesive banks
	FA4	Minor Tabular to Lenticular Mudstone/ Sandy Mudstone	Fl, Fr, Fb, Fcf, Sm, Sr, Sh, rare St	Root traces, burrows, termite nest traces, disturbed bedding, pedogenic carbonate	Abundant isolated micro-vertebrates – frogs, mammals, fish, crocodiles; freshwater crabs, bivalves, gastropods	Channel fills, overbank ponds, paleosols, and crevasse splays
	FA5	Laminated siltstone and claystone	Fl, Fcf, Fb, Sm, Sr	Root traces, burrows	Dominated by gastropods and freshwater crabs; rare fish and mammals	Floodbasin lakes and wetlands with abundant carbonatite ashfall and ashflow tuffs

Architectural elements: CH – channels; CF – channel fills; GB – gravel bars; SB – sandy bedforms; SO – scour hollows; DA – downstream accretion macroforms.

type 4—recycled Karoo (or Galula Formation pebbles in the Nsungwe Formation), type 5—metamorphic or vein quartz; type 6—mafic igneous and metamorphic; and type 7—foliated metamorphic (Fig. 10).

In the Galula Formation, intraformational type 1 and 2 clasts are typically abundant in major conglomerate units. Type 1 and 2 clasts are nearly ubiquitous in conglomeratic lithofacies within the amalgamated sandstone facies association, particularly along the base of many third-, fourth-, and fifth-order erosional surfaces and lining foresets of planar-and trough-cross-beds in many locations. The most common extraformational lithologies in FA1 and FA2 are metamorphic-derived type 6 and 7 clasts, with fewer type 3 and 5 clasts.

Major conglomerates are almost exclusively restricted to the basal 50 m of the Mtuka Member, although rare, thinner sequences

are observed in the Namba Member (Fig. 7). The greatest concentration of major conglomerates is in the Galula region along the Mtuka, Namba, and Shizi river sections, as well as basal portions of the Tukuyu and Usevia areas. Fossils in this FA are restricted to extremely fragmentary, heavily abraded dinosaur limb elements and bone pebbles.

5.1.2. Interpretation: major conglomerate (FA1)

Based on grain size, sorting, clast composition, matrix vs. clast support and close association with FA2 units, major conglomerate (FA1) is typically interpreted to represent fluvially-reworked alluvial fan deposits, within a large perennial braided fluvial channel system. In some instances, FA1 units are interpreted to represent unmodified debris flows based on the chaotic, matrix-supported nature of some of these deposits with large, angular blocks located
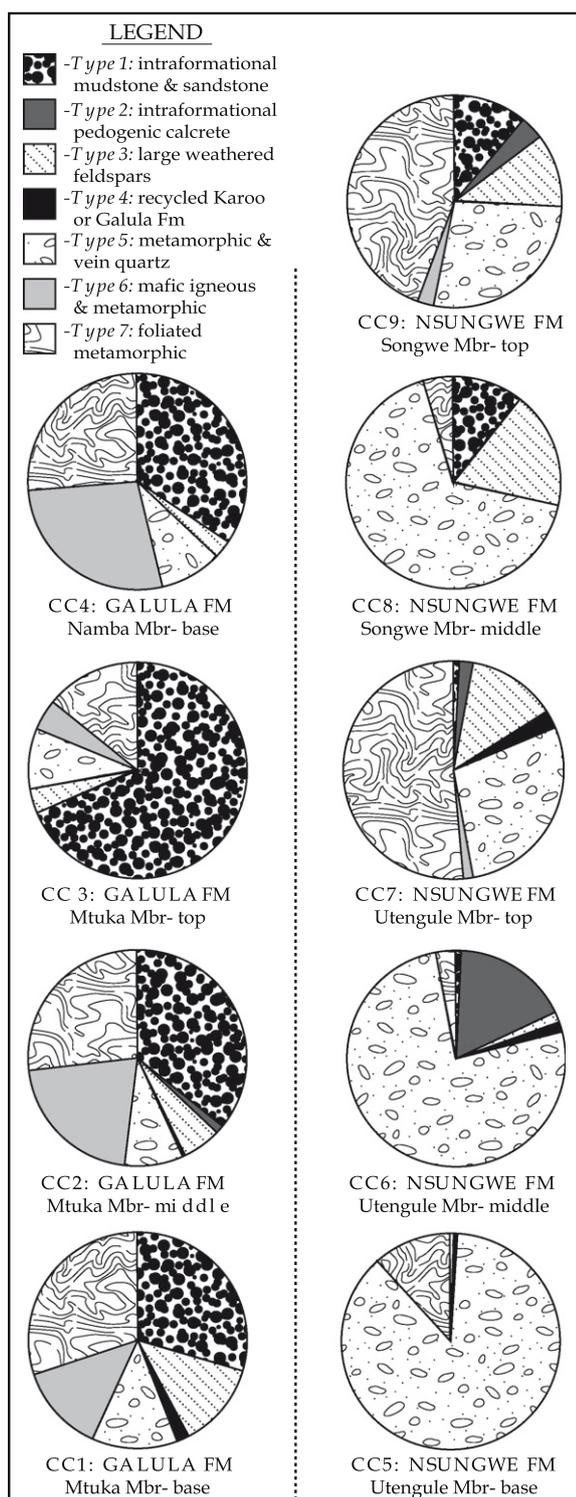
LEGEND

- *Type 1:* intraformational mudstone & sandstone
- *Type 2:* intraformational pedogenic calcrete
- *Type 3:* large weathered feldspars
- *Type 4:* recycled Karoo or Galula Fm
- *Type 5:* metamorphic & vein quartz
- *Type 6:* mafic igneous & metamorphic
- *Type 7:* foliated metamorphic

CC9: NSUNGWE FM Songwe Mbr- top

CC4: GALULA FM Namba Mbr- base

CC8: NSUNGWE FM Songwe Mbr- middle

CC3: GALULA FM Mtuka Mbr- top

CC7: NSUNGWE FM Utengule Mbr- top

CC2: GALULA FM Mtuka Mbr- middle

CC6: NSUNGWE FM Utengule Mbr- middle

CC1: GALULA FM Mtuka Mbr- base

CC5: NSUNGWE FM Utengule Mbr- base

Fig. 10. Pebble count results for nine sample localities throughout the Galula and Nsungwe Formations. All pebble- to cobble-sized grains within two separate randomly selected 50 cm^2 grids were counted at each locality.

directly adjacent to border faults along the western margin of the basin in the Galula area. Other FA1 sequences are clast-supported with better rounding and sorting, suggesting distal, fluvially-dominated alluvial fan or fully fluvial deposits. This association suggests that alluvial fans and steep-gradient tributary streams likely entered into a major braided river system that flowed northwest along the axis of the rift (see FA2 interpretation for details).

Such alluvial fans would have provided much of the gravel-sized sediment input in the channel system. There are insufficient paleocurrent data available for FA1 to completely validate this assertion; however, the source for most of the pebble-to cobble-sized clasts in the lower unit can be traced directly to mafic and foliated high-grade Ubendian metamorphic rocks exposed in the western rift flank. Metamorphic source terrains are within tens of meters to a few kilometers from the deposits observed in this study (Fig. 5; Spence, 1954). Alluvial fans would have produced most of the gravel-sized sediment during early stages of rift development, perhaps entering the main trunk channel system via steep ravines, or from high-gradient, transverse tributary streams (Ori and Roveri, 1987; Orton, 1988; Stanistreet and McCarthy, 1993). The gravel and other material entering the axial braidplain channel system would have been mostly reworked and redeposited into large-scale macroform elements such as gravel bars and bedforms (GB) and downstream accretion units (DA) (Miall, 1992). This assertion is supported by paleocurrent data indicating that GB and DA elements are typically oriented parallel to the dominant paleoflow direction within the Mtuka Member. The rapid upward fining and loss of the major conglomerate FA above the basal 50 m of the Galula Formation suggests an initial pulse of intense uplift and rapid denudation of the rift margins, followed by a longer period of steady subsidence and slower generation of accommodation space.

5.1.3. Description: amalgamated tabular sandstone (FA2)

The amalgamated tabular sandstone FA dominates the Galula Formation, representing 70–75% of the stratigraphic sequence (Figs. 7, 11 and 12). This FA is defined as single-to-amalgamated sheet-like sandstone beds exceeding 2 m in thickness, but more typically between 5 and 10 m thick and sometimes in excess of 15 m. Both single and amalgamated tabular sandstone bodies, exposed in many of the river drainages in the Galula area, are typically hundreds of meters in lateral extent, with width/thickness ratios exceeding 15:1. Based on the criteria established by Friend et al. (1979) and Friend (1983), these units qualify as amalgamated sheet sandstones. The base of each FA2 unit is well-defined by the presence of a sharp- to erosionally-incised fourth- or fifth-order surface, whereas individual stacked sheets within a single FA2 are defined by basal third and fourth-order surfaces (Figs. 11 and 12). Grain size generally decreases from medium-coarse-grained sand in the Mtuka Member to fine- to medium-grained sand in the Namba Member, although a high degree of variation is noted throughout the formation.

Samples collected from FA2 in the Galula Formation have also been studied by Dypvik and Nesteby (1992a,b) and Sokhela (2006), with all studies revealing a general upward increase in rounding and sorting, and an overall subarkose to arkose petrofacies, respectively (sensu Pettijohn et al., 1987). Several samples also fall out within the lithic arkose field. QFL percentages documented in this study, and by Sokhela (2006), are commonly $Q_{63}F_{30}L_7$ for the Mtuka Member of the Galula Formation and $Q_{50}F_{21}L_{29}$ for the Namba Member (Fig. 13). Dypvik and Nesteby (1992a, 1992b) also point counted 38 sandstone samples from undefined stratigraphic levels within Galula Formation in the Galula, Namwele, and Kipande areas. They identified similar modal QFL percentages although their results suggest slightly higher proportions of lithic fragments. Heavy mineral content is unusually high in many samples, ranging between 2% and 10%. Whereas porosity is typically high, ranging between 10% and 28%, matrix content varies between 4% and 12%, and cement content is between 3% and 25%. The cement is most commonly calcite, with hematite and chert cements also present. There is minimal evidence of chemical dissolution of grains in the Galula Formation, although Dypvik and Nesteby (1992a) noted minor chemical disso-
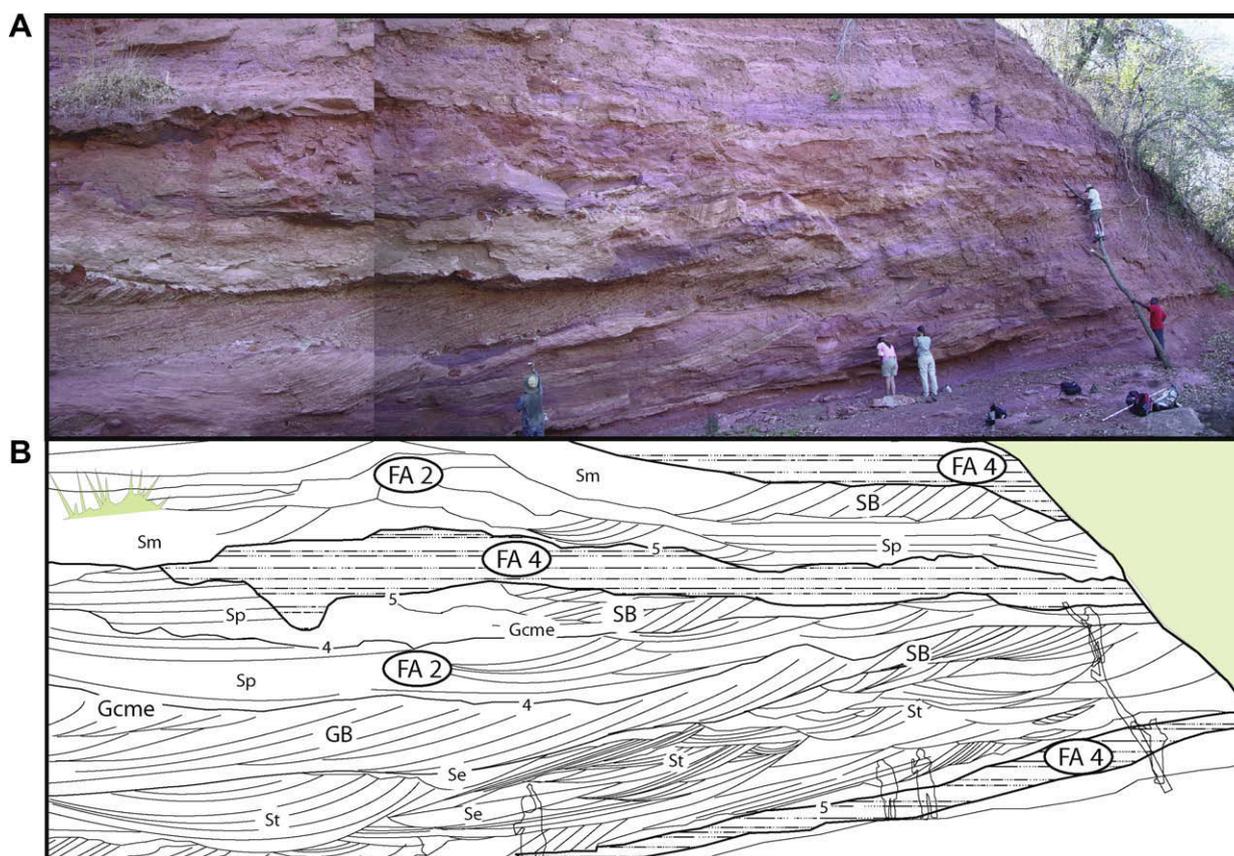
Fig. 11. Photomosaic (A) and interpretation (B) of a well-exposed W–E section through the Namba Member of the Galula Formation along the Mtuka River type section. Section shows a typical sequence of the Red Sandstone Group dominated by the amalgamated tabular sandstone (FA2), with thinner interbedded sequences of the minor tabular to lenticular mudstone/sandy mudstone (FA4). See Tables 1–3 for lithofacies and facies association codes and descriptions. Architectural elements: *SB* = sandbars, *GB* = gravel bars. 4 and 5 = fourth- and fifth-order bounding surfaces, respectively. Cliff is ∼9 m tall by 25 m long.

lution along with the presence of minor diagenetic hematite and K-feldspar cements.

FA2 units are composed of the following lithofacies, in descending order of abundance: St, Sp, Sh, Se, Gcmi, Gcme, Sm, and Sr (Table 1). Bed set thickness is generally quite constant throughout, with St and Sp sets typically range from ∼20 to 150 cm thick and a mean set thickness of 48 cm ($n = 109$) for the Mtuka Member and 51 cm ($n = 99$) for the Namba Member (Fig. 14). Intraformational claystone and siltstone intraclasts commonly line the base of third- to fifth-order surfaces, as well as along individual foresets of St, Sp (Fig. 12C and D). In many cases, claystone intraclasts are perfectly rounded and armored by an outer layer of gravel and sand embedded into the claystone ball (Fig. 12E). This feature is most common in the lower unit, although armored mudballs can be found throughout the sequence. Convoluted bedding is also quite common throughout the Galula Formation. Particularly intense soft-sediment deformation and exceptionally preserved fluid-escape structures, sometimes in 3D with evidence of surface expulsion of fluidized sand, are most evident in the middle part of the Namba Member (Fig. 15).

Paleocurrents were recorded throughout the spatial and stratigraphic extent of the Galula Formation, measured primarily on three-dimensionally exposed trough- and planar-cross-bedding in the Songwe, Usevia, Galula, Kipande, and Tukuyu areas (Figs. 7 and 16). Additional paleocurrent measurements were recorded in the putatively correlative Cretaceous Dinosaur beds of Malawi, south of Karonga in the Mwakasyunguti area (Figs. 1 and 16).

Larger scale macroform architectural elements, including channels (CH), channel fill (CF), sand bars (SB), gravel bars (GB), scour hollows (SO) and downstream accretion (DA) units are commonly observed in the Galula Formation. The internal architecture of many FA2 units consists of stacked tabular–lenticular CH elements and rare lenticular CF elements that extend for tens to hundreds of meters laterally and are up to 5 m thick. Paleocurrent directions on St within CH elements are dominantly oriented normal to observed or inferred channel-form cross-section. CH elements are infilled with uniformly-sized sediment and sedimentary structures throughout, while grain size and set thickness clearly decrease and fine upwards in CF elements.

Among the most common architectural elements are SB and GB. They are defined by large-scale cross-bedding (St, Sh, Sp, Sr, Se, Gcmi, Gcme) commonly exceeding 1 m in height, with third-order internal reactivation surfaces. Paleocurrent readings in these facies are generally oriented in the same direction as the regional paleocurrent direction. GB and SB are commonly interbedded in the basal parts of the Mtuka Member. GB is much less common in the Namba Member. Smaller scale erosional scours bounded by basal fourth-order surfaces and filled with coarse-grained sand and gravel-sized material are recognized as scour hollows (SO). Sandstone dominated macroform elements exceeding 1.5–2 m in thickness, composed of multiple cosets of St, Sp, Sh, and Sr that attain composite lengths of tens to hundreds of meters along the Mtuka, Namba, and Songwe Rivers, are defined as DA elements. These elements have wedge-shaped geometry, are bounded by basal fourth-order surfaces, have internal third-order surfaces, and where possible to measure, are typically oriented parallel to paleoflow (Fig. 11).
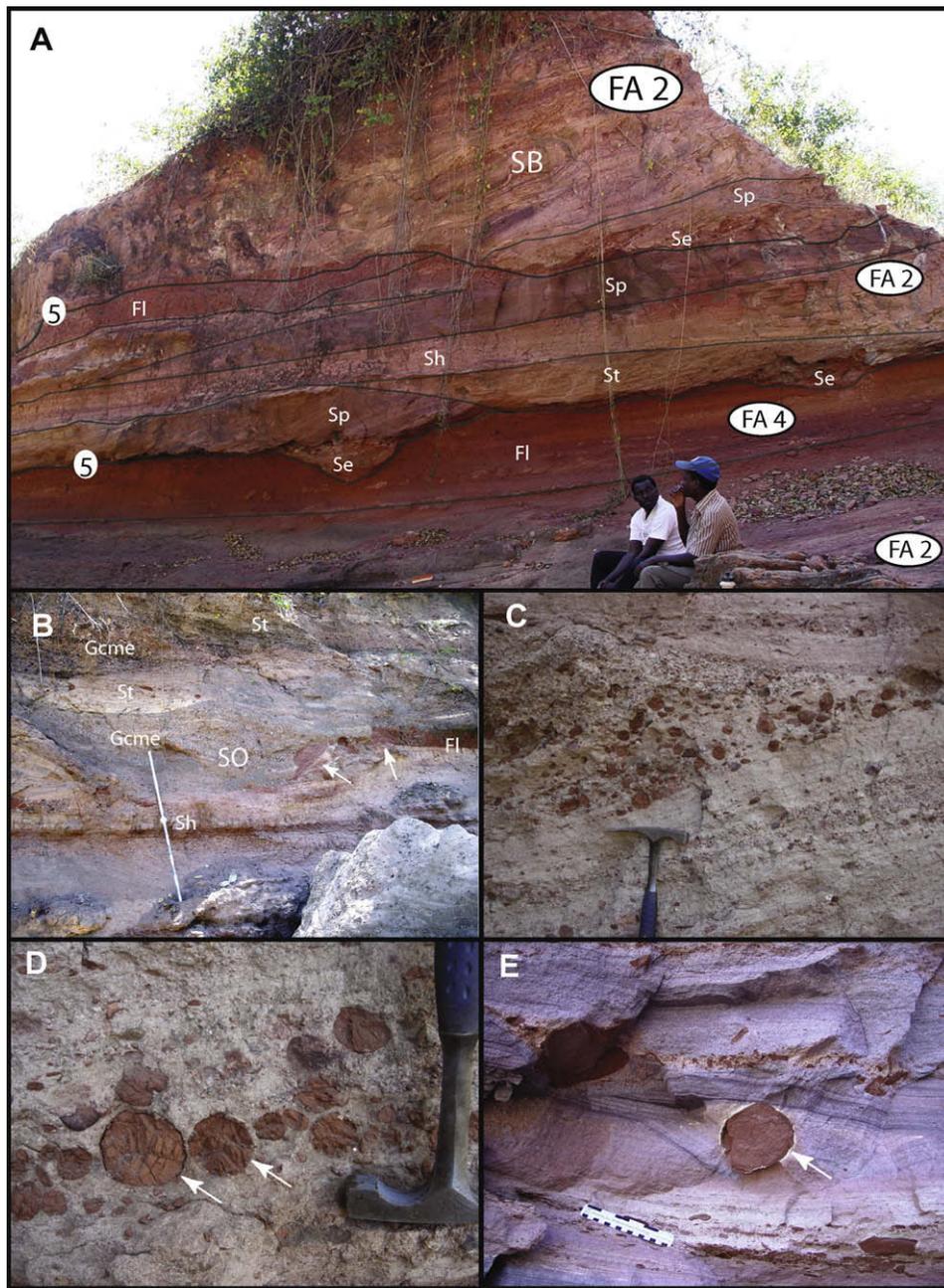
Fig. 12. Fluvial deposits of the Galula Formation. (A) Interpreted photograph of a typical amalgamated tabular sandstone channel (FA2) incised into a mudstone sequence (FA4). Cliff is ∼8 m tall by 14 m long; located in the type area along the Mtuka River. (B) Interpreted photograph of an amalgamated sandstone (FA2) in the Mtuka Member with evidence of a fluvial scour hollows (SO) and cannibalization of fine-grained facies (arrows). (C) Intraformational rounded mudstone and siltstone pebbles (including well-preserved armored mudballs) lining foresets of lithofacies St. (D) Large block of root-mottled pedogenic mudstone (see arrow) ripped-up out of underlying unit and incorporated into overlying tabular sandstone sequence. (E) Close up view of armored mudballs (arrows). Note the coarse sand-pebbles armoring the outside of the perfectly spherical mudballs.

Bioturbation is rare in FA2, but where present, is more abundant near the tops of individual sheets or the top of amalgamated sequences. Root traces and burrows with meniscate backfill (5–15 mm in diameter) are most common along upper surfaces of the FA, while at several locations, large burrow structures are preserved. These unusual traces are 10–20 cm diameter oblate tubes up to 3 m long and excavated horizontally within fine-medium grained St, Sm, and Sh lithofacies (Fig. 17A). Cross-cutting relationships indicate that the burrows were produced after deposition, but prior to lithification. They are infilled with massive fine-medium-grained sandstone. The burrow structures are preserved in positive relief due to preferential calcite cementation of the burrow structures relative to the surrounding sandstone. More commonly, this unusual trace is preserved in cross-section, where the three-dimensional burrow structure is not evident.

Vertebrate fossils are relatively abundant throughout FA2 exposures in the Galula Formation from all areas of the Rukwa Rift Basin, except Tukuyu and Kipande. Fossil material tends to be more intensely abraded, disarticulated and fragmentary in FA2 than in FA4, but better preserved than fossils from FA1. Dinosaur remains are most common, particularly isolated vertebral and limb material and eggshell (O'Connor et al., 2003, 2006; Gottfried et al., 2004). In rare instances, dinosaur bone beds composed of numerous associated, but mostly disarticulated elements are preserved
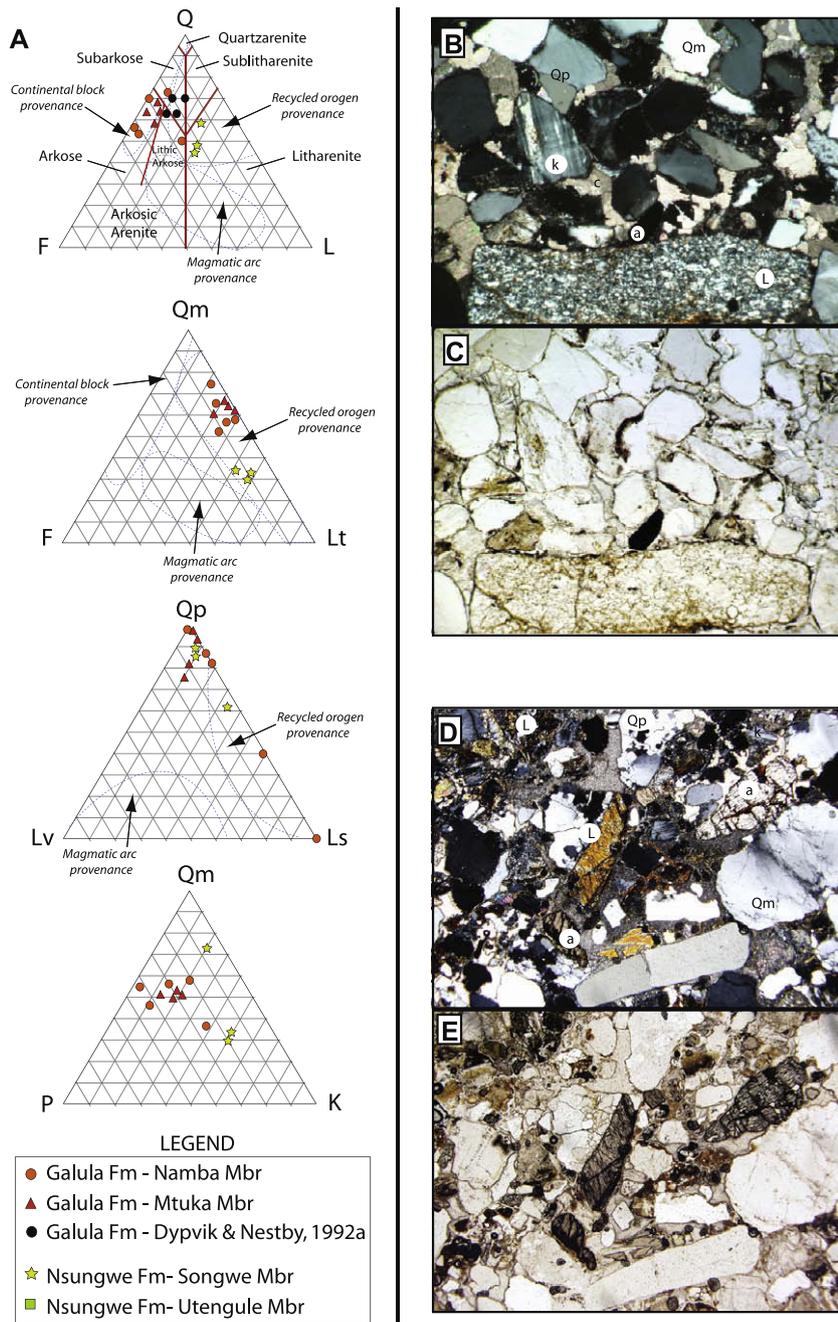
Fig. 13. (A) Point count data and sandstone classifications for the Galula and Nsungwe Formations (modified from Sokhela, 2006). All samples represent 350 points and follow the methodology of Gazzi–Dickinson (Ingersoll et al., 1984). Black circles represent sandstone provenance data for the Galula Formation (undifferentiated) reported by Dypvik and Nesteby (1992a). Sandstone classification after Pettijohn et al. (1987); (B and C) Photomicrographs (8×) of sandstone from the Galula Formation; (D and E) Photomicrographs (4×) of sandstone from the Songwe Member of the Nsungwe Formation; (B and D) Cross-polarized light; and (C and E) Plane polarized light.

(Fig. 17B). Isolated teeth and bones of fishes, crocodyliforms, and mammals, along with partial to nearly complete turtle shells, have also been discovered in FA2. In rare instances, well-preserved partial to fully-articulated vertebrate skeletons have been recovered (O'Connor et al., 2008). No plant macrofossils have yet been identified and palynomorphs and invertebrates (bivalves) are exceedingly rare in the Galula Formation (Smirnov et al., 1974; Kilembe and Rosendahl, 1992).

5.1.4. Interpretation: amalgamated tabular sandstone (FA2)

FA2 units in the Galula Formation are interpreted as fluvial channel deposits. This interpretation is based on a combination of sedimentary characteristics, including: sheet-like, amalgamated geometry of sandstone and conglomerate lithologies; basal fifth-order bounding surfaces; internal third- and fourth-order surfaces; and an array of architectural elements including channel, channel fill, sand and gravel bars, scour hollows and downstream accretion. The nature of the sandbodies and thin, discontinuous character of associated fine-grained floodplain facies (FA4), coupled with overall low dispersion of paleocurrents, suggest that deposition transpired within a relatively large low-sinuosity bedload stream system. The presence of a diverse fauna with some aquatic taxa suggests perennial flow conditions, whereas the abundance of reactivation surfaces and paucity of fine-grained, overbank facies
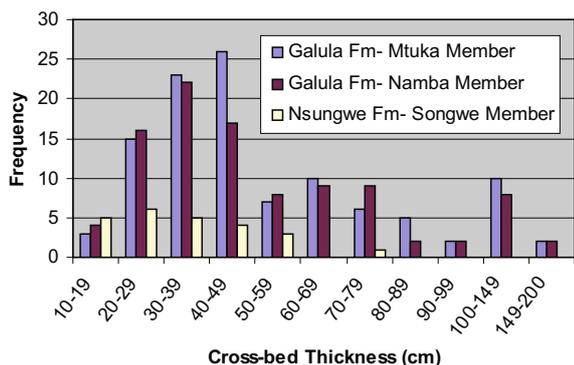
Fig. 14. Cross-bed thickness of the Galula Formation (Mtuka and Namba Members) and Nsungwe Formation (Songwe Member).

indicates slow generation of accommodation space (Shumm, 1981; Miall, 1990; Bridge, 2003). These characteristics are most consistent with braided-style alluvial channels (Miall, 1992).

Since the Galula Formation is only exposed along western margin of the half-graben basin (Fig 2), it is difficult to determine whether the large fluvial system representing FA2 was limited to the west flank of the rift or whether it spread across the entire basin, forming a massive braidplain. Well logs and cuttings from the Galula-1 and Ivuna-1 well were sampled and studied at the Tanzanian Petroleum Development Corporation headquarters in Dar es Salaam. Obvious changes in lithology, sandstone/mudstone ratios, or stacking patterns were not observed, thereby suggesting a relatively homogeneous depositional style towards the central portion of the basin. Grain size in the Galula Formation decreases from bottom to top, but facies composition remains relatively consistent throughout. Moreover, bedding style, cross-set thickness, and

architectural elements remain remarkably similar from bottom to top, indicating a relatively stable, broad braidplain channel system across the width of the narrow basin (Miall, 1992).

Variation observed in sandstone provenance between the Mtuka and Namba Members suggest that a progressive increase in recycling of lithic sedimentary source rocks into the basin. The most likely plausible mechanism to account for this is periodic syn-depositional reactivation of faults on the western boundary of the basin. This would lead to recycling of Karoo and older RSG deposits on the rift flanks. Alternatively, this shift may simply record the input from a new provenance source to the south.

Paleocurrents from the Galula Formation throughout the Rukwa Rift Basin (N = 210) reveal a dominant northwesterly flow direction (336°) with low dispersion, particularly within the Mtuka Member. A significant exception is from the southern Tukuyu region, where paleoflow is north–northeast, while only a few tens of kilometers to the north at Kipande, paleocurrents are oriented almost due north. The Tukuyu section is located at the approximate intersection between the Luangwa and Rukwa Rifts and the variation in flow direction may be associated with channels flowing northeast out of the Luangwa rift prior to intersecting the northwest trending trunk channel system (Fig. 16). The combination of facies, alluvial architecture, and paleocurrent data for FA2, coupled with detrital zircon geochronology (Roberts et al., 2007), support the interpretation that a large northwest flowing braidplain system developed in the Rukwa Rift with multiple point sources located in the highlands of Mozambique, Malawi and Zambia.

5.1.5. Description: minor tabular to lenticular mudstone/muddy sandstone (FA4)

Minor tabular to lenticular mudstones and sandstones are highly variable in their overall character and lithofacies composi-
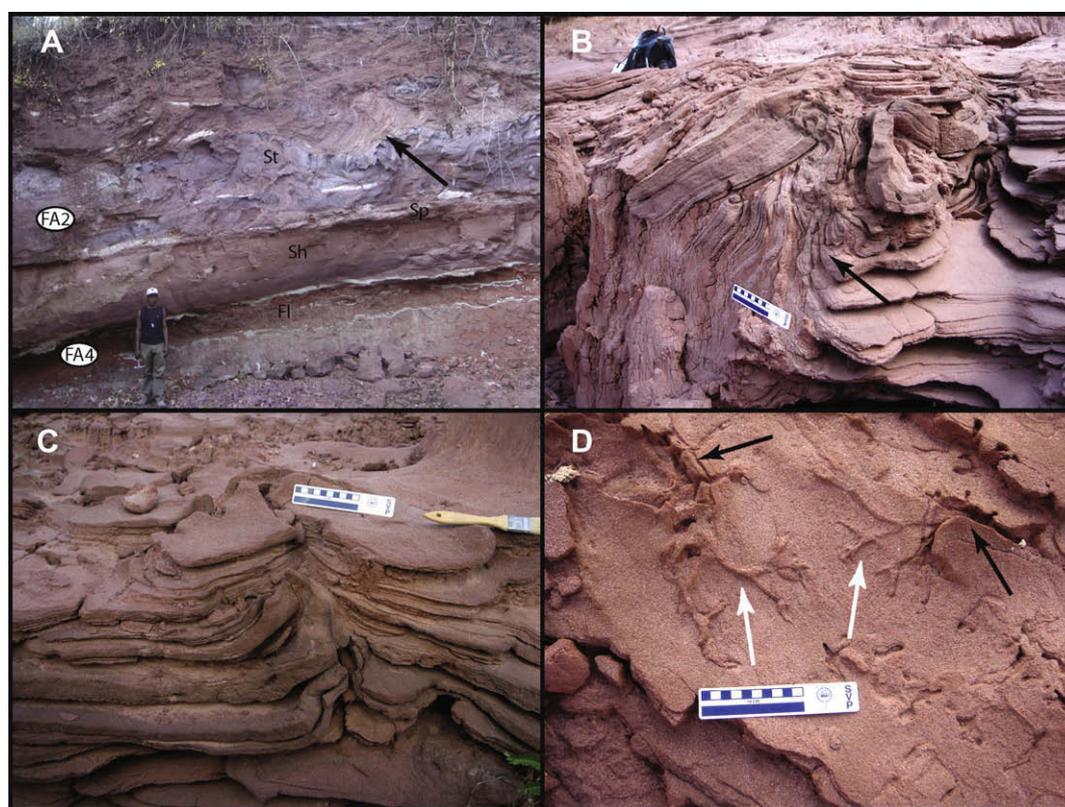
Fig. 15. Soft-sediment deformation in the Namba Member of the Galula Formation. (A) Meter-thick sequences of deformed trough cross-beds (St.) (black arrow) in FA 2 along the Namba River. (B) Fluidized sandstone and clastic dikes (black arrow) in the upper part of the Namba Member of the Galula Formation. (C) Fluid-escape structures in the same vicinity as B. (D) Surface ruptures (black arrows) and sand splays (white arrows) associated with fluid-escape structures in the same areas as B.
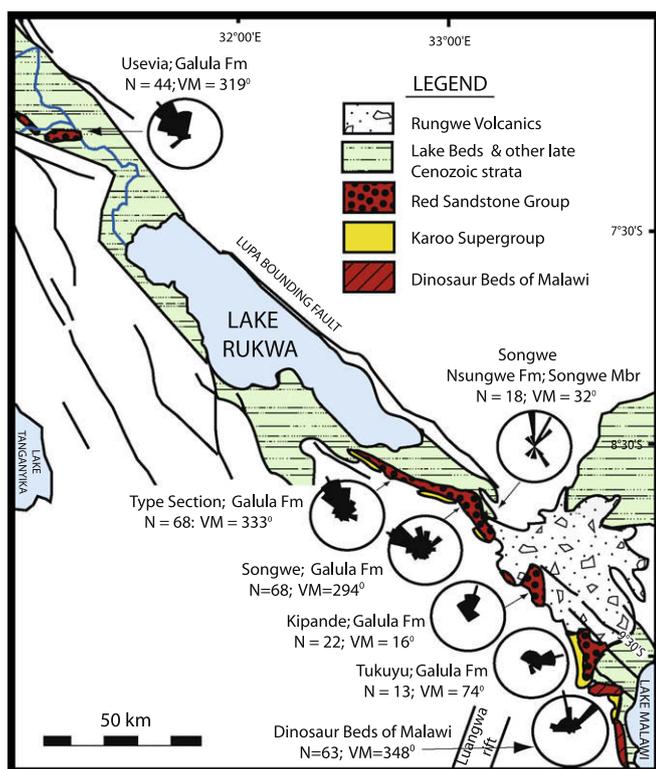
Fig. 16. Paleocurrent orientations from across the RSG. Note: paleocurrent data collected from 3D-exposed cross-bedding (St, Sp).

Fig. 17. Part of a mostly disarticulated sauropod dinosaur skeleton excavated in the Namba Member of the Galula Formation on the Namba River section. Large ribs and limb bones shown in photo.

tion. They are typically thin (10–70 cm), but may be up to ~2 m thick. They include both laterally extensive, tabular units and spatially restricted lenticular beds (Figs. 11, 12 and 17). Fine-grained lithofacies include Fl, Fr, and Fcf, while less abundant coarse-grained lithofacies include Sm, Sr, and Sh.

FA4 in the Galula Formation is subdivided into two distinct end members. The first end member is characterized by thin (10–50 cm thick), undisturbed, lenticular beds of well-laminated Fl and Sr with sharp lower contacts and sharp to erosional upper contacts (Fig. 18A). The other end member exhibits gradational basal contacts and variable upper contacts and is dominated by Sm, Fr, and Fcf with common evidence for bioturbation, mottling, slicken-

sides, ped structures, clay cutans, disturbed bedding and calcium carbonate nodules (Fig. 18). This FA preserves the majority of the associated-to-articulated-vertebrate fossil localities in the Galula Formation.

FA4 mudrock samples from the Galula Formation were sampled and studied in detail for clay mineralogy and geochemistry. Clay minerals were prepared using randomly oriented glycolated and unglycolated slides and analyzed with XRD. Although the full results of this study are presented elsewhere (Choh, 2007), the findings provide significant insight into the regional paleoclimate (discussed below). Significantly, a series of trends in clay mineralogy and bulk geochemistry were identified between the Mtuka and Namba Members of the Galula Formation, as well as between the Galula and Nsungwe Formations.

The Mtuka Member of the Galula Formation, based on samples from the Usevia and Galula areas, is dominated by illite and mixed-layer illite/smectite clay mineral assemblages, along with minor components of halyosite, saponite, kaolinite and montmorillinite (Table 4). In contrast, mudrock samples from the Namba Member in the Galula and Songwe areas reveal a slightly gradational, but distinct shift to kaolinite-dominated mudrocks, with lesser amounts of mixed-layer illite/smectite, montmorillinite and saponite (Table 4). Dypvik and Nesteby (1992b) also used XRD to analyze mudrock samples from the Namba Member of the Galula Formation at Kipande and nearby Itweri. Their results also indicate kaolinite-dominated clay mineral assemblages for the upper Namba Member at both areas, consistent with our findings.

5.1.6. Interpretation: minor tabular to lenticular mudstone/muddy sandstone (FA4)

FA4 in the Galula Formation, which is subdivided into two end members, represents both overbank and channel fill deposits within a large braidplain system. One end member—the lenticular to tabular beds of Fl, Sh, and Sr, where original bedding is preserved—is interpreted to represent typical overbank flooding or abandoned channel fill sequences in which little time elapsed between deposition and burial by subsequent depositional events. In many cases, these deposits developed in quiet-water subaqueous conditions, such as abandoned channel segments or small overbank ponds. The other end member of FA4 represents a similar depositional environment; however, these deposits were not buried rapidly, and were subjected to moderate to intense pedogenesis under subaerial conditions. Simple and cumulate paleosol profiles can be recognized in many units, dominated by Bt (subsurface clay accumulation), Bk (subsurface carbonate horizon), and C (unaltered mineral horizon) soil horizons, but subsequent incision and scouring by overlying fluvial channels (FA2) are probably responsible for erosion of much of the upper portion of the paleosols. The presence of root mottling, clay cutans, ped structures, slicken-sides, and calcium carbonate accumulations all indicate moderate to intense pedogenesis. Choh (2007) utilized XRF analysis of RSG paleosols, and noted that Bt horizons have well-developed illuvial deposits of clay, are poor in leached bases (CaO, Na_2O, K_2O, and MgO) and rich in sesquioxides (Al_2O_3 and Fe_2O_3). The soil horizons and the pedogenic features observed, coupled with deep red (5R 2/6) to orange–red (10R 6/6) colors, are suggestive of Alfisols.

5.2. Depositional environments and paleoclimate of the Galula Formation

The sedimentological investigation presented above provides important baseline data on the depositional environments and paleoclimate of the mid-Cretaceous Galula Formation. Multiple lines of evidence point towards a relatively long-lived fluvial system with thin and discontinuous floodplain deposits that show
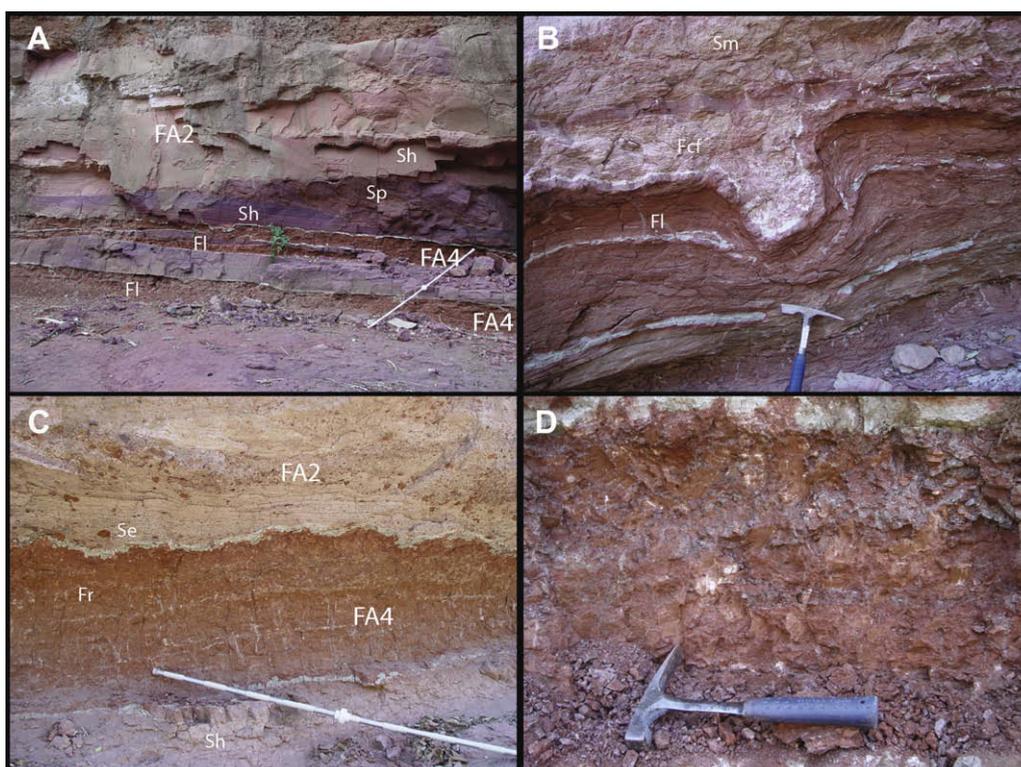
Fig. 18. Examples of the minor tabular to lenticular mudstone/sandy mudstone facies association (FA4) from the Galula Formation in the type section. (A) Thin, lenticular and tabular examples of FA4, showing evidence of scour and cannibalization by overlying fluvial channels of FA2. (B) Deformed laminated mudstones of FA4 by what is interpreted as one in a series of probable sauropod dinosaur tracks. The track is filled in by massive sandy mudstone (Fcf) and underlain by laminated mudstones (Fl) and overlain by massive sandstones (Sm). (C) Pedogenically modified FA4 unit, showing intense root mottling and calcium carbonate accumulations. Top of paleosol in C is erosionally scoured away by overlying channel body (FA2). (D) Close up view of paleosol showing blocky ped structures, gray root mottling, small white calcium carbonate accumulations, and minor slickensides.

Table 4
Mineralogical composition of the clay fraction (<4 μm) of FA4 and FA 5 in the Red Sandstone Group.

Formation/Member	Location	FA and Lithofacies	Sample number	Clay minerals								Interpretations
				Non-smectites					Smectites			
				K	H	V	I	I/S	M	Sa	N	
Nsungwe Formation Songwe Member	Type section	FA5; Fb	72506–4	–	–	+	–	+	++	+++	–	Devitrified volcanic ash
Nsungwe Formation Songwe Member	Type section	FA5; Fb	71206–5	–	–	+	–	+	+++	+	+	Devitrified volcanic ash
Nsungwe Formation Songwe Member	Type section	FA5; Fb	72606–7	–	–	+	–	+	+++	–	–	Devitrified volcanic ash
Nsungwe Formation Songwe Member	Type section	FA4; Fr	71206–3	++	–	–	–	+++	++	–	–	Paleosol; tropical, semi-arid
Nsungwe Formation Songwe Member	Type section	FA4; Fr	72005–9	–	–	–	+	+++	++	+	–	Paleosol; tropical, semi-arid
Galula Formation upper Member	Songwe section	FA4; Fr	71706–12	+++	–	–	–	–	+	–	–	Paleosol; tropical, humid
Galula Formation Namba Member	Songwe section	FA4; Fr	71706–4	+++	–	–	–	–	–	++	–	Paleosol; tropical, humid
Galula Formation Namba Member	Type section	FA4; Fr	71605–4	++	–	–	–	+++	–	++	–	Paleosol; tropical semi-arid to sub-humid
Galula Formation Mtuka Member	Type section	FA4; Fr	71005–3	++	–	–	+	+++	–	+	–	Paleosol; tropical semi-arid to sub-humid
Galula Formation Mtuka Member	Type section	FA4; Fr	71005–1	+	–	–	+	+++	+	–	–	Paleosol; semi-arid
Galula Formation Mtuka Member	Usevia section	FA4; Fr	73004–6	–	+	–	++	+	–	+++	–	Paleosol; semi-arid

K – kaolinite; H – halloysite; V – vermiculite; I – illite; I/S – mixed-layer illite/smectite; M – montmorillinite; Sa – saponite; N – ontronite. Relative abundance: –absent, + minor phase, ++ frequent phase, +++ major phase.

signs of pedogenesis, particularly within the Mtuka Member. The alluvial architecture and geometry suggests slow generation of accommodation space throughout most of the depositional history of the formation (Fig. 19). Seismic and well data from the central portions of the basin, coupled with facies, architecture, paleocurrent, and provenance data from outcrops across the western mar-
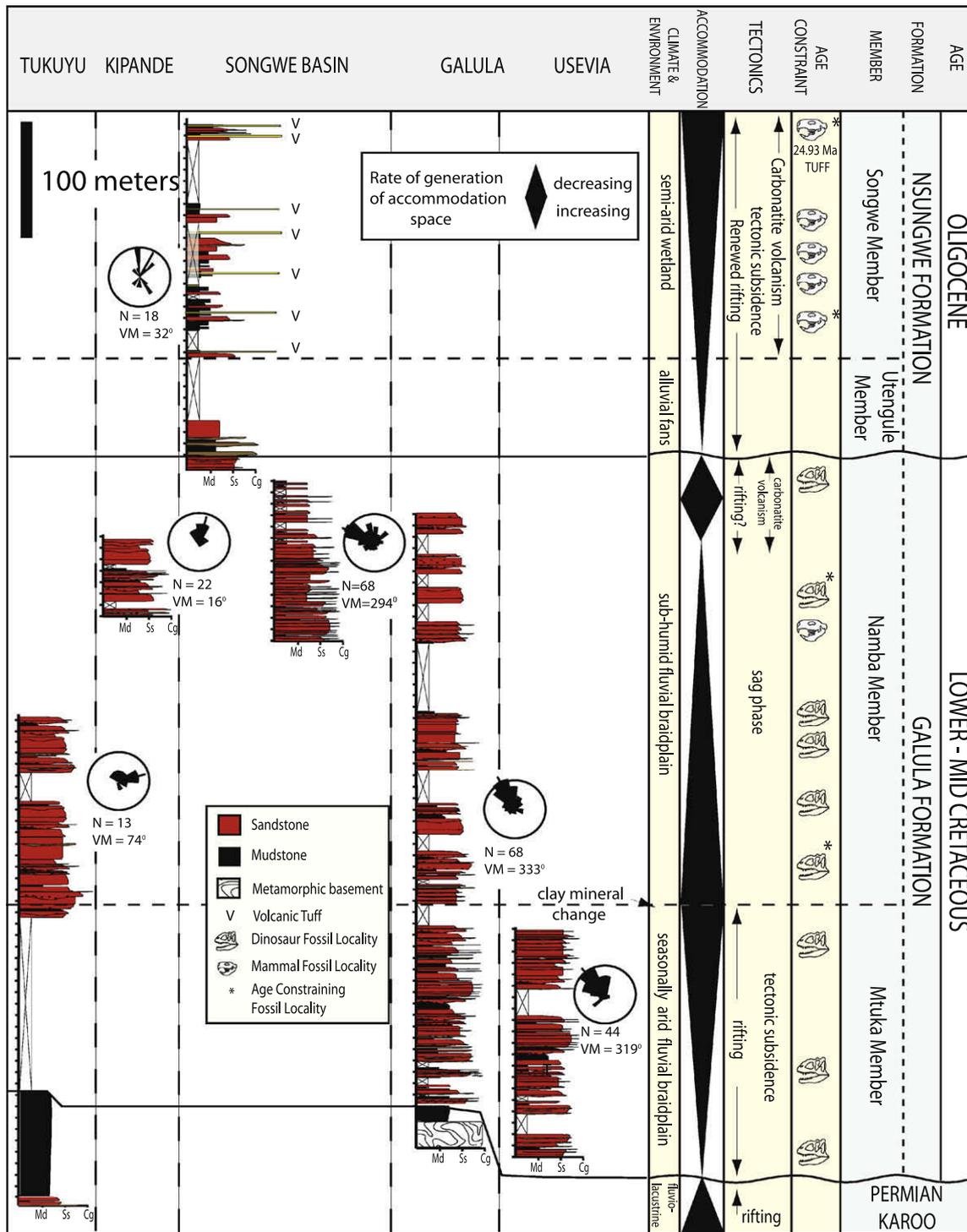
Fig. 19. Correlated measured sections with compiled paleocurrent data, fossil distribution, and age data for the Red Sandstone Group in the Rukwa Rift. Major changes in depositional environments, alluvial architecture, paleosol development and clay mineralogy likely reflect periods of continental–scale tectonic reorganization and possible regional climatic changes. Such changes are presumably linked to local episodes of rifting, volcanism, climate shifts and generation of accommodations space (subsidence).

gin of the rift, support the idea that a large, long-lived braidplain was established across much of the rift, with multiple parallel to interconnecting channels sourced from a variety of point sources to the south and southwest (Fig. 20).

A number of workers have used the ratio of dune height to water depth to estimate channel depth for ancient fluvial deposits

(Bridge and Tye, 2000; Leclair and Bridge, 2001; Adams and Battacharya, 2005; Miall, 2006; Allen and Fielding, 2007). Following these methods, cross-set thickness measurements from throughout the Galula Formation (and Nsungwe Formation, see below) were utilized to calculate mean cross-set thickness (S_m) and standard deviation (S_{sd}), and compared against the S_{sd}/S_m ratio of ~0.88

Fig. 20. Paleoenvironmental reconstruction for the Red Sandstone Group in the Rukwa Rift Basin. (A) Galula Formation represents a broad braidplain fluvial system flowing out of the highlands of Malawi and Zambia northwestward along the axis of the Rukwa Rift Bas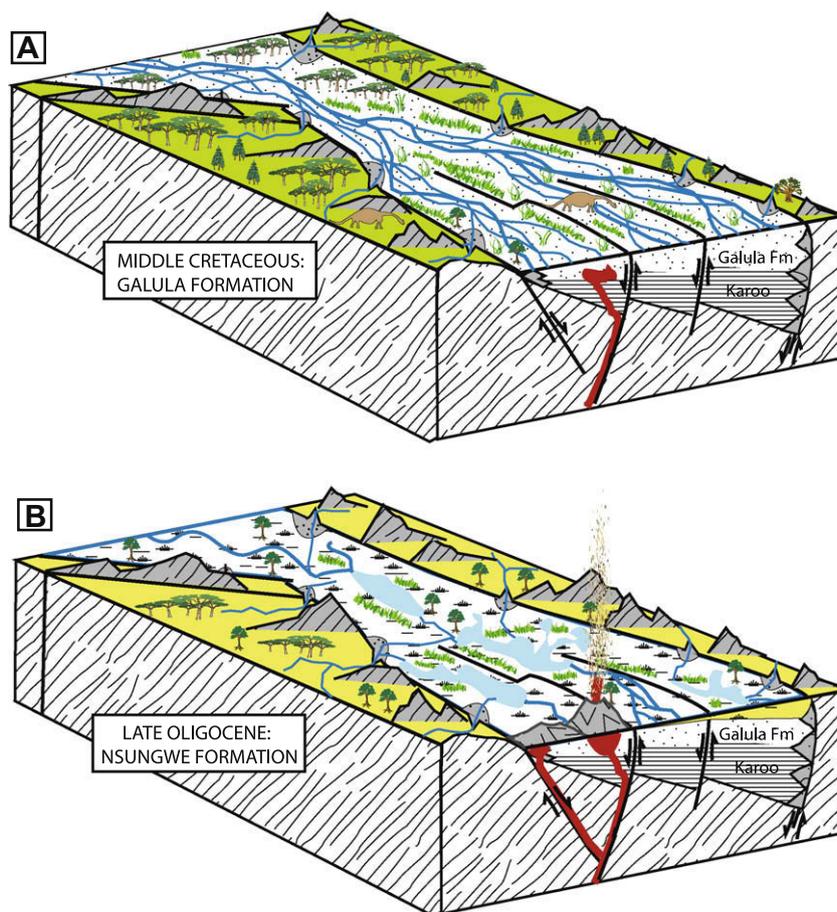in. (B) Nsungwe Formation represents a semi-arid wetland system that developed during the earliest episode of basin development associated with the "Modern" East African Rift System during the late Paleogene.

(±0.3) that Leclair and Bridge (2001) identified as necessary for calculating mean dune height. Measurements of numerous St and Sp sets ($n = 208$; Fig. 14) in the Mtuka and Namba Members of the Galula Formation in the Songwe, Galula, Tukuyu and Usevia areas indicate that the S_{sd}/S_m ratio for both members of the Galula Formation is within 0.88 (±0.3) suggesting that this method can be used to calculate mean dune height in the formation (Table 5). The formula used by Leclair and Bridge (2001) to estimate dune height is as follows:

$$\beta = S_m/1.8 \tag{1}$$
$$h_m = 5.3\beta + 0.001\beta^2 \tag{2}$$

Bridge and Tye (2000) indicate that the relationship between dune height and channel depth (d) typically average between $6 < d/h_m < 10$, although values can range as widely 3–20. Data from

the Galula Formation indicate that estimated bankfull flow depths of braided channels in the Mtuka Member ranged from 8.46 to 14.1 m deep, whereas in the Namba Member channels were slightly deeper, between 8.88 and 14.8 m (Table 5). Estimates of channel width are more difficult to determine, but based on cross-sectional dimensions of laterally continuous sheet sandstones, it is suggested that individual channels may have been up to several hundred meters wide, and that the entire braidplain system may well have been many kilometers wide (Fig. 20).

Inferences about middle Cretaceous paleoclimate are made possible through examination of preserved faunas, facies relationships, paleosols, sandstone petrology and clay mineralogy. Investigation of the fine-grained facies from the Galula Formation by Choh (2007) indicates a number of differences between the Mtuka and Namba Members. Although paleosols throughout the formation compare best with Alfisols-like soils, which are typical

Table 5
Estimated mean dune height (h_m) and mean bankfull channel depth (d) for the Red Sandstone Group based on mean cross-set thickness (S_m) (following Bridge and Tye, 2000).

Unit	Mean cross-set thickness (S_m) (m)	Standard deviation (S_{sd}) (m)	Standard deviation (S_{sd})/Mean cross-set thickness (S_m)	Mean dune height (h_m) (m)	Estimated bankfull channel depth (d) (m)
Nsungwe Formation Songwe Member ($n = 24$)	0.30	0.19	0.63	0.88	5.3–8.8
Galula Formation Namba Member ($n = 99$)	0.51	0.34	0.67	1.48	8.88–14.8
Galula Formation Mtuka Member ($n = 109$)	0.48	0.31	0.65	1.41	8.46–14.1

of open forest soils in tropical sub-humid climates (Soil Survey Staff, 1998), a variety of features in the Mtuka Member indicate significantly dryer (perhaps seasonally?) conditions than in the Namba Member. The presence of repeated Bt/Bk horizons in paleosol profiles, particularly from the Mtuka Member, reflects cumulative paleosol development; whereas the presence of clay and iron minerals suggests that there was significant downward movement of water and clay-sized soil materials associated with pedogenic processes. This suggests significant precipitation (Kraus, 1999), however the presence of carbonate accumulations in the Mtuka Member also indicates periodic or seasonal aridity (Retallack, 2001). In contrast, calcium carbonate accumulations are extremely rare in the mid to upper portions of the Namba Member. Paleosols in both members, but particularly the Mtuka Member, are characterized by blocky ped structures and slickensides that indicate expanding clays and provide strong evidence of fluctuating soil moisture. This is consistent with other evidence, particularly in the Mtuka Member, to suggest seasonal variation in precipitation (Duchaufour, 1982; Demko et al., 2004). Moreover, the predominance of illite and interstratified illite/smectite in the Mtuka Member is most likely a result of diagenetic processes during burial which led to the transformation of smectites into illite (Singer, 1980; Alonso-Azcarate et al., 1997; Kraus, 1999). This is most typically associated with semi-arid depositional settings (Singer, 1980). In contrast, a clear shift to kaolinite-dominated clay mineral assemblages and the general decrease in calcium carbonate accumulations (Bk horizons) in paleosol profiles of the Namba Member are both consistent with a transition from a semi-arid climate in the Mtuka Member to a wetter, sub-humid climate in the Namba Member. Sandstone petrology suggests that this transition was probably not particularly extreme or prolonged because the subarkose to arkose petrofacies associated with the Mtuka Member persists during deposition of the Namba Member. Additionally, there is very little evidence of feldspar alteration in the Namba Member, as would be expected for weathering under prolonged or extremely wet, humid, tropical conditions. Therefore it is surmised that although multiple lines of evidence strongly suggest a climatic shift between the Mtuka and Namba Members, that this shift was not extreme.

5.3. Age of the Galula Formation and new perspectives on Cretaceous tectonics

Following decades of intense debate concerning the age, stratigraphy and tectonic framework of the RSG, we are now able to provide convincing evidence for resolving the tectono-sedimentary history of these strata. Novel data presented herein, and in other venues (Krause et al., 2003; Gottfried et al., 2004; Roberts et al., 2004; O'Connor et al., 2003, 2006, 2008), confirms the existence of a Cretaceous phase of deposition in the RSG, which we recognize and describe herein as the Galula Formation.

Following deposition of the Karoo Supergroup in the Rukwa Rift Basin, a hiatus, perhaps one as long as 150 million years, occurred prior to the onset of deposition of the Galula Formation, which initiated in the Early Cretaceous (Fig. 19). Although the depositional timing for the base of the Galula Formation is still uncertain, detrital zircon age data (see Roberts et al., 2007) provide a maximum depositional age of ~150 Ma (Late Jurassic), yet the preponderance of faunal data indicate a "middle" Cretaceous age (ca. 120–90 Ma) for the formation (see O'Connor et al., 2006). Such diagnostic taxa as gondwanatherian mammals, titanosaurian sauropods, notosuchian crocodyliforms, and osteoglossomorph fish are found within the Namba Member of the Galula Formation (Table 6). These forms are most typically associated with Aptian–Late Cretaceous and early Paleogene (in the case of the gondwanatherians) sedimentary sequences from Gondwanan landmasses.

Table 6
Faunal list of vertebrate and invertebrate groups recovered from the Red Sandstone Group.

Galula Formation		Nsungwe Formation	
Mtuka Member	Namba Member	Utengule Member	Songwe Member
Osteichthyes	Osteichthyes	Indet bone	Mollusca
Sarcopterygii	Actiinopterygii		Gastropoda (x3)
Ceratodontidae	Osteoglossomorpha		Bivalvia (x2)
Testudines	Testudines		Arthropod a
Crocodyliformes	Crocodyliformes		Decapoda
Dinosauria	Notosuchia		Brachyura
Saurischia	Sebecia		Potamonautidae
Theropoda (x2)	Dinosauria		Tanzanonautes tuerkai
Sauropoda (x2)	Saurischia		Osteichthyes
Titanosauria	Theropoda (x2)		Sarcopterygii
	Sauropoda (x3)		Dipnoi
	Titanosauria		Actinopterygii
	Mammalia		Polypteriformes
	Gondwanatheria		Siluriformes (x2)
			cf. Characiformes
			Acanthomorpha
			Anura
			Testudines
			Lepidosauria
			Squamata
			Crocodyliformes (x2)
			Avialae
			Mammalia
			Rodentia
			Phiomorpha (x4)
			Kahawamys mbeyaensis
			Hyracoidea
			Rukwalorax jinokitana
			Macroscelideans (x2)
			Primates (x2)

The sedimentology of the Galula Formation is remarkably similar to the Dinosaur Beds of Malawi in the Karonga area (Dixey, 1928; Jacobs et al., 1990; Winkler et al., 2000). The Dinosaur beds preserve a diverse fauna, including Aptian ostacodes, which form the basis for its mid-Cretaceous age assignment (Colin and Jacobs, 1990; Jacobs et al., 1990). The Dinosaur Beds are composed of virtually identical lithofacies and with generally similar facies associations as the Galula Formation. Many other similarities, including abundant intraformational conglomerates, arkosic sandstone, northwesterly orientated paleoflow, and highly comparable faunas are also apparent. The Galula Formation preserves at least some of the same taxa as the Dinosaur Beds, including skeletal remains of turtles, sauropod and theropod dinosaurs and a notosuchian crocodyliform closely-related to *Malawisuchus* (O'Connor et al., 2008). Based on these unifying sedimentological and faunal characteristics, the Dinosaur Beds of Malawi and the RSG are interpreted to be at least partially equivalent to one another. Intensive sampling and preparation of samples from the Galula Formation have resulted in minimal recovery of palynomorphs of extremely poor preservation, consistent with the poor recovery reported from the Ivuna-1 and Galula-1 wells (Wescott et al., 1991; and others).

Other lines of evidence support a middle Cretaceous age assignment for the formation, including cross-cutting relationships with the Panda Hill carbonatite, indicating that the carbonatite intruded through at least a portion of the Galula Formation. In one area of Panda Hill, Fawley and James (1955) reported the presence of a carbonatite dyke that had been truncated by sandstone units of

the Galula Formation (presumably the Namba Member), indicating that emplacement of the carbonatite body was at least partially contemporaneous with deposition of the Galula Formation. Extensive investigations and mapping of Panda Hill and a number of other local, intrusive carbonatite bodies (Fawley and James, 1955; James and McKie, 1958; Basu and Mayila, 1986; Van Straaten, 1989), along with radiometric dating, indicate that regional carbonatite emplacement occurred between ~116 and 96 Ma (Snelling, 1965; Pentelkov and Voronovskii, 1977; Cahen and Snelling, 1984). Approximately 3–5 km north of the Panda Hill Carbonatite, extensive syn-depositional soft-sediment deformation, including evidence of fluid-escape structures and clastic dikes, along with evidence of syn-depositional growth faulting, is evident within the mid to upper levels of the Namba Member of the Galula Formation. These features are all consistent with intense tectonic activity and emplacement of local intrusive/extrusive igneous bodies (e.g., the Panda Hill carbonatite). A detailed provenance and heavy mineral analysis of fluvial sandstones from the lower and middle levels of the Namba Member of the Galula Formation in the Songwe sub-basin (Sokhela, 2006) indicate that significant input of carbonatite-sourced sediment did not occur until after deposition of the Namba Member. However, it is still likely that sedimentation was at least partially coeval with intrusion and possibly extrusion of the Panda Hill carbonatite.

Milga (1994) applied Faust's method for estimating the age of the RSG, based on seismic interval velocity and sonic log velocity from the Ivuna-1 well logs. Faust (1951) showed that a quantitative relationship exists between velocity, depth of burial and geological time since deposition of sediment, which permits estimation of depositional age based on sonic log velocities and seismic interval velocity. Milga's (1994) results indicate two distinct depositional age brackets for the RSG. He noted an older sequence that broadly correlates to deposition between 180 and 100 Ma (Galula Formation), and a younger sequence in which deposition began between 56 and 25 Ma (Nsungwe Formation). Apatite-fission track dating of the Rukwa and Malawi rift flanks by Van der Beek (1998) identified evidence of rapid cooling and denudation of rift flanks associated with a major Late Jurassic–Early Cretaceous rifting event. Similar apatite-fission track studies in southern Africa and Kenya have documented major episodes of cooling and denudation associated with continent–scale tectonic reactivation of major rifts, sutures, and zones of crustal weakness, all centering around 140–120 Ma (Foster and Gleadow, 1992), and in many cases associated with syn- and post-tectonic Cretaceous sedimentary sequences. In fact, across continental Africa, a number of workers have recognized contemporaneous Lower to middle Cretaceous continental rift–fill sequences. This continent–scale pattern of basin development and synchronous deposition is most often ascribed to far-field stresses associated with rifting and reorganization of the African and South American plates during this time (Bosworth, 1992; Guiraud et al., 1992; Burke et al., 2003).

6. Sedimentology and Geological History of the Nsungwe Formation

6.1. Facies analysis of the Nsungwe Formation

Lithofacies identification was utilized in conjunction with detailed analysis of internal and external geometry and bounding surfaces, architectural element analysis, and paleontology to subdivide the Nsungwe Formation into four distinct facies associations (FAs), including: major conglomerate (FA1), major tabular to lenticular sandstone (FA3), minor tabular to lenticular mudstone/muddy sandstone (FA4), and laminated siltstone and claystone (FA5) (Table 3).

6.1.1. Description: major conglomerate (FA1)

Major conglomerates in the Nsungwe Formation are defined as thick, laterally persistent, extraformational dominated, matrix- to clast-supported conglomeratic units. They are typically composed of multiple thin, stacked beds dominated by either Gcme or Gmm. Pebble count data from the Nsungwe Formation deviate significantly from the Galula Formation. The most apparent variation in the Nsungwe Formation is the relatively low concentration of intraformational type 1 pebbles (Fig. 10). Major conglomerates are dominantly found within the basal portion of the Utengule Member. They can be divided into two distinct groups. Group 1 conglomerates are dominated by well-rounded, matrix- to clast-supported type 4 metamorphic and vein quartz pebbles in a quartz sandstone matrix. Group 2 conglomerates are typically matrix-supported and composed of type 4 quartz clasts, along with more distinctive type 2 pedogenic calcrete pebbles and type 7 foliated metamorphic basement pebbles (Fig. 10). Both conglomerate groups also contain minor amounts of type 3 and 6 clasts. A lithologically unique major conglomerate dominated by type 4 quartz clasts is recognized at the base of the Utengule Member, directly atop the low-angle unconformity on the underlying Galula Formation.

The Songwe Member has very few conglomeratic units in general; when present, these typically contain varying proportions of type 4 metamorphic/vein quartz and type 7 foliated metamorphic clasts, along large white feldspars (Fig. 10). Thin, interbedded lenses of lithofacies Se, Sm, Sh, St, Fcf and Fr are commonly associated with both end members (Groups 1 and 2) of FA1 in the Utengule Member. Major conglomerates have third- and fourth-order internal bounding surfaces, whereas the bases of individual units are demarcated by erosional fifth-order bounding surfaces. No diagnostic fossil material has been recovered from this FA.

6.1.2. Interpretation: major conglomerate (FA1)

Major conglomerates of the Utengule Member are divided into two groups (Group 1 and Group 2), and are here interpreted to represent two distinct depositional environments. The Group 1 major conglomerate, represented by a 3 m-thick bleached quartzose unit at the base of the Utengule Member, is interpreted as a major braided fluvial pediment surface. The ultra mature conglomerate with well-rounded, quartzose pebbles indicate long-distance transport by braided streams in a low-accommodation system.

Long-distance transport down a paleoslope, or extensive reworking in a localized basin, would result in the destruction of less resistant lithologies and account for the texturally mature and quartzose character of this unit. Heller et al. (2003) suggested that regional tilt necessary to produce such conglomerates may be a result of dynamic topography caused by mantle convection. The presence of a low-angle unconformity between the Galula and Nsungwe Formations (Fig. 8) suggests that this unit was deposited prior to or during initial stages of rift reactivation during the mid-late Paleogene. Small-scale regional tilting and deposition of the white conglomerate at the base of the Utengule appears similar to the depositional process proposed for the Ogallala Group conglomerates in the United States (Heller et al., 2003). Heller et al. (2003) linked the Ogallala deposition to regional uplift and extension associated with development of the Rio Grande Rift System. A similar mechanism is envisioned for the basal Utengule Member, which presumably coincides with initiation of the volcanism under the Afar region and development of the East African Rift System (Chorowicz, 2005). This would imply that quartz pebbles were derived from the north, as doming developed to the north and east associated with mantle upwelling. Although there is no paleocurrent data from the Utengule Member to test this hypothesis, investigation of detrital zircon geochronology in the Rukwa Rift Basin (Roberts et al., in preparation) strongly supports this assertion.

The pilot detrital zircon data from this unit document the presence of a major population of Mesoproterozoic grains that were most likely derived from the 1.38 Ga Kibaran Belt located several hundred kilometers to the northwest in the DRC. Regional doming to the north (focused beneath the Afar region) presumably resulted in a short-term drainage reversal in the Rukwa Basin, prior to reactivation of deep, Precambrian crustal structures bounding the Rukwa Rift.

Group 2 conglomerates in the middle–upper Utengule Member are interpreted as proximal–medial debris flow dominated alluvial fans. These likely represent deposition along the basin margins during a period of rapid rifting and basin development during the late Paleogene (associated with rifting across East Africa). Clasts are dominated by reworked extraformational, rounded quartz pebbles (presumably from the basal Group 1 unit) along with upwardly increasing intraformational calcrete nodules that were presumably reworked from well-developed local soils. Upwardly increasing foliated metamorphic clasts in the Group 2 conglomerates are typically more angular, suggesting a proximally derived source from recently uplifted Ubendian basement rocks along the rift flanks.

6.1.3. Description: major tabular and lenticular sandstone (FA3)

Major lenticular sandstone is exclusively found within the Songwe Member of the Nsungwe Formation. This FA is characterized by 2–10 m thick, isolated lenticular sandstone bodies composed of lithofacies St, Sp, Sh, Sm, Se, Gcmi, and Gcme, with basal fifth-order bounding surfaces that are incised into underlying mudrock (FA4 and 5) (Fig. 21A). Sandstone facies are dominantly medium- to coarse-grained sand with abundant clay and silt matrix and minor calcite cement. Higher proportions of matrix and metamorphic lithic fragments are observed in the Nsungwe
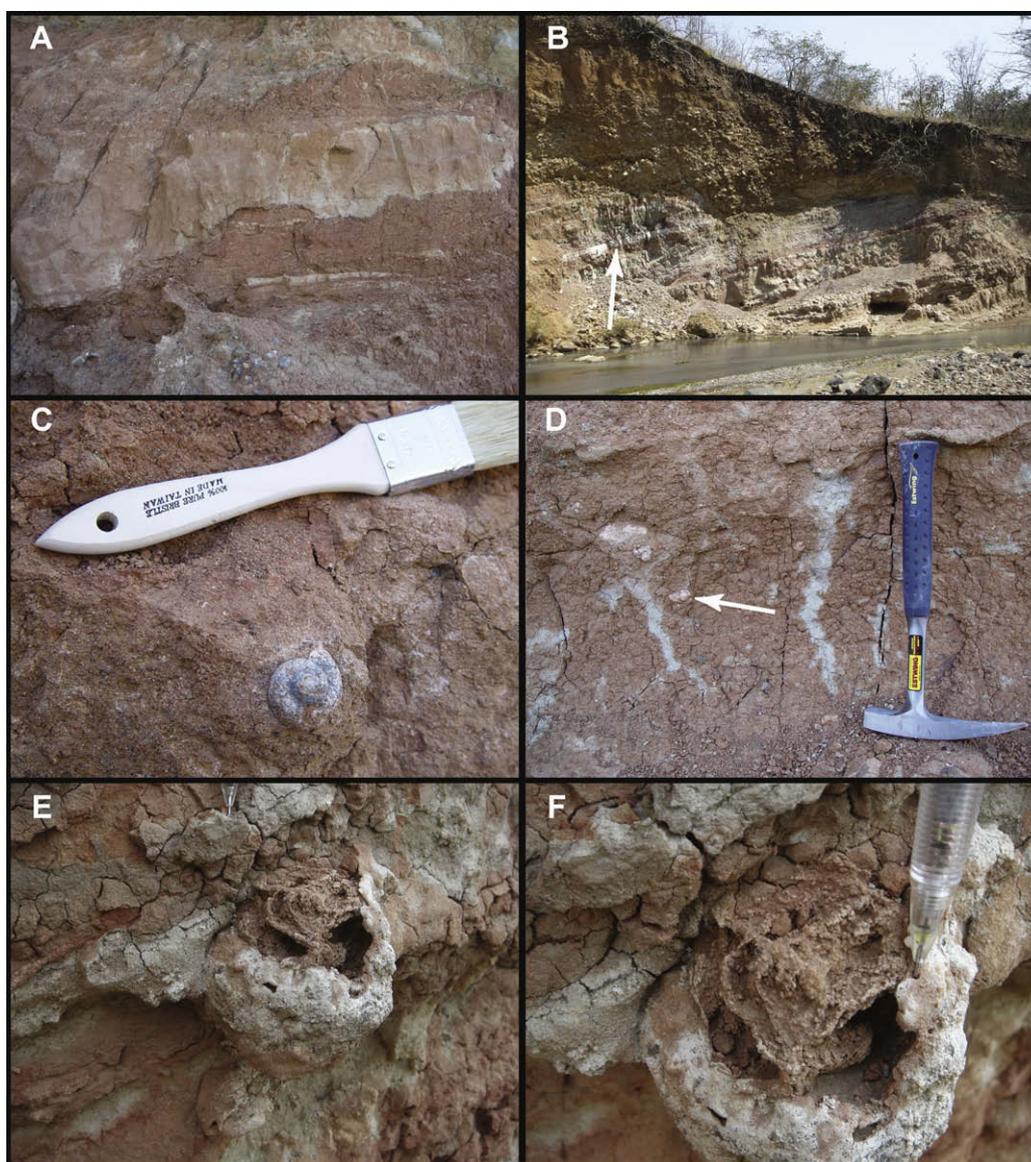

Fig. 21. Outcrop photos of facies associations 3, 4 and 5 (FA3, FA4, FA5) in the Songwe Member of the Nsungwe Formation, in the type section. (A) Lenticular channel sandstone (FA3) incised into and buried by laminated to massive mudrocks of FA4 and FA5. (B) Interbedded sequence of FA4 and FA5. Note white arrow pointing to distinctive white, devitrified lapilli tuff bed. (C) Internal mold of an aquatic gastropod in muddy sandstone of FA2. (D) Root traces and small calcium carbonate nodules (white arrow) preserved in a typical FA4 sequence. (E and F) Well-preserved termite nest structure, *Termitichnus*. Note the large central spherical chamber, with a network of spiraling, pellet-filled galleries. This trace fossil is similar to the ichnotaxon *Termitichnus* from the penecontemporaneous Oligocene Jebel Qatrani Formation in the Fayum Province of Egypt (Bown, 1982).

Formation than in the Galula Formation, qualifying most sandstones as litharenites (sensu Pettijohn et al., 1987), with an average modal composition of $Q_{50}F_{21}L_{29}$ (Fig. 13). Cross-set thickness is considerably smaller than in the underlying Galula Formation, with a mean height of 0.30 m ($n = 24$) (Fig. 14; Table 5). Paleocurrent data are limited to 18 measurements taken on 3D trough cross-beds that indicate high dispersion and a vector mean of 32° (Fig. 16).

Grain size, bed thickness and cross-bed thickness exhibit distinctive fining upward patterns. Internal third- and fourth-order bounding surfaces are common; however large-scale macroform elements are rarely distinguishable, with the exception of a number of well-defined channel elements (CH). Although it is not possible to observe extensive outcrop exposures of the Nsungwe Formation, apparent width/thickness ratios for FA3 are well-below 15:1, consistent with ribbon sandstone bodies (sensu Friend et al., 1979; Friend, 1983).

Fossils are rare to abundant, dominated by microvertebrate remains (<10 cm) of fishes, frogs, turtles, crocodiles, and mammals (Stevens et al., 2005, 2006, 2008, 2009a,b). In most cases, specimens consist of isolated fragmentary elements to whole bones and teeth; however, in rare instances more complete material ranging from partial jaws to articulated partial skeletons are also preserved (Simons, 2008; Stevens et al., 2008). Less commonly, larger vertebrate remains (>10 cm), including fragmentary limb elements, ribs and vertebrae are also preserved. An abundance of freshwater invertebrates, including the earliest fossil record of freshwater crabs (Feldmann et al., 2007), and numerous taxa of aquatic and terrestrial gastropods and bivalves are preserved in the Songwe Member. Bioturbation, dominated by root traces, and ichnotaxa representative of the *Scoyenia* ichnofacies, is most abundant near the top of major lenticular sandstones. Plant macrofossils and palynomorphs are not preserved in FA3, or in any other facies association in the formation.

6.1.4. Interpretation: major tabular and lenticular sandstone (FA3)

Major tabular and lenticular sandstones are interpreted as fluvial channel deposits. Most FA3 units contain abundant clay- and silt-sized matrix, which, considered with their typical encasement in thick floodplain sequences (FA4), is suggestive of mixed to suspended load channels with stable banks. The limited paleocurrent data that are available suggest more flow dispersal than in the Galula Formation. Rivers of the Nsungwe Formation were quite different from those of the Galula Formation, and are perhaps more closely aligned with meandering and anastomosing channels; however the lack of extensive outcrop prohibits detailed reconstruction of channel morphology. The abundance of an aquatic fauna in parts of the Nsungwe suggests perennial flow conditions, although weak stratification, poor sorting and the muddy character of many beds (Sm, St, Se) indicate fluctuating flow conditions, perhaps associated with seasonal changes in the hydrologic cycle. The upper Utengule and Songwe Members were likely deposited during a period of relatively high subsidence and rapid generation of accommodation space. This is accounted for by channel morphology and the greatly increased preservation of fine-grained facies as documented below.

6.1.5. Description: minor tabular to lenticular mudstone/muddy sandstone (FA4)

The minor tabular to lenticular mudstones/muddy sandstones in the Nsungwe Formation are highly variable in their overall character and lithofacies composition. They are typically thin (10–70 cm), but may be up to ~2 m thick. They include both laterally extensive, tabular units and spatially restricted lenticular beds (Fig. 21). Fine-grained lithofacies include Fl, Fr, and Fcf, while less abundant coarse-grained lithofacies include Sm, Sr, and Sh. Bioturbation ranges from minimal to intense. FA4 is particularly variable

in the Songwe Member, where it ranges from tabular units dominated by Sm, Sh, and Sr to fining upward packages of Fcf, Fl and Fr, to densely interbedded variants of these two end members. Moreover, FA4 is routinely interbedded with thick sequences of FA5 and FA3. Contacts tend to be sharp to gradational, with rare evidence for erosional contacts. Clay cutans, ped structures and rare calcium carbonate accumulations are relatively common. Bioturbation is observed throughout the Songwe Member, and bedding ranges between mildly and intensely disturbed. Root traces and indistinct burrows are the most commonly observed biogenic structures. Well-preserved meniscate backfilled burrows are also locally abundant, and at one location exquisitely preserved complex trace fossils composed of a tentatively identified as the termite nest trace *Termitichnus* (Bown, 1982) are preserved (Fig. 21E and F). These trace fossils are identified as fossil termitarium based on the presence of spheroidal central chambers, each with a network of galleries. Many of the galleries are filled with what appears to be fecal pellets. Body fossils are generally rare, however a series of densely packed gastropod shell beds, along with isolated microvertebrate bones and teeth, are preserved in the basal portion of the Songwe Member.

6.1.6. Interpretation: minor tabular to lenticular mudstone/muddy sandstone (FA4)

FA4 is interpreted to represent both abandoned channel and overbank depositional environments. Tabular FA4 units dominated by Sm, Sh, and Sr are interpreted as crevasse splay deposits, whereas FA4 units dominated by fine-grained lithofacies are interpreted to represent short-lived floodplain ponds and paleosols. In many instances, coarse and fine-grained FA4 units are interbedded, representing cyclical episodes of overbank flooding, ponding, drying, and soil development. This scenario is well-supported in places by repeated lithofacies changes from Fcf and Fl with abundant aquatic gastropods, grading upwards into Fr with abundant root mottling, clay cutans, ped structures and occasional calcium carbonate accumulations.

6.1.7. Description: laminated siltstone and claystone (FA5)

Laminated siltstone and claystone is a facies association restricted entirely to the Songwe Member of the Nsungwe Formation, where it represents ~30–35% of the section (Fig. 9). FA5 is best exemplified by maroon, red, orange, gray, and white beds of Fl and Fb, although beds of Fcf, Sm, and Sr are also present (Fig. 22). A typical FA5 sequence is characterized by interbedded sequences of mottled, bioturbated, sandy siltstones, laminated mudstones (Fl) and thin ultrapure claystone beds (Fb). Carbonate cemented nodules and indistinct bioturbation features are common in laminated to massive siltstone horizons. In general, fossil preservation is quite poor, although some siltstones preserve gastropods and freshwater crabs in relatively high abundance as well as local concentrations of microvertebrate fossils dominated by isolated fish, frog, and turtle elements, as well as mammal bones and teeth.

The ultrapure claystone beds of Fb represent the most distinctive facies within this FA. These pure claystones range from 5 to 250 cm thick and are very finely laminated. However in some cases their original lamination has been modified, by shrinking and swelling properties of the clay, to form what appear to be granule- to pebble-size claystone breccias (Fig. 22). Several claystone units were separated for grain size analysis, revealing that only minor amounts (<5%) of detrital sand is present, along with concentrations of heavy minerals. Detailed XRD analysis of Fb samples from FA5 reveals that montmorillinite and vermiculite represent the dominant clay fraction, along with minor amounts of saponite, nontronite and mixed-layer illite/smectite (Table 4). Moreover, petrographic and geochemical analysis of heavy mineral separates
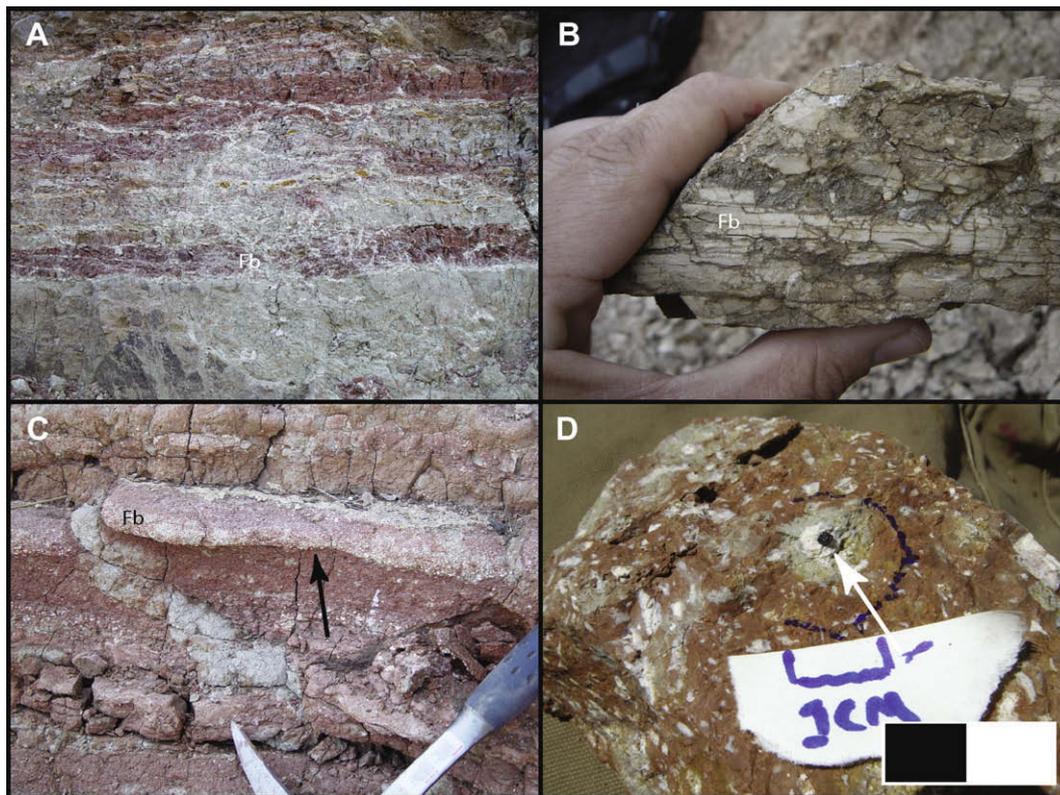
Fig. 22. Examples of the laminated siltstone and claystone facies association (FA5) in the type section of the Songwe Member of the Nsungwe Formation. (A) Laminated, maroon claystones (Fb) interpreted as devitrified volcanic ash beds. (B) Pure tan claystone (Fb) showing partial brecciation due to shrinking and swelling properties of the montmorillinite clays; also interpreted as devitrified volcanic ash. (C) Diagnostic calcite pebble tuff bed from the top of the Songwe Member, dated at 24.93 ± 0.49 Ma. (D) Hand sample of a devitrified volcanic ash (bentonitic claystone-Fb) with a euhedral andradite garnet (commonly associated with carbonatite volcanics) exposed in the center. Scale bar is 2 cm.

reveals fresh, euhedral minerals, including such unusual niobate minerals as pyrochlore and perovskite, along with calcium garnets including andradite (var. Melanite; Fig. 22D), the calcic amphiobole pargasite, and other minerals including magnetite, zircon, phlogopite, and particularly abundant concentrations of titanite and apatite. Several of the pure claystone (Fb) beds are even more distinctive, containing the same minerals described above, but also with dense concentrations of granule- to pebble-sized clasts of calcite. These calcite pebble claystones appear tuffaceous in hand sample (Fig. 22C) and in thin section they appear to preserve relict glassy textures. Geochemical comparison between Fb and FA4 mudrock facies (Fl, Fcf, Fm) in the Nsungwe and Galula Formations reveals that the Fb in FA5 have highly elevated concentrations of Nb, along with Rb, Zr, Sr and Zn, as compared to typical mudrock of the RSG (Choh, 2007). Moreover, comparison of clay mineral XRD analysis between FA4 and FA5 (lithofacies Fb) in the Nsungwe Formation indicate distinctive variations. As described earlier, FA4 mudrocks are typified by mixed-layer illite/smectite with moderate to minor phases of montmorillinite, kaolinite and saponite. In contrast, pure claystones (Fb) of FA5 are dominated by montmorillinite with vermiculite, and saponite, but only minor phases of mixed-layer illite/smectite (Table 4).

6.1.8. Interpretation: laminated siltstone and claystone (FA5)

The laminated siltstone and claystone FA is interpreted to represent subaqueous deposition in floodbasin lakes and wetlands. A number of repeated microenvironments are recognized, including low-energy central lake settings, mixed-input delta-marsh settings, and marginal sandy delta and shoreline regions. Pure laminated to brecciated claystones and calcite pebble breccias are interpreted as airfall ash and airflow tuff deposits, respectively. Petrographic and geochemical investigation of these units demonstrates a general paucity of detrital sand in these units. The presence of euhedral phenocrysts of phlogopite, pyrochlore, magnetite, andradite, titanite, apatite, and other unusual minerals, along with calcite tephra clasts, relic glassy textures and elevated trace element concentrations such as niobium, are all features consistent with a volcanic origin. Specifically, these mineral assemblages and elevated levels of niobium and other trace elements are consistent with an alkaline volcanic source, interpreted here to be a carbonatite volcano.

6.2. Depositional environments and paleoclimate of the Nsungwe Formation

Depositional environments of the Utengule Member indicate a transition from an initial low-accommodation distal alluvial fan system (perhaps a fluvial pediment) to a proximal alluvial fan system associated with fault reactivation and rifting. A more pronounced change in depositional style occurs between the Utengule Member and the Songwe Member. The Songwe Member records the transition from proximal alluvial fans to a fluvial–lacustrine sequence, which we interpret to be associated with rapid generation of accommodation space during this time (Figs. 19 and 20). Following methods outlined above (Bridge and Tye, 2000; Leclair and Bridge, 2001), mean dune height (h_m) is calculated at ~0.88 m in the Songwe Member, indicating that bankfull channel depths ranged from 5.3 to 8.8 m deep (Fig. 14; Table 5). The general paucity of extensive lateral exposures in the Nsungwe Formation limits estimates of channel width, but a number of well-defined

lenticular sandstones (CH elements) encased within thick flood-plain fines (FA4) are observed to be between 20 and 40 m wide. Width of larger major tabular sandstones is unclear, as is determination of true channel morphology, which we generally interpret as being more consistent with meandering or anastomosing rivers than braided rivers. The facies architecture of mudrocks (FA4 and 5) in the Songwe Formation indicates a myriad of quiet-water lake and wetland depositional settings (Fig. 20). In particular, the preservation of well-laminated claystones (FA5) and the high concentration of aquatic organisms in many facies indicate the perennial availability of surface water associated within this wetland or lacustrine system, which was either fed or drained by small-to medium-sized rivers with cohesive banks.

Geochemistry and clay mineralogy of overbank mudrocks and paleosols of the Songwe Member provide significant insight into late Paleogene paleoclimate. Mudrocks are dominated by mixed-layer illite/smectite clay minerals, with minor phases of kaolinite, illite, montmorillinite and saponite, which taken together suggest a generally arid to semi-arid climate and weathering of volcanic protoliths (Table 4). The presence of calcium carbonate, blocky ped structures, slickensides and root halos all indicate moderate pedogenesis within an overall semi-arid climate. The overall sedimentology and depositional environments observed for the Songwe Member are strikingly similar to those documented by Ashley et al. (2004) for the semi-arid, freshwater wetlands of the Loboi Swamp region in Kenya.

6.3. Age of the Nsungwe Formation and new insights into Paleogene tectonics

A low-angle unconformity, best exposed in the Songwe area, representing a 50–70 million year hiatus separates the Cretaceous Galula Formation from the overlying Paleogene Nsungwe Formation, which is a previously unrecognized depositional sequence representing an extremely rare and important terrestrial African Paleogene ecosystem. It represents the only significant fully continental, vertebrate-bearing Paleogene sedimentary sequence in sub-equatorial Africa, other than isolated kimberlite pipe lakes (e.g., Mahenge in central Tanzania; Harrison et al., 2001; Gunnell et al., 2003) and a possible Eocene Karst deposit from Namibia (Pickford et al., 2008). Age constraint for the lower Utengule Member is poor at present, but inferred as Paleogene. However, the overlying Songwe Member preserves important age-constraining vertebrate taxa including phiomorph rodents, primates, hyraxes, and macroscelideans (Table 6). Many vertebrate taxa from the Nsungwe Formation are intermediate in form between well-documented taxa from the Eocene–early Oligocene of the Fayum Depression in Egypt and other localities along the Arabian Peninsula, and younger faunas from East Africa (Stevens et al., 2008). The absence of small-bodied Eurasian immigrant taxa (e.g., sciurids, muroids, leporids), which are well-documented throughout East Africa during the early Neogene (Winkler, 1992), is also consistent with a late Paleogene age (Stevens et al., 2008).

Apatite-fission track dating by Van der Beek (1998), which identified Karoo and Cretaceous-age rifting events in the Rukwa Basin, also identified the presence of a third rifting event, during the Paleogene (50–40 Ma). This is consistent with Milga's (1994) identification of a second depositional phase of the RSG beginning sometime between 56 and 25 Ma. Tiercelin et al. (1988) obtained late Eocene and early Oligocene age dates (40.4 and 34 Ma) from several nephaline basalts located in the Tukuyu region (near the Rungwe massif), which are from the "Older Extrusives" of Harkin and Harpum (1957). Although this data has been disputed by some
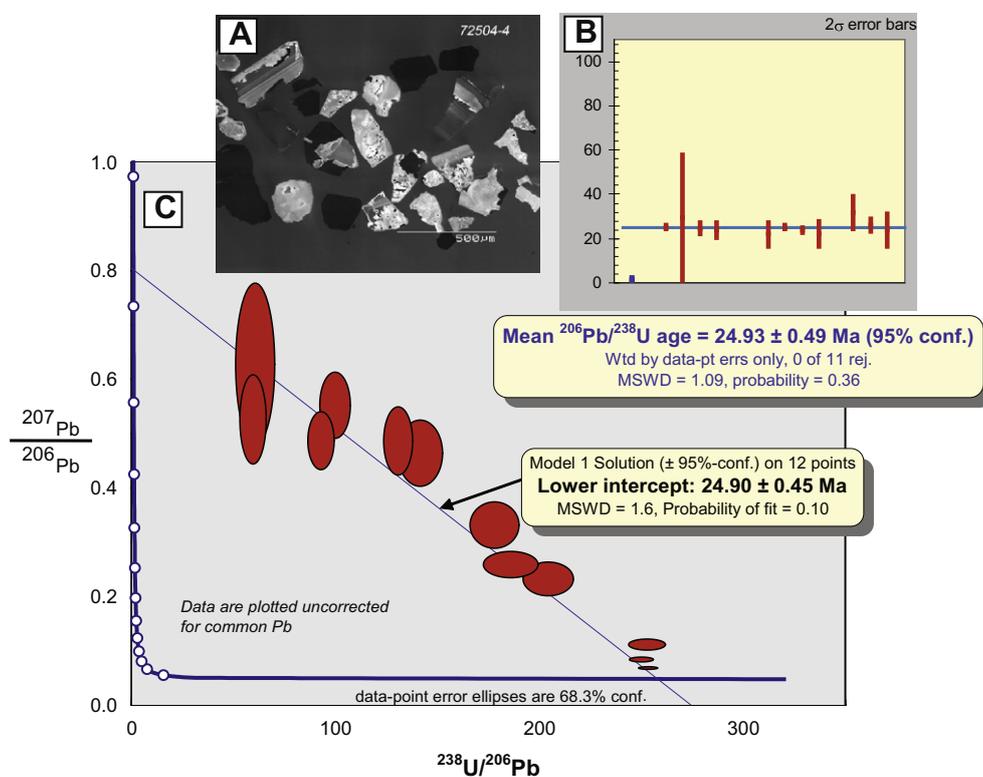

Fig. 23. U–Pb geochronology data for tuff sample 72404-4 from 7 m below the top of the Songwe Member of the Nsungwe Formation. (A) Cathodoluminesence image of phyrochlore phenocrysts. (B) $^{206}Pb/^{238}U$ Age spectra for 11 pyrochlore grains shown with 2σ error bars. (C) Tera–Wasserburg Concordia plot with lower intercept for sample 72504-4.

workers, it fits in with a variety of other data that indicate rift reactivation as early as the late Eocene.

The early phase of this renewed Paleogene rifting event is quite likely represented in the sedimentary record by deposition of the distinctive basal white conglomerate bed and overlying alluvial fan facies of the Utengule Member. Later, increasing generation of accommodation space led to the development of internally draining lakes/wetlands and deposition of the Songwe Member during the mid-late Oligocene (Fig. 19).

6.4. Radiometric dating of Nsungwe Formation carbonatite tuff

A radiometric age date was obtained on one of several intercalated volcanic airfall and ashflow tuff horizons located within the Songwe Member. The tuff bed (sample 72504-4) that was chosen for dating is located ~7 m below the top of the Songwe Member. This sample appears to be a calcite–pebble vitric tuff supported by a maroon claystone matrix that presumably represents devitrified ash, containing abundant pyrochlore, andradite garnets, phlogopite and relict glassy textures. This unusual unit is interpreted as a devitrified carbonate-rich, vitric tuff sourced from an explosive carbonatite volcano. Most other volcanic tuffs in the Songwe Member are devitrified ash beds, recognized as purple to gray colored, ultrapure smectitic claystone beds with highly distinctive phenocrysts of calcite, andradite, pyrochlore and other diagnostic minerals.

6.4.1. U–Pb dating results

Single crystal U–Pb dating of 11 pyrochlore phenocrysts from sample 72504-4 reveals a mean age of 24.93 ± 0.49 Ma (Fig. 23A and B; Table 7). Regression of the data uncorrected for common Pb and as represented on the Tera-Wasserburg Concordia plot yields the same age as the weighted mean for the $^{206}Pb/^{238}U$ age calculated at 24.93 ± 0.49 Ma (Fig. 23A and C).

Concurrent investigation of detrital zircon geochronology from fluvial sandstones of the Galula and Nsungwe Formations reported in Roberts et al. (2007) provide additional constraints and confirmation of the late Oligocene age of the Nsungwe Formation. The highest detrital zircon sample collected near the top of the Songwe Member, ~3 m above tuff sample described herein, yields a detrital zircon age spectra between 24.5 and 27.8 Ma for the youngest grain population. Given that tuff sample 72504-4 was collected 7 m below the top of the 400+ m-thick Nsungwe Formation, 24.93 Ma is considered a maximum depositional age for the formation (Fig. 19). Moreover, it seems likely that the Utengule Member and lower portion of the Songwe Member may be significantly older. Several other tuff samples from lower down in the Songwe Member have been collected and are being processed for addi-

tional U–Pb dating to further constrain the deposition age of these deposits.

6.4.2. Source of carbonatite volcanics and implications for regional tectonics

Although no Paleogene carbonatite volcanic complexes have been positively identified in the region, there is a well-documented record of Cambrian-Recent alkaline volcanism throughout the Rukwa Rift. In fact, within a radius of 2–5 km from the Nsungwe Formation type section, at least five different putatively Cretaceous-aged carbonatite complexes have been identified (Van Straaten, 1989). Not all have been dated and the Cretaceous-age associated for each carbonatite is based on the assumption that all carbonatites in the local area are penecontemporaneous, which now seems unlikely. Panda Hill is the best characterized carbonatite in the area, which has been dated by K/Ar dating (on phlogopite), yielding an age between 115 and 96 Ma (Snelling, 1965; Cahen and Snelling, 1984). Various workers have studied Panda Hill and identified pyroclastic facies indicative of explosive volcanic eruptions (Basu and Mayila, 1986). Perhaps renewed carbonatite volcanism during the late Oligocene was sourced in or around the same region as Panda Hill, but post-emplacement weathering and erosion denuded the landscape down to Cretaceous levels, removing any evidence of an Oligocene-aged vent or source. An angular unconformity marks the contact between the late Oligocene Nsungwe Formation and late Neogene volcanic units in the Songwe area (Ebinger et al., 1989) supporting the idea that considerable post-Oligocene erosion or non-deposition occurred prior to deposition of the later volcanics.

An alternative explanation is that an Oligocene alkaline volcanic center was located 10–50 km south of the field area, in a region largely or completely buried by ash and lava flows of the late Neogene Rungwe Volcanic province. Alkaline volcanic tuffs intercalated in the Nsungwe Formation may represent an earlier phase of volcanism associated with the Rungwe Volcanic province.

Regardless of the source of the late Oligocene (~25 Ma) airfall and ashflow volcanics, they represent one of the earliest records of volcanism in the Western Branch of the East African Rift System (see Ebinger et al., 1989). This provides critical new temporal and tectonic constraints on the timing of rift initiation in the Western Branch of the East African Rift System.

7. A Neogene age for the Red Sandstone Group?

Wescott et al. (1991) and Morley et al. (1999) argued that most, if not all, of the Red Sandstone Group was deposited during the late Neogene. Their argument is based primarily on the presence of a sparse microfossil assemblage, and an assumption that these beds

Table 7
Summary of SHRIMP U–Pb pyrochlore data for sample 72504-4.

Grain spot	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{206}Pb^*$ (ppm)	$^{206}Pb/^{238}U$ Age[a]		Total $^{238}U/^{206}Pb$	± (%)	Total $^{207}Pb/^{206}Pb$	± (%)	$^{206}Pb/^{238}U$[a]	± (%)
F-35.1	2.77	217	2119	10.10	0.74	25.0	0.4	250.21	1.6	0.0684	4.6	0.00389	1.7
F-36.1	72.97	1	17	18.33	0.01	29.4	14.2	59.21	11.0	0.6238	16.1	0.00457	48.5
F-37.1	21.89	17	161	10.03	0.07	24.6	1.3	204.18	4.0	0.2196	9.4	0.00383	5.3
F-38.1	34.80	11	5	0.48	0.05	23.6	1.7	177.66	4.5	0.3216	8.8	0.00367	7.2
F-41.1	51.80	6	147	24.31	0.04	22.0	2.7	141.00	5.2	0.4560	9.0	0.00342	12.1
V-9.1	0.67	521	10,746	21.32	1.77	25.2	0.3	253.45	1.2	0.0518	3.1	0.00392	1.2
V-9.2	6.27	50	106	2.19	0.17	23.8	0.6	253.07	2.4	0.0960	7.3	0.00370	2.6
V-10.1	54.78	11	689	65.43	0.07	22.4	2.8	130.20	3.7	0.4796	8.9	0.00347	12.7
V-12.1	54.73	5	1661	372.68	0.04	31.7	3.6	91.77	4.8	0.4796	7.6	0.00493	11.5
V-13.1	25.29	20	975	51.56	0.09	25.9	1.4	185.59	4.7	0.2466	6.6	0.00403	5.5
V-14.1	63.19	5	24	5.39	0.04	24.0	3.7	98.56	5.0	0.5462	7.6	0.00374	15.4

Errors are 1-sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively.
Error in Standard calibration was 0.38% (not included in above errors but required when comparing data from different mounts).
[a] Common Pb corrected by assuming $^{206}Pb/^{238}U–^{207}Pb/^{238}U$ age-concordance.

are associated with opening of the East African Rift System during the Miocene. These authors also cited references (e.g., Carter and Bennett, 1973; Crossley and Crow, 1980) that inaccurately identified the age of the putatively correlative Dinosaur Beds of Malawi as Tertiary or Quaternary. A wealth of paleontological research in the Dinosaur Beds during the 1980s and 1990s has provided strong evidence to support a middle Cretaceous age for these deposits (Colin and Jacobs, 1990; Jacobs et al., 1990, 1992, 1993, 1996; Gomani, 1997, 1999; Winkler et al., 2000).

Our work, involving sedimentology, geochronology, provenance analysis, vertebrate paleontology, invertebrate paleontology and palynology, has failed to identify evidence of a third phase of RSG deposition during the late Neogene in the study areas described herein. Kilembe and Rosendahl (1992) also examined sidewall cores from the same wells as Wescott et al. (1991), and were unable to document the presence of Neogene microfossils, but did identify Late Jurassic–Early Cretaceous palynomorphs. One explanation to account for the presence of the late Miocene–Holocene diatoms in well cuttings from the Ivuna-I and Galula-I wells is that they represent incidental contamination from the overlying Lake Beds sequence. Both wells were drilled in dusty, low elevation regions near lake level, where the Lake Beds silts are loosely exposed at the surface and contamination by wind-blown Lake Beds dust represents a plausible scenario. Furthermore, following the description provided by Damblon et al. (1998) for the location of the fossil wood specimen—*Pahudioxlyon*, our group endeavored to find the sample locality. Our best efforts placed us within a sequence of red colored pebble- to cobble-conglomerates dissimilar to any of the facies documented in either the Galula Formation or the Songwe Member of the Nsungwe Formation. We interpret two possible scenarios for this sequence. First, it may represent a hitherto undescribed sequence of younger alluvial deposits (perhaps part of the Lake Beds sequence?). Alternatively, these deposits are generally similar to the debris flow alluvial fan facies of the Utengule Member of the Nsungwe Formation. We consider this second hypothesis a likely possibility, considering that *Pahudioxylon* has a stratigraphic range into the Paleogene. Moreover, Damblon et al. (1998) postulated as much, indicating that the RSG may be Paleogene as opposed to Neogene, although they still favored a late Neogene age based on better correlation with the microfloral evidence of Wescott et al. (1991). This interpretation is consistent with our faunal data from the Songwe Member, and with apatite-fission track data by Van der Beek (1998) that indicate a period of rapid denudation and subsequent sedimentation during the early to mid Paleogene. Although a Neogene-aged depositional sequence associated with the top the RSG is still possible, work conducted to date has not found data supporting this interpretation.

8. Conclusions

A synthesis of sedimentological, paleontological and geochronological data collected over eight field seasons in the RSG in the Rukwa Rift Basin provides critical new insight into regional stratigraphy, depositional environments, paleoclimate and tectonics. Controversial age assessments for these deposits have variably ranged between the Middle Jurassic and Late Miocene. The seemingly incompatible assignments of both Cretaceous and late Tertiary ages purported by various workers (e.g., Wescott et al., 1991; Kilembe and Rosendahl, 1992) for the RSG is clarified, and two new formations are established. A middle Cretaceous age (Aptian–Cenomanian) and a late Paleogene (Oligocene) age are assigned to the Galula and Nsungwe Formations, respectively, based on paleontological, geochronologic, and sedimentological data, and cross-cutting relationships.

The Galula Formation represents deposition by large, long-lived braided fluvial systems that drained the highlands of Mozambique, Malawi and Zambia. These deposits represent a northwestward-flowing fluvial system that traversed the continent for over 1000 km through the Rukwa Rift, across the present location of Lake Tanganyika, and ultimately, through the Luama Rift, and into the Congo basin. During this time, the Rukwa Rift Basin was characterized by large, variable discharge (torrential) rivers occupying wide braidplains along the western margin of the rift. Although subsidence was limited throughout the depositional history of the Galula Formation, generation of accommodation space appears to have decreased during deposition of the Namba Member, while climate ameliorated, with a tropical sub-humid climate replacing the drier, semi-arid climate of the Mtuka Member. Reactivation of the Rukwa Rift occurred during the late Paleogene, likely concurrent with emplacement of a large mantle plume (the African Superplume) under the Afar region, and initiation of the East African Rift System to the north. Intercalated carbonatite volcanics in the Nsungwe Formation provide evidence of Paleogene volcanism in the Western Branch of the East African Rift System. Following initial deposition of the alluvial fan-dominated Utengule Member, an interior drainage basin apparently developed in the Rukwa Rift leading to wetland development and abundant preservation of aquatic and terrestrial vertebrates and invertebrates in the overlying Songwe Member.

Because of Africa's central location on the Gondwanan landmass, strata and faunas from Cretaceous and Paleogene sedimentary basins are critical for understanding the sequence and timing of events that led to the separation of the southern continents. Furthermore, these deposits provide an important window for reconstructing mid-Cretaceous and Paleogene environments and climate changes in sub-equatorial Africa.

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