

Micropalaeontology and geochemistry of outcropping Paleogene and Neogene marine sediments of southern Tanzania

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ABSTRACT

The Paleogene and Neogene marine sediments of southern Tanzania are well known for their excellent fossil preservation and contain an unrivalled record of tropical palaeoclimate and biotic evolution. Previous research and scientific drilling have spanned much of the available record, from the Albian to lower Oligocene, but the upper Eocene to Miocene succession has not so far been recovered in its entirety and provides a promising target for future research. Here we report on a series of over fifty outcrop samples of these ages from a variety of areas in the Kilwa and Lindi districts that were collected by us over several field excursions from 1998 to 2018. We provide a variety of chronostratigraphic age constraints including from nannofossils, planktonic foraminifera, larger benthic foraminifera, and strontium isotopes. Organic geochemistry shows exceptional preservation of biomarkers. Microfossil preservation in the claystones is highly variable because of surface weathering and oxidation, often producing gypsum and siderite. Despite this, seven samples were found to have excellent preservation and were studied in greater detail. Collectively, the samples provide useful information for geological mapping and deciding future drilling targets.

1. Introduction

The Tanzania passive margin developed after the rifting of Madagascar and East Africa in the Jurassic. Subsidence of the margin adjacent to the weathering granitic craton initiated a long interval of marine sedimentation on a clay-dominated continental slope and adjacent narrow shelf that lasted from the Late Cretaceous to Neogene (Kent et al., 1971; Nicholas et al., 2007; Franke et al., 2015). Compressional tectonics and structural inversion since the Miocene, associated with the East African Rift System, uplifted and emplaced large areas of these marine sediments onshore in southern Tanzania (Nicholas et al., 2007). The Upper Cretaceous and Paleogene sediments are mostly mudstones with accessory sandstone and limestones. These were first described by Bornhardt (1900), followed by notable stratigraphic and palaeontological studies by Blow and Banner (1962), Ramsay (1962), Moore

et al. (1963), Kent et al. (1971), Blow (1979), Gierlowski-Kordesch and Ernst (1987), Ernst and Zander (1993), and Mpanda (1997). The succession was formally divided into formations and described as the Kilwa Group by Nicholas et al. (2006).

Despite wide geographic spread along ~120 km of strike, surface outcrop exposures of the Kilwa Group are generally poor because of the soft lithology, dense vegetation and deep weathering. For this reason, it was targeted in a series of scientific drill cores in the Tanzania Drilling Project (TDP) in which 40 shallow boreholes of up to ~150m was drilled between 2002 and 2009 (Pearson et al., 2004, 2006; Nicholas et al., 2006; Berrocso et al., 2010, 2012, 2015). The Kilwa Group claystones have attracted considerable attention because of their frequently exquisite preservation of carbonate microfossils (Pearson et al., 2001, 2015; Sexton et al., 2006; Bown et al., 2008; Dunkley Jones et al., 2008a; Wendler and Bown, 2013; Haynes et al., 2017; Proctor et al., 2024).

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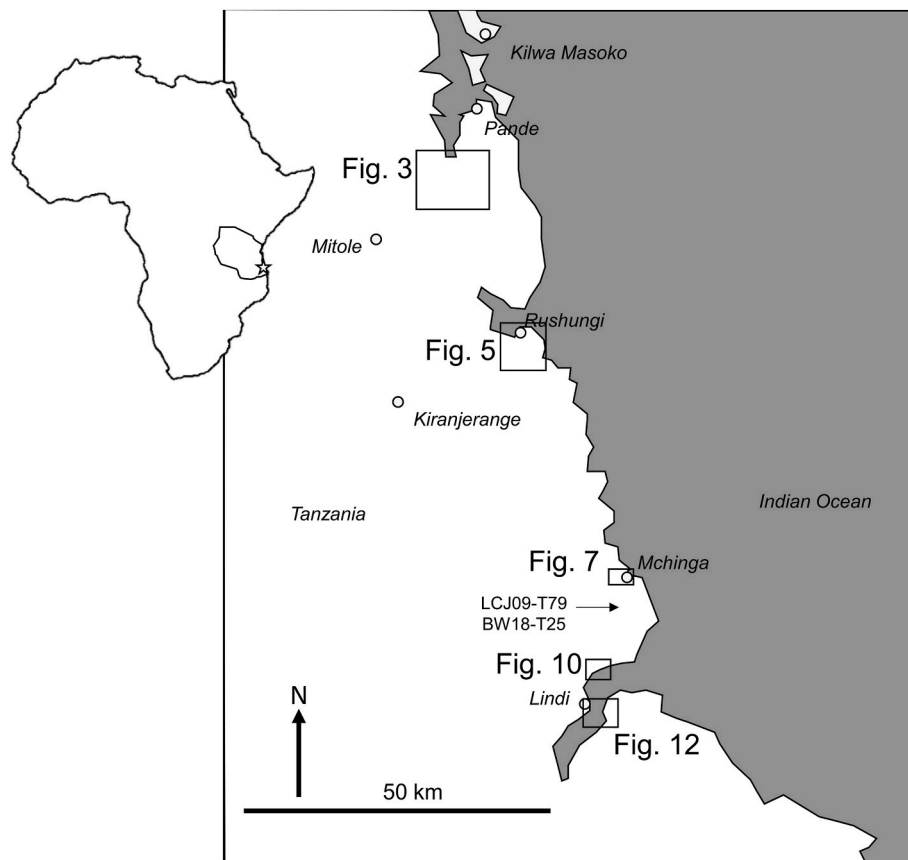


Fig. 1. Sketch map of southern coastal Tanzania showing the areas highlighted by local maps shown in Figs. 3, 5, 7, 10, and 12, and the position of Samples LCJ09-T79 and BW18-T25 from Likong'o village between Mchinga and Lindi.

Organic biomarkers are very well-preserved, indicating shallow maximum burial depths (Van Dongen et al., 2006; Pearson et al., 2007; Handley et al., 2008, 2012; Inglis et al., 2015). This preservation makes them attractive for micropalaeontological studies, including taxonomy, biodiversity and evolution. The nannofossils in particular have received much attention because of the very high level of biodiversity and exquisite preservation of ultrafine detail, including holococcoliths which rarely fossilize, and many new taxa have been named (Bown, 2005, 2016; Bown and Dunkley Jones, 2006; Lees, 2007; Bown et al., 2007, 2009, 2017; Dunkley Jones et al., 2008b; Bown and Pearson, 2009; Lees and Bown, 2016). Planktonic foraminifera have also been studied in detail, with new species described and evolutionary relationships documented (Olsson et al., 2006; Premoli Silva et al., 2006; Coxall and Pearson, 2006; Berggren et al., 2006; Wade and Pearson, 2008; Falzoni et al., 2013; Wendler et al., 2013a; Pearson and Coxall, 2014; Pearson and Wade, 2015, 2015b; Wade et al., 2018a, b; Huber et al., 2025). Other groups that have received detailed attention are the smaller benthic foraminifera (Wendler et al., 2011), larger benthic foraminifera (LBFs) (Cotton and Pearson, 2011, 2012; Cotton et al., 2016; Koorapati et al., 2025), calcitarchs (Wendler et al., 2013b), pteropods (Cotton et al., 2017), dinoflagellates (Emanuel et al., 2017), bryozoans (Di Martino et al., 2017), otoliths (Schwarzahns and Cotton, 2025) and angiosperm pollen (Warney et al., 2019). The excellent preservation also makes the sediments ideal for geochemical analysis of carbonates (e.g., Pearson et al., 2001, 2007; Wade and Pearson, 2008; Evans et al., 2018, 2026; Boscolo-Galazzo et al., 2021; Staudigel et al., 2022; Crichton et al., 2023; John et al., 2023; Cotton et al., 2025). Because of these circumstances, the Kilwa Group has proved a valuable resource for tracing the long-term climate history of the tropics including palaeotemperature (Pearson et al., 2001, 2007, 2008; Stewart et al., 2004; Lear et al., 2008; MacLeod et al., 2013; Aze et al., 2014;

Ando et al., 2015; Inglis et al., 2015; Petrizzo et al., 2017), carbon cycling (John et al., 2013, 2014; Boscolo-Galazzo et al., 2021) and atmospheric CO₂ (Pearson et al., 2009; Anagnostou et al., 2016, 2020).

The geologically youngest of the TDP drill sites spans the Eocene–Oligocene transition (TDP Sites 11, 12 and 17) and include lowermost Oligocene sediments assigned to planktonic foraminifer Zone O1 and nannofossil Zone NP21 (Nicholas et al., 2006; Pearson et al., 2008). The top of the Kilwa Group is not exposed, and the succession apparently continues upward, albeit covered with Quaternary sands and gravels in the area these sites were drilled on the Pande peninsula (Nicholas et al., 2006). Lower and middle Miocene sediments are known further south in the Lindi area (e.g., Blow and Banner, 1962; Stewart et al., 2004; Nicholas et al., 2006), but their relation to the underlying Oligocene and the intervening stratigraphy are poorly known.

We conducted field expeditions in 2009 and 2018 to investigate areas of Oligocene and Miocene outcrop as a preliminary survey for possible future drilling (Pearson and Hudson, 2014) and to obtain additional samples for geochemical analysis where possible. Our focus was primarily on Oligocene and Miocene sediments, but we also report here on a few Eocene localities and samples collected from the same areas in earlier field exploration in 1998. The sample set treated here comprises over 50 surface samples which range in age from middle Eocene to middle Miocene. They have variously been studied for their micropalaeontology (planktonic and benthic foraminifera and calcareous nannofossils), strontium isotopes, and organic geochemistry. Here we report the results of these investigations and identify a subset of samples with excellent preservation suitable for further geochemical analysis. We assess the future potential of shallow drilling to obtain more material that will clarify the relationship between the Miocene and Paleogene formations and enable the Tanzania palaeontological and palaeoclimate record to be extended upward. A sketch map of the area



Fig. 2. Field sampling. (a) Auguring a coastal exposure of weathered middle Miocene clays at Ras Tipuli (Sample BW18-T22). (b) Roadside gully with poor exposure of lower Oligocene clays near Rushungi. (c) Auguring weathered upper Oligocene clay amid vegetation at Kitunda Slope north (Sample BW18-T29). (d) Comparatively fresh clay sample of upper Eocene claystone from the wave-cut platform at Kitunda shore (Sample BW18-T56).

covered with key to more detailed sketch maps is provided in Fig. 1.

2. Methods

2.1. Fieldwork

The study area is best traversed in the dry season using four-wheel drive vehicles. The Kilwa Group claystones are monotonous in appearance and can only be distinguished in the field using secondary lithologies such as turbidites, and with micropalaeontology. Sample splits were routinely washed and studied at the field camp for their foraminiferal assemblages to guide ongoing exploration, supplemented by an examination of publicly available satellite imagery for additional likely exposures in stream beds, roadside cuts and ditches, and along coastal sections. When in situ sediments were found, we exposed fresh material by digging and cleaning the exposure, using a hand-held auger when possible.

While some of the samples are relatively fresh, most notably in areas of coastal erosion, they are all weathered to some extent, and many of them are strongly desiccated, and oxidized (Fig. 2). The nature of the sampling means that the possibility of contamination by modern microbial and plant material must be considered, as discussed further below. Sediment samples, mostly silty clays, were divided for micropalaeontology and organic geochemistry analyses. The micropalaeontological samples were subdivided for foraminifer and nannofossil study.

2.2. Organic geochemistry

In total, 33 sediment samples were processed for lipid biomarker analysis at the University of Southampton. Sediments were freeze-dried, crushed, and homogenized using a mortar and pestle. Lipids were extracted from approximately 25 g of powdered sediment using an accelerated solvent extractor (Thermo ASE 350) with DCM:MeOH (9:1, v/v) at 100 °C for three 15 min extraction cycles at 1500 psi. The total lipid extract (TLE) was dried under a gentle stream of nitrogen (N_2). The TLE was subsequently separated into neutral, fatty acid, and TLE-rest fractions by LC-NH₂ column chromatography using 4 mL DCM:isopropanol (2:1, v/v), 4 mL DCM:acetic acid (96:4, v/v), and 4 mL MeOH, respectively. The neutral fraction was then dried and separated into apolar, ketone, and polar fractions by silica column chromatography using 4 mL hexane:DCM (9:1, v/v), 4 mL hexane:DCM (1:1, v/v), and 4 mL DCM:MeOH (1:1, v/v), respectively. Each fraction was collected, dried under N_2 , and stored at −20 °C until analysis.

The apolar fraction, containing hopanes and hopenes, was analysed using a Thermo Fisher Scientific TRACE 1310 gas chromatograph coupled to a Thermo TSQ8000 triple quadrupole mass spectrometer (GC-MS/MS). Compounds were separated on an Agilent DB-5 column (30 m × 0.25 mm internal diameter, 0.25 μm film thickness) using helium as the carrier gas. The GC oven temperature started at 40 °C for 2 min, increased to 310 °C at 6 °C min^{−1}, and was held at 310 °C for a further 15 min. MS data were acquired in full-scan mode over a mass-to-charge (m/z) range of 50–650 Da. An in-house standard was measured after every 10 samples to monitor long-term instrument stability. Hopanes and hopenes were identified by comparison of their mass

spectra, characteristic fragment ions, and retention times with published data (Ingliš et al., 2025) and references therein). Peak areas were integrated from the extracted ion chromatogram at m/z 191 (Ingliš et al., 2025). A table of data is available as Supplementary Information 1.

2.3. Nannofossils

Calcareous nannofossils were analysed using smear slides and standard light microscope techniques (Bown and Young, 1998). Stratigraphic distribution data was collected semi-quantitatively using an Olympus photomicroscope at $\times 1,000$ magnification (Table 1 – stratigraphic distribution of age diagnostic taxa). Species abundances were estimated per field of view (FOV) after looking at least three slide transects (hundreds of fields of view). The relative abundance of each species was recorded according to the following parameters: R = Rare (<1 per 10 FOV – fields of view), F = Few (1 per 10 FOV), C = Common (1 per FOV), A = Abundant (>10 per FOV). Taxonomy follows *Nannotax* (<http://www.mikrotax.org/Nannotax3>) and previously published Tanzania nannofossil work, e.g., Bown (2005, 2010, 2016), Bown and Dunkley Jones (2006) and Dunkley Jones et al. (2008a). Nannofossil biostratigraphy is described with reference to the Paleogene NP zones of Martini (1971) and CN zones of Agnini et al. (2014), and the Neogene NN zones of Martini (1971) and CN zones of Backman et al. (2012).

2.4. Planktonic foraminifera

Sample splits of ~ 50 cc were soaked in water and mechanically disaggregated by gently massaging the sediment by hand, then washed over a $63\ \mu\text{m}$ sieve. Residues were oven dried at 40°C , photographed under the Light Microscope, then assessed for foraminifer abundance and preservation. Planktonic foraminifera were identified using the Eocene and Oligocene taxonomic atlases (Pearson et al., 2006; Wade et al., 2018a,b,c) and other relevant literature (Blow and Banner, 1962; Pearson and Wade, 2015). The biozonation follows Wade et al. (2011) adjusted to the timescales of Speijer et al. (2020) and Raffi et al. (2020). A full report on planktonic foraminifer assemblages is available as Supplementary Information 2.

2.5. Benthic foraminifera

Selected clay samples were processed for benthic foraminiferal analyses. Around one gram of samples was processed by water sieving ($>63\ \mu\text{m}$) for quantitative assemblage analyses. The dried residues were split with a micro-splitter into aliquots of 300 to 500 foraminifera in order to estimate the foraminiferal yield per gram. The number of planktonic foraminifera and all smaller and larger species of benthic foraminifera were identified (Holbourn et al., 2013; Cotton and Pearson, 2012) and counted in this fraction. Benthic foraminiferal assemblages and the percentage of planktonic foraminifera were used to estimate relative oxygenation and palaeodepth (van der Zwaan et al., 1990; van Hinsbergen et al., 2005). In addition to clay samples, selected limestones and sandstones were prepared as petrological thin sections and LBFs were identified to genus level. Some thin sections were stained with Alazarin red and potassium ferrocyanite to check for the presence of dolomite. A small number of oriented sections were made. LBF ages are based on Serra Kiel et al. (1998), Cahuzac and Poignant (1997), BouDagher-Fadel (2018), and Lunt and Luan (2022).

2.6. Strontium isotopes

Foraminifera from selected samples were picked and processed following the methods of McArthur et al. (2025) to obtain $^{87}\text{Sr}/^{86}\text{Sr}$ ages. 50–80 specimens of benthic, epifaunal foraminifera (*Cibicides* spp. and *Lenticulina* spp.) and infaunal taxa were picked and 14 samples analysed. Specimens were cleaned by sonicating in a solution of 50% deionized water and 50% methanol for 3 min, before being crushed

under a clean glass slide. Crushed specimens were then sonicated for 3-min rounds in alternating solutions of deionized water and deionized water-methanol, with the supernatant being pipetted out after each round of sonication to remove any suspended particles.

All samples were ground to a fine powder using an agate mortar and pestle. The powdered sample was then leached in 2 mL of 0.5M acetic acid and dried on a hotplate for 1 h and converted to chloride form. Samples were then redissolved in 6M HCl at 140°C over 12 h, then taken to dryness on hotplate at 140°C . Strontium separation was performed using ion chromatography by redissolving in 8M nitric acid with Sr extraction using 50–100 μm Eichrom Sr resin in 3 mL Biocomma columns, following the modified method of Krabbenhöft et al. (2009). Isotopic analysis used 100×5 s multidynamic Sr measurements carried out on an Isotopx Phoenix Thermal Ionization Mass Spectrometer (TIMS) at the University of Adelaide. Data were corrected for instrumental mass-dependent fractionation of $^{86}\text{Sr}/^{88}\text{Sr}$ of 0.1194 using an exponential mass fractionation correction. SRM987 reference material was analysed before and after analyses of the unknowns, and, to maximise precision, 20 blocks each of 10, 16s scans were collected for each sample (Supplementary Information 3).

3. Chronostratigraphic determinations

Samples were mostly treated independently, without consideration of their relative stratigraphic positions, except for instances where a clear stratigraphic relationship between samples can be established. Ages are quoted on the timescale of Gradstein et al. (2020). Sub-series (such as ‘upper Miocene’, ‘lower Oligocene’) are considered informal to avoid switching between formal and informal units because only some have been formalised. Study of the nannofossils and planktonic foraminifera usually permitted samples to be assigned to a biozone, that is, an interval between defined bioevents. In some instances, this could be refined further using secondary marker events. For the Neogene, tables of ages for these bioevents are provided by Raffi et al. (2020). For the Paleogene, ages of bioevents were inferred from the biozone boundaries depicted on the chronostratigraphic charts of Speijer et al. (2020). Strontium isotope ratios were converted to ages with errors based on the calibration of McArthur et al. (2025). Sources of uncertainty in the derived age include: (i) the error on the global $^{87}\text{Sr}/^{86}\text{Sr}$ seawater curve using the upper and lower limits as reported by McArthur et al. (2025); (ii) the error in the measurement of the $^{87}\text{Sr}/^{86}\text{Sr}$ of the reference material; and (iii) the error on the measurement of the $^{87}\text{Sr}/^{86}\text{Sr}$ of the unknown samples (Supplementary Table 2). Root sum of squares of sources of uncertainty used for error propagation. For LBFs, as it is uncertain whether Tanzania is encompassed more by the Shallow Benthic Zonation of the Tethys or Letter Classification of the Indo West Pacific, we give a maximum age range across both schemes.

The foraminifer, nannofossil and strontium ages estimates were compared and combined to refine age estimates where possible. Discrepancies were considered and resolved either by preferring one or other age constraint as appropriate, or broadening the estimated age range to encompass all constraints, as is discussed below on a case-by-case basis. Data are synthesized in Table 1 and discussed by area below.

3.1. The Pande area

The Pande peninsula is an area of previous mapping and drilling. The lowermost Oligocene occurs at the surface near the location of TDP Site 12 in which the Eocene/Oligocene boundary is at a depth of 44.28 m (Nicholas et al., 2006). The Oligocene sediments are mostly covered by much younger (probably Quaternary) sands and gravels. We searched for additional localities of possible Oligocene outcrop at the northern and southern ends of the peninsula, and along the eastern coast, but without success. A sketch map of the inner part of the Pande peninsula is shown in Fig. 3.

Two clay samples were collected from the slope below TDP Site 12.

Table 1
Synthesis of biostratigraphic and chemostratigraphic age constraints ordered by region.

Sample	Type	Longitude (WGS84, 37L)	Latitude (WGS84, 37L)	Nannofossil biozone	Nannofossil age estimate (Ma)	Planktonic foraminifer Biozone	Planktonic foraminifer age estimate (Ma)	Larger Benthic Foraminifer Stage	Larger Benthic Foraminifer age (Ma)	Sr isotope age estimate (Cibicidoides) (Ma)	Sr isotope age estimate (Lenticulina) (Ma)	Sr isotope age estimate (elongate taxa) (Ma)	Combined best age range estimate (Ma)	Age estimate (Ma)
<u>Pande area</u>														
BW18-T2	auger	560,118	8,981,304	NP21 (upper)	32.92–34.44	O1	32.1–33.9	n/a	n/a	n/a	n/a	n/a	32.1–33.9	33.00 ± 0.40
LJC09-K19	hammer	560,073	8,981,374	n/a	n/a	n/a	n/a	Priabonian	33.9–37.71	n/a	n/a	n/a	32.1–33.9	33.00 ± 0.40
LJC09-K18	hammer	560,034	8,981,434	n/a	n/a	n/a	n/a	Priabonian	33.9–37.71	n/a	n/a	n/a	33.9–34.6	34.25 ± 0.35
BW18-T1	auger	559,950	8,981,308	NP21 (lower)	32.92–34.44	E16	33.9–34.6	n/a	n/a	n/a	n/a	n/a	33.9–34.6	34.25 ± 0.35
LJC09-K16	hammer	558,697	8,976,038	n/a	n/a	n/a	n/a	Bartonian/ Lutetian	37.71–48.07	n/a	n/a	n/a	37.71–48.07	42.89 ± 5.18
BW18-T12	hammer	558,562	8,975,718	NP16	38.7–43.7	E11	40.3–41.8	n/a	n/a	n/a	n/a	n/a	40.3–41.8	41.05 ± 0.75
BW18-T13	hammer	557,883	8,975,597	? Middle Eocene with reworking	n/a	E11	40.3–41.8	n/a	n/a	n/a	n/a	n/a	40.3–41.8	41.05 ± 0.75
<u>Rushungi Road</u>														
BW18-T10	auger	566,022	8,953,485	NP23 (upper)	26.93–30.0	O3	29.2–30.3	n/a	n/a	n/a	n/a	n/a	29.2–29.5	29.35 ± 0.15
LJC09-T145	hammer	566,018	8,953,487	n/a	n/a	n/a	n/a	Eocene/ Oligocene	23.04–48.07	n/a	n/a	n/a	29.2–29.5	29.35 ± 0.15
BW18-T7	auger	566,017	8,953,484	NP23 (upper)	26.93–30.0	O3	29.2–30.3	n/a	n/a	28.2–29.9	29.5–32.1	n/a	29.2–29.5	29.35 ± 0.15
LJC09-T144	hammer	566,017	8,953,484	n/a	n/a	O3	29.2–30.3	n/a	n/a	n/a	n/a	n/a	29.2–29.5	29.35 ± 0.15
LJC09-T143	hammer	566,013	8,953,481	n/a	n/a	n/a	n/a	Eocene/ Oligocene	23.04–48.07	n/a	n/a	n/a	30.0–30.3	30.15 ± 0.15
BW18-T9	hammer	566,010	8,953,473	NP23 (lower)	30.0–32.2	n/a	n/a	Eocene/ Oligocene	23.04–48.07	n/a	n/a	n/a	30.0–30.3	30.15 ± 0.15
BW18-T8	auger	565,942	8,953,372	NP23 (lower)	30.0–32.2	O3	29.2–30.3	n/a	n/a	n/a	n/a	n/a	30.0–30.3	30.15 ± 0.15
<u>Rushungi approach</u>														
BW18-T19	hammer	566,658	8,956,051	NP23 (lower)	30.0–32.2	O2	30.3–32.1	n/a	n/a	n/a	n/a	n/a	30.0–32.1	31.05 ± 1.05
BW18-T18	hammer	566,863	8,956,222	NP23 (lower)	30.0–32.2	O2	30.3–32.1	n/a	n/a	30.4–31.6	31.0–31.9	n/a	31.0–31.6	31.30 ± 0.30
<u>Mchinga turn</u>														
LJC09-T81	hammer	579,662	8,922,248	NN4-5/ CNM7	14.86–15.85	M6	14.06–14.66	n/a	n/a	n/a	n/a	n/a	14.06–14.66	14.36 ± 0.30
BW18-T27	hammer	579,675	8,922,227	NN4-5/ CNM7	14.86–15.85	M6	14.66–15.12	n/a	n/a	14.7–15.5	14.2–15.2	n/a	14.66–15.12	14.89 ± 0.23
BW18-T26	hammer	579,670	8,922,308	NN4-5/ CNM7	14.86–15.85	M5b	15.12–16.26	n/a	n/a	15.1–15.7	15.2–15.7	15.1–15.7	15.20–15.70	15.45 ± 0.25
<u>Mchinga school</u>														
LJC09-T84	hammer	578,185	8,924,712	n/a	n/a	n/a	n/a	Upper Oligocene to middle Miocene	11.63–27.29	n/a	n/a	n/a	15.12–16.26	15.69 ± 0.57
LJC09-T83	hammer	578,185	8,924,712	n/a	n/a	n/a	n/a	Upper Oligocene to	11.63–27.29	n/a	n/a	n/a	15.12–16.26	15.69 ± 0.57

(continued on next page)

Table 1 (continued)

Sample	Type	Longitude (WGS84, 37L)	Latitude (WGS84, 37L)	Nannofossil biozone	Nannofossil age estimate (Ma)	Planktonic foraminifer Biozone	Planktonic foraminifer age estimate (Ma)	Larger Benthic Foraminifer Stage	Larger Benthic Foraminifer age (Ma)	Sr isotope age estimate (Cibicidoides) (Ma)	Sr isotope age estimate (Lenticulina) (Ma)	Sr isotope age estimate (elongate taxa) (Ma)	Combined best age range estimate (Ma)	Age estimate (Ma)
LJC09- T85	hammer	578,185	8,924,712	n/a	n/a	M5b	15.12–16.26	middle Miocene n/a	n/a	n/a	n/a	n/a	15.12–16.26	15.69 ± 0.57
<u>Mbuyuni quarry</u>														
LJC09- T100; -T101; -T165	hammer	574,048	8,923,537	n/a	n/a	n/a	n/a	Upper Oligocene to Lower Miocene (Aquitainian)	20.45–27.29	n/a	n/a	n/a	11.63–27.29	19.46 ± 7.83
<u>Likong'o</u>														
LCJ09- T79	hammer	580,261	8,914,225	n/a	n/a	n/a	n/a	Upper Oligocene to middle Miocene	11.63–27.29	n/a	n/a	n/a	11.63–27.29	19.46 ± 7.83
BW18- T25	auger	580,121	8,914,854	CNM7	13.6–15.85	Miocene	15.0–24.0	n/a	n/a	n/a	n/a	n/a	13.6–15.85	14.72 ± 1.13
<u>Ras Tipuli</u>														
BW18- T24	auger	579,368	8,900,251	NN6-7	10.89–13.60	M12?	9.89–10.54	n/a	n/a	n/a	n/a	n/a	10.89–13.6	12.24 ± 1.35
180,906/ 1	hammer	579,310	8,900,170	n/a	n/a	M11-M12	10.54–11.67	n/a	n/a	n/a	n/a	n/a	10.54–11.67	11.10 ± 0.13
BW18- T23	auger	579,293	8,900,135	NN6-7	10.89–13.60	M10-M11	10.54–11.93	n/a	n/a	n/a	n/a	n/a	10.54–11.93	12.24 ± 0.70
BW18- T22	auger	579,222	8,900,061	NN6-7	10.89–13.60	M11 (lowermost)	11.57–11.67	n/a	n/a	11.9–14.1	11.7–14.1	n/a	11.57–11.90	11.74 ± 0.16
BW18- T21	auger	579,193	8,900,015	NN6-7	10.89–13.60	M11 (lowermost)	11.57–11.67	n/a	n/a	n/a	n/a	n/a	11.57–11.67	11.74 ± 0.16
BW18- T20	auger	579,180	8,899,990	NN6-7	10.89–13.60	M11 (lowermost)	11.57–11.67	n/a	n/a	n/a	n/a	n/a	11.57–11.67	11.74 ± 0.16
LJC09- T69	hammer	578,734	8,899,948	n/a	n/a	M10	11.67–11.93	n/a	n/a	n/a	n/a	n/a	11.67–11.93	11.80 ± 0.13
RAS99- 38	hammer	578,746	8,899,949	n/a	n/a	M9	13.13–13.40	n/a	n/a	n/a	n/a	n/a	13.13–13.40	13.26 ± 0.14
RAS99- 42	hammer	568,616	8,899,929	n/a	n/a	M2 (lower)	20.99–21.12	n/a	n/a	n/a	n/a	n/a	20.99–21.12	21.05 ± 0.07
<u>Ras Mongo</u>														
BW18- T59	auger	580,545	8,900,570	NN6/CNM8	12.57–13.60	M12	9.89–10.54	n/a	n/a	n/a	n/a	n/a	9.89–13.60	11.75 ± 1.86
BW18- T58	auger	580,398	8,900,581	NN6-7	10.89–13.60	M12	9.89–10.54	n/a	n/a	n/a	n/a	n/a	9.89–13.60	11.75 ± 1.86
LJC09- T71	hammer	580,276	8,900,635	NN6-7	10.89–13.60	M10-M11	10.54–11.93	n/a	n/a	n/a	n/a	n/a	10.89–11.93	11.41 ± 0.52
BW18- T57	auger	580,254	8,900,647	NN6-7	10.89–13.60	M10-M11	10.54–11.93	n/a	n/a	n/a	n/a	n/a	10.89–11.93	11.41 ± 0.52
<u>Kitunda shore</u>														
BW18- T55	hammer	579,759	8,894,821	NP20/ CNE19	35.24–36.13	E14	35.8–38.0	n/a	n/a	n/a	n/a	n/a	35.8–36.13	35.96 ± 0.17
BW18- T56	hammer	579,755	8,894,790	NP19/20/ CNE19	35.24–36.13	E14	35.8–38.0	n/a	n/a	31.5–32.4	n/a	n/a	35.8–36.13	35.96 ± 0.17
<u>Kitunda slope north</u>														

(continued on next page)

Table 1 (continued)

Sample	Type	Longitude (WGS84, 37L)	Latitude (WGS84, 37L)	Nannofossil biozone	Nannofossil age estimate (Ma)	Planktonic foraminifer Biozone	Planktonic foraminifer age estimate (Ma)	Larger Benthic Foraminifer Stage	Larger Benthic Foraminifer age (Ma)	Sr isotope age estimate (Cibicoides) (Ma)	Sr isotope age estimate (Lenticulina) (Ma)	Sr isotope age estimate (elongate taxa) (Ma)	Combined best age range estimate (Ma)	Age estimate (Ma)
BW18-T28	auger	580,204	8,893,838	NP24	26.81–27.17	O3	29.2–30.3	n/a	n/a	n/a	n/a	n/a	26.81–27.17	26.99 ± 0.18
BW18-T29	auger	580,179	8,893,835	NP24	26.81–27.17	O3	29.2–30.3	n/a	n/a	n/a	n/a	n/a	26.81–27.17	26.99 ± 0.18
BW18-T50	auger	580,165	8,893,783	NP24	26.81–27.17	O3	29.2–30.3	n/a	n/a	n/a	n/a	n/a	26.81–27.17	26.99 ± 0.18
BW18-T30	auger	580,156	8,893,836	NP23 (lower)	30.00–32.02	O1	32.1–33.9	n/a	n/a	n/a	n/a	n/a	32.1–33.9	33.0 ± 0.90
BW18-T31	auger	580,141	8,893,839	NP23 (lower)	30.00–32.02	O1	32.1–33.9	n/a	n/a	n/a	n/a	n/a	32.1–33.9	33.0 ± 0.90
BW18-T32	auger	580,106	8,893,811	NP23 (lower)	30.00–32.02	O1	32.1–33.9	n/a	n/a	n/a	n/a	n/a	32.1–33.9	33.0 ± 0.90
BW18-T33	auger	580,087	8,893,827	NP23 (lower)	30.00–32.02	O1	32.1–33.9	n/a	n/a	n/a	n/a	n/a	32.1–33.9	33.0 ± 0.90
BW18-T34	auger	580,071	8,893,789	NP23 (lower)	30.00–32.02	O1	32.1–33.9	n/a	n/a	n/a	n/a	n/a	32.1–33.9	33.0 ± 0.90
<u>Kitunda slope south</u>														
LJC09-T61	hammer	580,940	8,892,982	n/a	n/a	n/a	n/a	Upper Oligocene to Lower Miocene (Aquitainain)	20.45–27.29	n/a	n/a	n/a	11.63–27.29	19.46 ± 7.83
LJC09-T63	hammer	580,899	8,892,977	n/a	n/a	n/a	n/a	Upper Oligocene to Lower Miocene (Aquitainain)	20.45–27.29	n/a	n/a	n/a	11.63–27.29	19.46 ± 7.83
LJC09-T62	hammer	580,915	8,892,978	n/a	n/a	n/a	n/a	Upper Oligocene to Lower Miocene (Aquitainain)	20.45–27.29	n/a	n/a	n/a	11.63–27.29	19.46 ± 7.83
LJC09-T64	hammer	580,621	8,892,914	n/a	n/a	upper Oligocene	23.04–27.29	n/a	n/a	n/a	n/a	n/a	23.04–27.29	25.16 ± 2.13
BW18-T51	hammer	580,100	8,893,473	NP23 (lower)	30.00–32.02	O3	29.2–30.3	n/a	n/a	n/a	n/a	n/a	30.0–30.3	30.15 ± 0.15
BW18-T52	hammer	580,063	8,893,428	NP23 (lower)	30.00–32.02	O2	30.3–32.1	n/a	n/a	n/a	n/a	n/a	30.3–32.02	31.16 ± 0.86
BW18-T53	hammer	580,106	8,893,088	NP23 (lower)	30.00–32.02	O2 (?upper)	30.3–32.1	n/a	n/a	30.4–31.5	31.4–32.4	n/a	30.9–32.02	31.46 ± 0.56
BW18-T54	hammer	579,957	8,893,290	NP23 (lower)	30.00–32.02	O2	30.3–32.1	n/a	n/a	n/a	n/a	n/a	30.3–32.02	31.16 ± 0.86

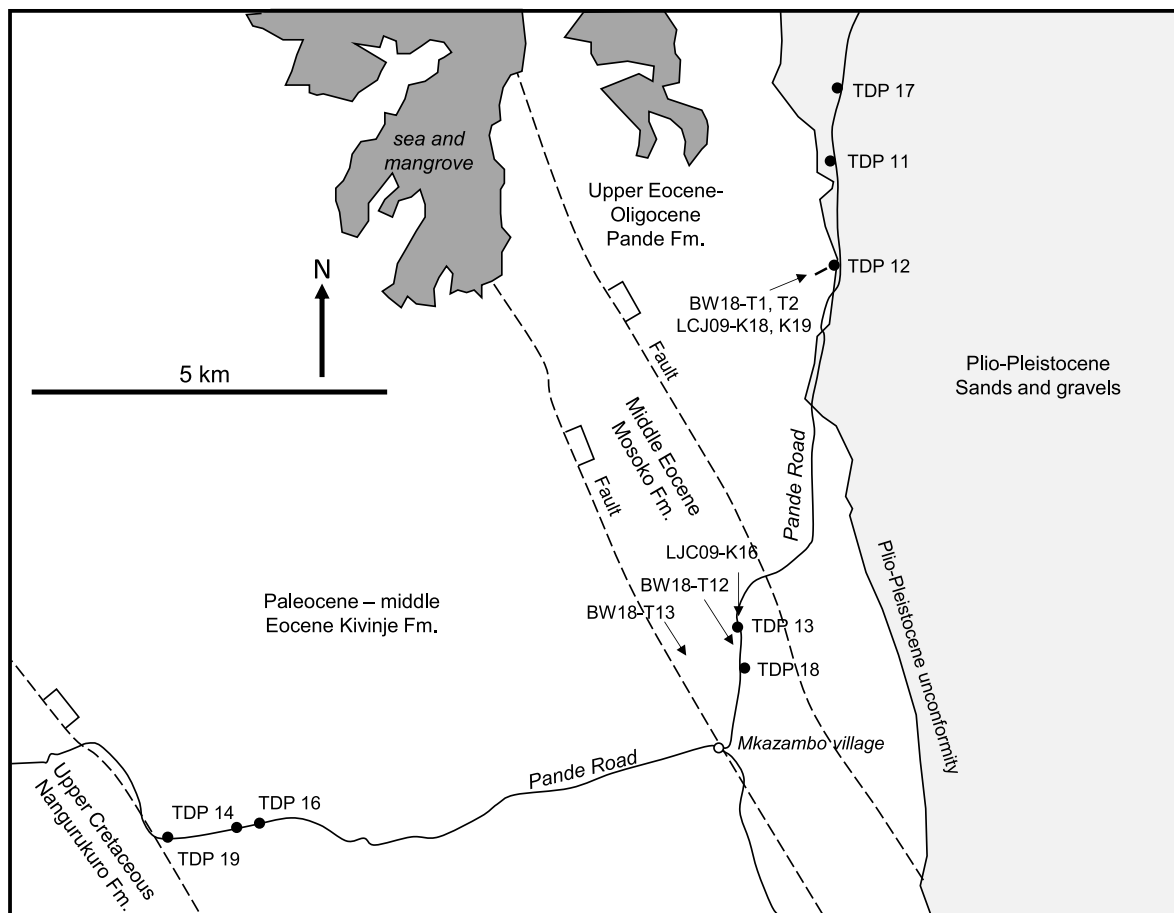


Fig. 3. Sketch map of the Pande Road area based on Nicholas et al. (2006) showing previous TDP drill sites and the locations of Samples BW18-T1–3, BW18-T12 and BW18-T13. Faults are shown as dashed lines with boxes on the down-thrown side.

Sample BW18-T1 is uppermost Eocene Biozone E16 (33.9–34.6 Ma), as confirmed by the presence of *Hantkenina alabamensis* and *Turborotalia cunialensis*. Sample BW18-T2 lacks *Hantkenina* and the *T. cerroazulensis* group and so is assigned to Oligocene planktonic foraminifer Biozone O1 (32.1–33.9 Ma). Thus, the Eocene/Oligocene boundary runs between these two samples. Nannofossil biostratigraphy is consistent with this, with Sample BW18-T1 assigned to lower nannofossil Biozone NP21 (with no heliodiscoasters but common *Umbilicosphaera protoannula*) and Samples BW18-T2 assigned to upper nannofossil Biozone NP21 (with no heliodiscoasters or *Umbilicosphaera protoannula*).

Two limestone samples were collected from the same slope area (Fig. 4). Sample LJC09-K18 is a debris flow limestone from close to the Eocene/Oligocene boundary position on the hillside, and contains reticulate *Nummulites*, *Discocyclus*, orthophragmines and *Spiroclipeus* along with *Pellatispira* c.f. *madarazi*. The presence of orthophragmines indicates it is Eocene, and *Pellatispira* c.f. *madarazi* indicates the Priabonian stage (Hottinger et al., 2001; Cotton and Pearson, 2012). Sample LJC09-K19 was taken further up the hillside and is a fine sandy carbonate containing fragments of LBF and flattened orthophragmines, also dating to before the Eocene/Oligocene boundary.

When visiting the Pande area in the vicinity of the previous TDP Site 13 and 18 coreholes north of the village of Mkazambo (Nicholas et al., 2006), we encountered a long linear clearing in the bush that had been made by a previous commercial seismic survey. Two claystone exposures were found along this which we sampled to help refine the regional geological map. Samples BW18-T12 and -T13 both yielded planktonic foraminifer assemblages indicating planktonic foraminifer Biozone E11 (40.3–41.8 Ma) and nannofossils indicating lower nannofossil Biozone NP16. Sample BW18-T12 appears the slightly younger of

the two, based on more ‘advanced’ forms of *Globigerinatheka*, *Morozovelloides*, and *Hantkenina*, as would be expected from the regional dip. Nicholas et al. (2006) inferred a fault running NW–SE through Mkazambo village, downthrown to the NE. These samples strengthen this interpretation, both being from the downthrown side of the fault. A limestone exposed along the road close to the sites of the TDP 13 corehole, Sample LJC09-K16, contains *Nummulites* belonging to the *N. perforates* group, alongside *Assilina* and orthophragmines, indicating a broadly middle Eocene (Lutetian or Bartonian) age.

3.2. Rushungi Road section

As described above, the Oligocene of the Pande peninsula is mostly covered by Plio-Pleistocene terrestrial clastic sediments and has well-drained reddish soils. Examination of satellite images along strike to the south indicates that this cover is patchier, revealing surface exposures of slightly younger sediments that continue above the hitherto known top of the Kilwa Group. We followed the dirt road towards the fishing village of Rushungi (also known on some maps as Kiswere) (Fig. 5). Along this route, a short section of ~55 m of stratigraphy is exposed continuously, albeit poorly (see Fig. 2b), in a roadside ditch on the northwest side, starting at UTM 37L 0565835/8953661.

The Rushungi road section is dominated by silty mudstones with frequent interbeds of very fine sandstone, ranging in thickness from a few cm to ~2 m, some of which contain larger benthic foraminifera. Four samples were taken from the road section, three of weathered claystone and one specimen of sandstone. In order from the bottom, these are Samples BW18-T8, -T9, -T7 (the sandstone), and -T10. The three mudstone samples all belong to planktonic foraminifer Biozone O3

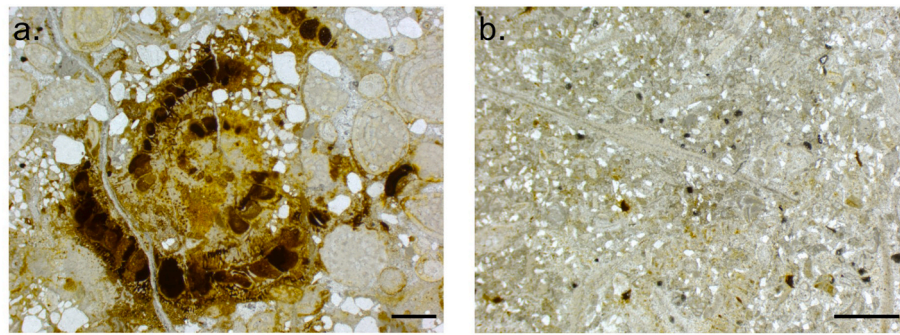


Fig. 4. Thin sections of samples from the Pande Road area showing Eocene Larger Benthic Foraminifera. (a) Sample LJC09-K18 showing *Pellatispira* c.f. *madarazi* with reticulate *Nummulites* and coarse quartz grains. (b) Sample LJC09-K19 showing flattened orthophragmines in finer sandy limestone matrix with foraminiferal fragments. Scale bars 1 mm.

(29.2–30.3 Ma), the interval above the extinction of *Turborotalia ampliapertura*, which is a common species elsewhere in the Tanzania succession so its absence can be relied upon. The nannofossils are from the relatively long-duration nannofossil Biozone NP23 (26.93–32.2 Ma). Notably, the upper two samples contain *Sphenolithus distentus* (which appeared at 30.0 Ma) and the samples can be assigned to upper Biozone NP23 (= Biozone CNO4), whereas the lower two samples lack this species, and the samples can be assigned to lower Biozone NP23 (= Biozone CNO3). The lower two samples, Samples BW18-T8 and -T9, are

dated to 30.0–30.3 based on the absence of both the foraminifer *T. ampliapertura* and the nannofossil *S. distentus*.

The buff-coloured sandstones and sandy limestones are all likely formed from sediment transported downslope, sometimes bringing with them shallow-water debris including mollusc and echinoid fragments and LBFs. They are relatively flaggy to massive and do not show obvious grading or other evidence of emplacement by turbidity currents. Two such beds from the upper part of this succession were sampled in 2009, Samples LJC09-T143 and -T145, which were either side of a mudstone

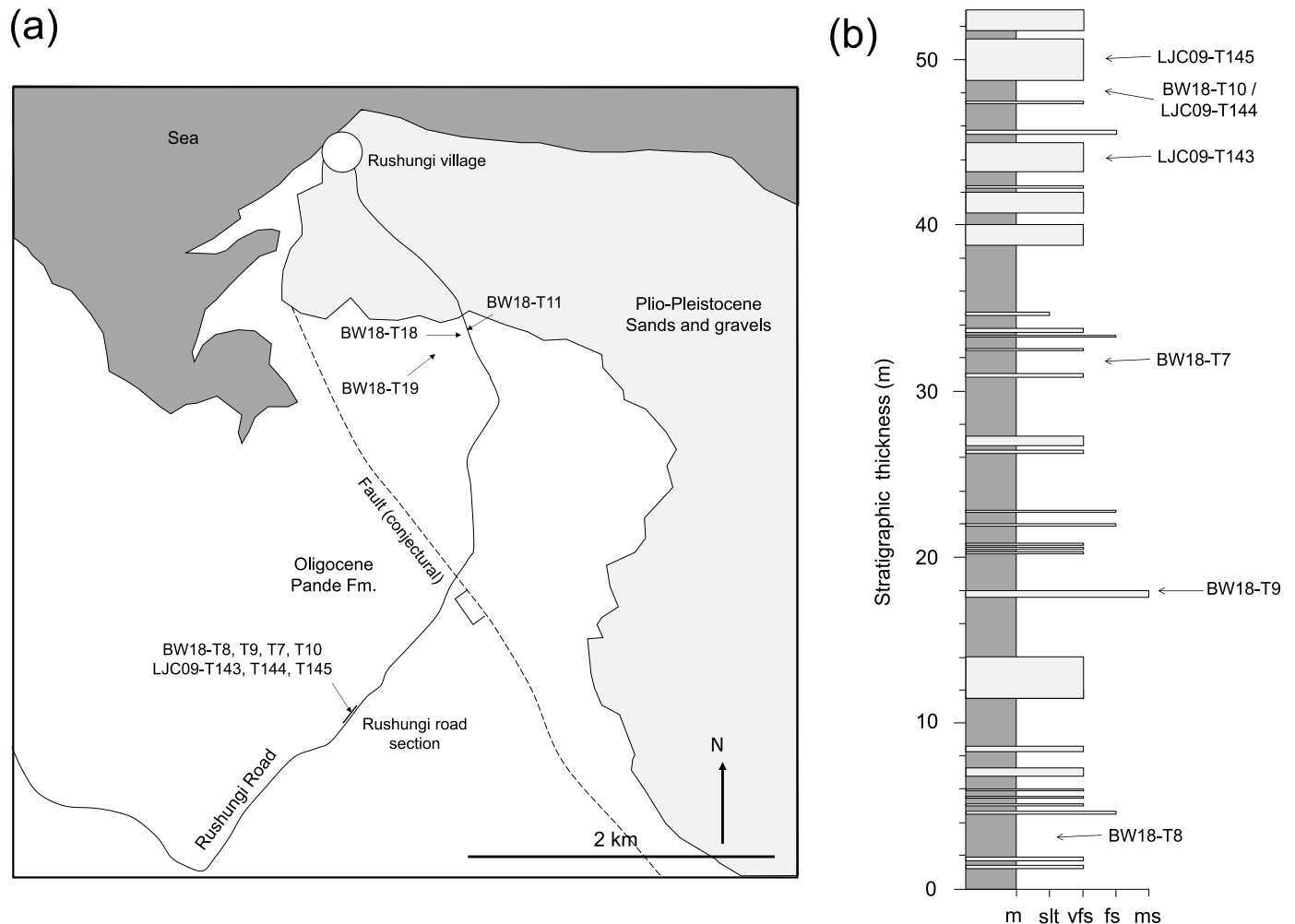


Fig. 5. (a) Sketch map of the Rushungi area showing the locations of the Rushungi Road section and Rushungi approach. (b) Stratigraphic log of the Rushungi Road section showing the relative stratigraphic positions of Samples BW18-T8, -T9, -T7, and T10. m = mudstone, slt = silt, vfs = very fine sand, ms = medium sand.

sample belonging to foraminifer Zone O3, Sample LC09-T144. This latter sample is very close or identical to the level of Sample BW18-T10. Their relative positions shown on the log in Fig. 5b. The sandstones were examined in thin section. Both LJC09-T143 and -T145 are pack-grainstones (Fig. 6). Sample LJC09-T143 contains large *Nummulites* in a carbonate matrix which includes LBF fragments and smaller foraminifera; Sample LJC09-T145 is similar, with *Nummulites* and a LBF fragment-rich carbonate matrix with *Planostegina* and poorly preserved dasyclads. The LBF genera are long-ranging from middle Eocene to upper Oligocene. The high numbers of fragments indicate they are likely derived from a penecontemporaneous carbonate platform up-slope.

Two splits of foraminifera from Sample BW18-T7 were analysed separately for $^{87}\text{Sr}/^{86}\text{Sr}$ age dating. The genus *Cibicidoides* spp. yielded Sr isotope ratios indicative of 28.2–29.9 Ma, which is consistent with the foraminifer and nannofossil ages. *Lenticulina* spp. yielded a lower isotope ratio, possibly indicating a slightly older age of 29.5–32.1 Ma, although the two analyses are within error. Combining the biostratigraphic and Sr isotope information for Sample BW18-T7 suggests a relatively precise age of 29.2–29.5 Ma which also applies to Sample BW18-T10 which is stratigraphically higher. This and other samples from the area also contain rare to frequent nannofossils reworked from Cretaceous formations which were presumably exposed to submarine erosion up or along the slope.

3.3. Rushungi approach

Further to the east along this road, in the approach to Rushungi village, apparent surface exposures were observed on an extensive slope overlooking the salt pans. Three samples were taken from this area, in ascending order of likely stratigraphic position given the regional strike, Samples BW18-T18, -T19, and -T11, although the latter was very weathered and did not yield useful results. Although Samples BW18-T18 and -T19 occur further east than the road section and might be expected to be younger according to the regional dip, they are in fact slightly older, likely due to faulting or other tectonic disturbance. In contrast to the road section, planktonic foraminifera assemblages contain *Turbotalia ampliapertura*, indicating Biozone O2 (30.3–32.2 Ma), while nannofossils indicate the lower part of Biozone NP23 (= Biozone CNO3) (30.0–32.2 Ma) (i.e., without *Sphenolithus distentus*). Strontium isotope analysis of *Cibicidoides* spp. from Sample BW18-T18 yielded an estimated age of 30.4–31.6 Ma, while *Lenticulina* from the same sample gave a slightly older age estimate, although within error (31.0–31.9 Ma).

3.4. Mchinga turn

The main highway ('B2') that runs inland of the Pande and Rushungi areas approaches the coast further south at Mchinga where it turns in the direction of Lindi (Fig. 7). At this point ('Mchinga turn'), there is a

roadcut exposing weathered clays atop an LBF-bearing sandy limestone with abundant small lepidocyclinids (Fig. 8). We took a mudstone sample from the top of this roadcut in 2009 (Sample LJC09-T81) and two further samples in 2018, one from near the bottom (Sample BW18-T26) and the other from near the top (Sample BW18-T27). Both BW18-T26 and -T27 contain the nannofossil markers *Sphenolithus heteromorphus* and *Discoaster signis* in the absence of large *Reticulofenestra*, suggesting a lower middle Miocene (Langhian) age of 14.86–15.85 Ma (nannofossil Biozone CNM7). The foraminifera suggest slightly different ages for the two samples either side of the '*Orbulina datum*'. Sample BW18-T26 lacks *Orbulina* but contains *Praeorbulina glomerosa* and *Globorotalia archeomenardii* suggesting an age of 15.12–16.26 Ma (Subzone M5b). In contrast, Sample BW18-T27 contains more 'advanced' *Praeorbulina* species (*P. curva* and *P. circularis*) with rare *Orbulina suturalis*. It also contains *Globigerinatella insueta*, the overlap of which with *Orbulina* places it in the lower part of Zone M6 (14.66–15.12 Ma). Sample LJC09-T81 appears to be slightly younger still, by containing more abundant *O. suturalis* and lacking *G. insueta*. The Sr isotope data are broadly consistent with these age determinations. In particular, the three Sr isotope analyses from Sample BW18-T26 tighten the age estimate of that sample to 15.20–15.70 Ma. Samples BW18-T26 and -T27 were deemed suitable for geochemical analysis and the planktonic foraminifera are illustrated and discussed in greater detail in Section 6 below.

3.5. Mchinga school

On the opposite side of the bay, just north of Mchinga village, two samples (Samples LJC09-T83 and LJC09-T84) were taken from a ~5 m high limestone ridge below Mchinga school, plus a claystone (Sample LJC09-T85) at the ground level. The latter sample contains planktonic foraminifer assemblages including *Praeorbulina glomerosa* in the absence of *Orbulina*, indicating Zone M5b (15.12–16.26 Ma). The limestone samples contain *Nephrolepidina*, *Miogypsina* and *Sphaerogypsina* in a sparry cement (see Fig. 8c) consistent with this age.

3.6. Mbuyuni quarry

West of Mchinga, the 'B2' highway passes Mbuyuni quarry which contains one of the largest exposures of limestones of this area, possibly the same stratum exposed at Mchinga school. A weathered clay sample, Sample LJC09-T104, contained very poorly preserved Miocene planktonic foraminifera. In 2009, the main quarry consisted of 12 m of well-bedded stratigraphy, including weathered clays, sandy clayey limestones with large lepidocyclinids (up to around 6 cm in diameter) and harder more cemented limestones with smaller bioclasts. The LBF assemblages consist of microspheric large lepidocyclinids, *Nephrolepidina*, *Operculina*, *Heterostegina*, *Miogypsina*, and *Spirochlopeus* (Samples LJC09-

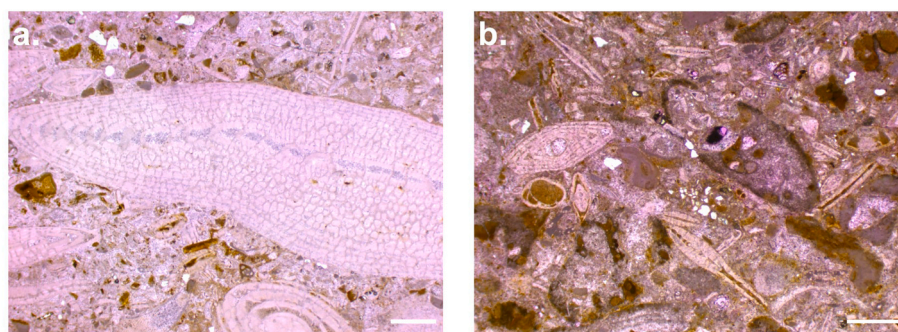


Fig. 6. Thin sections of larger benthic foraminiferal samples from Rushungi road. (a) Sample LJC09-T143 showing large reticulate *Nummulites* with smaller *Nummulites* and LBF fragments. (b) LJC09-T145 reticulate *Nummulites* and *Planostegina*. Scale bars 1 mm.

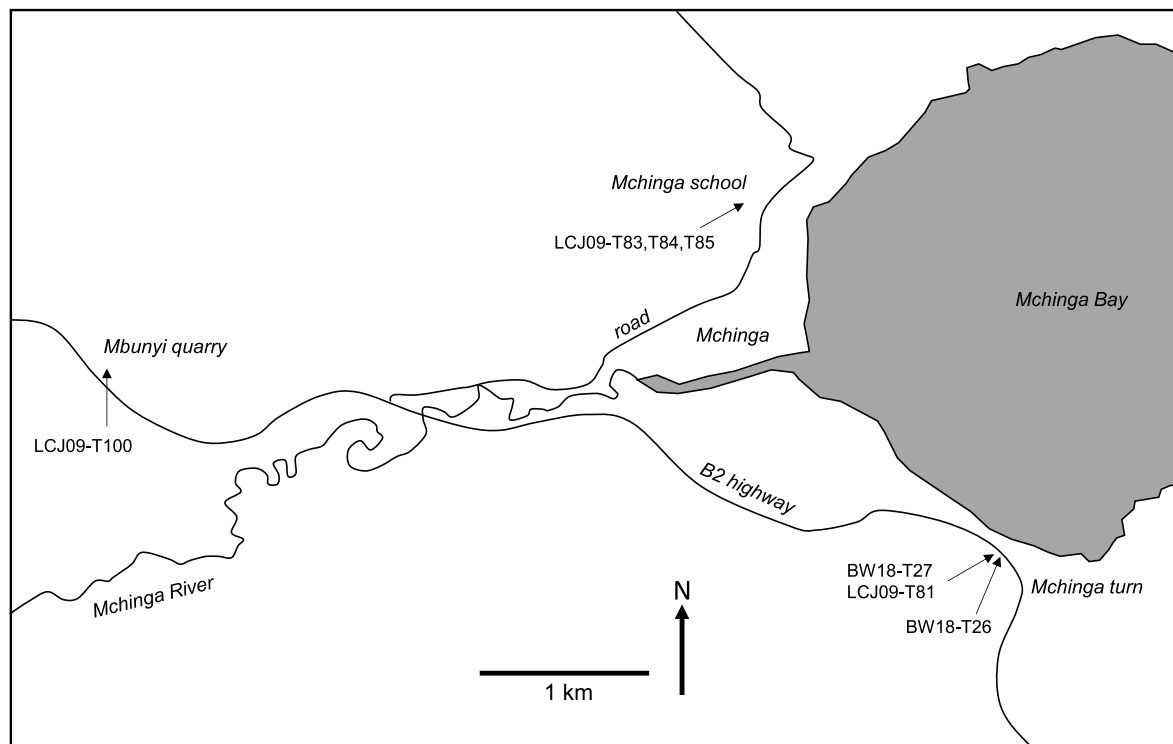


Fig. 7. Sketch map of the Mchinga area showing the locations of the Mchinga turn, Mchinga school and Mbuyuni Quarry.

T100) giving an upper Oligocene to lower Miocene age. Large unbroken lepidocyclinids, along with complete echinoids, indicate these are shallow marine deposits and not redeposited. Thus, there is at least one level in the Miocene with in-situ sediments deposited within the photic zone.

3.7. Likong'o

Sample BW18-T25 was taken from a small, isolated exposure in a roadside ditch at the north end of Likong'o village. Foraminifer assemblages are poorly preserved, but the nannofossils are sufficient to date the sample to approximately the same age as the sediment at Mchinga turn, i.e., nannofossil Biozone CNM7. Sample LJC09-T79 was taken south of Likong'o village on the south bank of the river toward the top of a 5 m high limestone outcrop, possibly correlative with the limestones at Mchinga and Mbuyuni quarry. The sample is a LBF rich pack-grainstone with a high medium to fine quartz grain content. LBF consist of *Mio-gypsina*, *Nephrolepidina* (<5 mm) and possible *Operculina* along with fragments of red algae, including *Distichoplax* (Fig. 9). The LBF indicate a broadly upper Oligocene to middle Miocene age. In the lower part of the outcrop the limestone is rubby and contains coral fragments.

3.8. Ras Tipuli

The north side of Lindi Bay comprises a number of headlands (from the west, Ras Mtama, Ras Tipuli, Ras Mongo, and Ras Bura). The geological succession youngs to the east, from middle Eocene at Ras Mtama to Miocene at Ras Bura, but there is substantial structural complexity, especially in the Ras Tipuli area (known as Ras Tapuri in the older literature, e.g., Blow and Banner, 1962), where a spectacular 'geobreccia' of large (up to ~50m) blocks of Miocene sands and sandy limestones occur across an extensive wave-cut platform, with marls exposed along the inner foreshore beneath the modern low cliff line (Kent et al., 1971; Stewart et al., 2004; Nicholas et al., 2007; Harzhauser, 2009) (Fig. 10). The lithology of the blocks appears similar to the

Miocene deposits seen elsewhere in the area; bioclastic sandy packstones rich in LBFs with the dominant taxa varying between blocks. *Planostegina* and both micro- and megalospheric lepidocyclinids were observed in hand specimen, with microspheric forms reaching up to 10 cm in diameter (Fig. 11).

We collected dark green marls from a number of localities on four visits to Ras Tipuli, in 1999 (Samples RAS99-38 and -42), 2001 (Sample, 180906/1), 2009 (Sample LJC09-T69), and 2018 (Samples BW18-T20 through -T24). Samples from 1999 to 2001 were studied previously by Stewart et al. (2004); note that the coordinates have been revised here on the field maps, because early public GPS coordinates at that time were only approximate and it is now possible to locate the samples more precisely.

In general, there is an age progression from southwest to northeast along the Ras Tipuli coast despite the structural complexities described by Nicholas et al. (2007). Sample RAS99-42 is reassigned to the lower part of Biozone M2 (20.99-21.12 Ma) based on the absence of *Paragloborotalia kugleri* and presence of *Ciperoella angulisuturalis* and *Trilobatus trilobus* s.l. reported by Stewart et al. (2004). Sample RAS99-38 contains *Fohsella fohsi* and so is placed in Biozone M9 (13.13-13.40 Ma). Sample LJC09-T69 lacks *F. fohsi* and *Globoturbotalita nepenthes* and so is placed in Biozone M10. The run of samples from BW18-T20 to -T24 are all in nannofossil biozones NN6-7 (10.89-13.6 Ma). Of these, Samples BW18-T20 through -T22 all contain *G. nepenthes* and *Globigerinoides subquadratus* which placed them in the lowermost part of Biozone M11 (11.57-11.67 Ma). There is, however, a slight conflict with the Sr isotope ages of *Cibicidoides* and *Lenticulina* from Sample BW18-T22, which are in the range 11.70-14.10 Ma, hence we broaden the best age estimate to incorporate these constraints. Sample BW18-T24 has few age-diagnostic foraminifera; the possible assignment to Zone M12 is based on an absence of evidence and conflicts with the nannofossil age, which is preferred here (see Table 1).

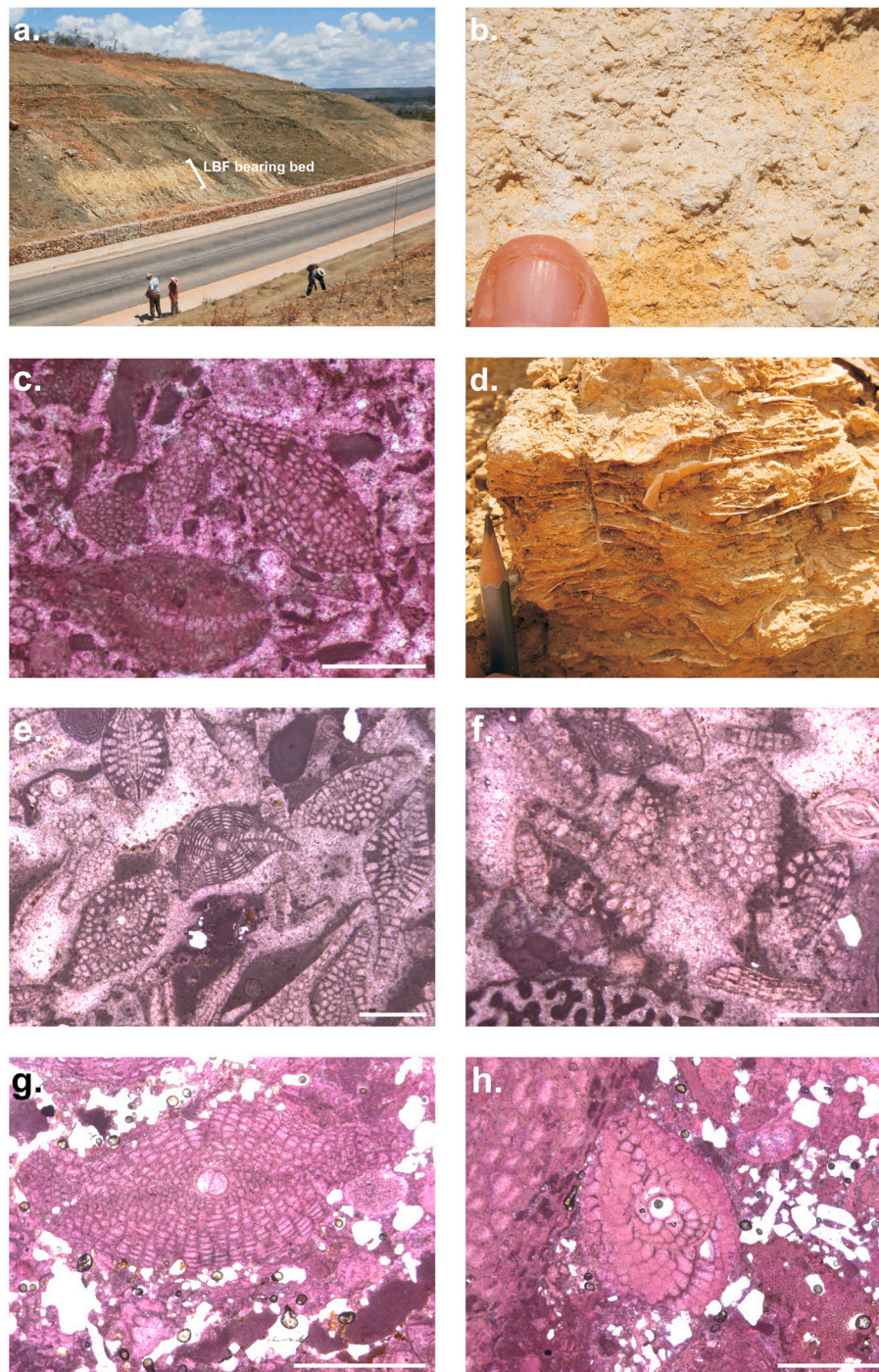


Fig. 8. Larger benthic foraminifera from Mchinga area. (a) The roadcut at Mchinga turn in 2009, soon after it was cut, showing the LBF-bearing limestone near its base. (b) LBFs visible on surface of rock at Mchinga turn, including small lepidocyclinids. (c) Thin section from Sample LJC09-T84 taken at Mchinga school with *Miogypsina*. (d) field sample from Mbuyuni quarry showing very large microspheric lepidocyclinids. (e–h) thin sections of samples from Mbuyuni quarry. (e) sample LJC09-T165 showing *Nephrolepidina*, *Spiroclypeus* and *Borelis* and (f) showing *Miogypsina* and *Amphistegina*. (g) sample LJC09-T101 showing *Nephrolepidina* and (h) *Spiroclypeus*. Scale bars 1 mm.

3.9. Ras Mongo

Additional coastal exposures were found a little further to the east of Ras Tipuli on the western side of the headland known as Ras Mongo. Sample BW18-T57 has consistent foraminifer and nannofossil biostratigraphy suggesting the age range 10.89–11.93 Ma. Sample LJC09-T71 has a foraminifer assemblage indicating the same broad age range. However, there is a mismatch in biostratigraphic age determinations for

Samples BW18-T58 and -T59, both of which are slightly younger than Sample BW18-T57 and LJC09-T71 according to the foraminifera (9.84–10.54 Ma) but similar age according to the nannofossils (12.00–13.60 Ma). The discrepancy arises from negative evidence, the absence of the foraminifer *Paragloborotalia mayeri/siakensis* in these samples. The nannofossils include *Cyclicargolithus floridanus* which disappeared at ~12.0 Ma according to Raffi et al. (2020), although that level is described therein as not well-defined and low reliability. These

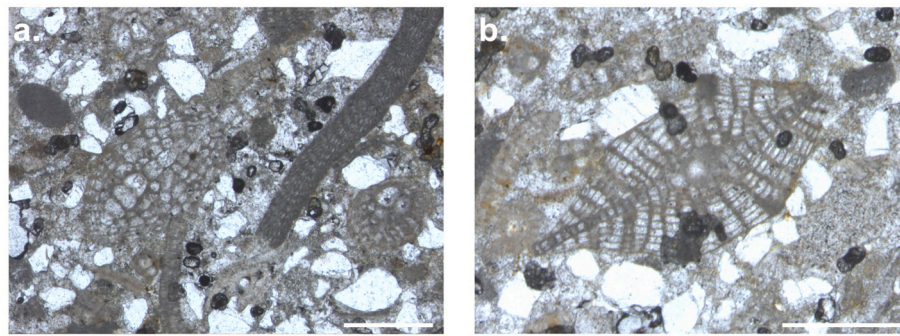


Fig. 9. Thin sections of limestone sample LJC09-T79 from Likong'o. (a) *Miogypsina* and the red alga *Distichoplax*. (b) *Nephrolepidina*. Scale bars 1 mm.

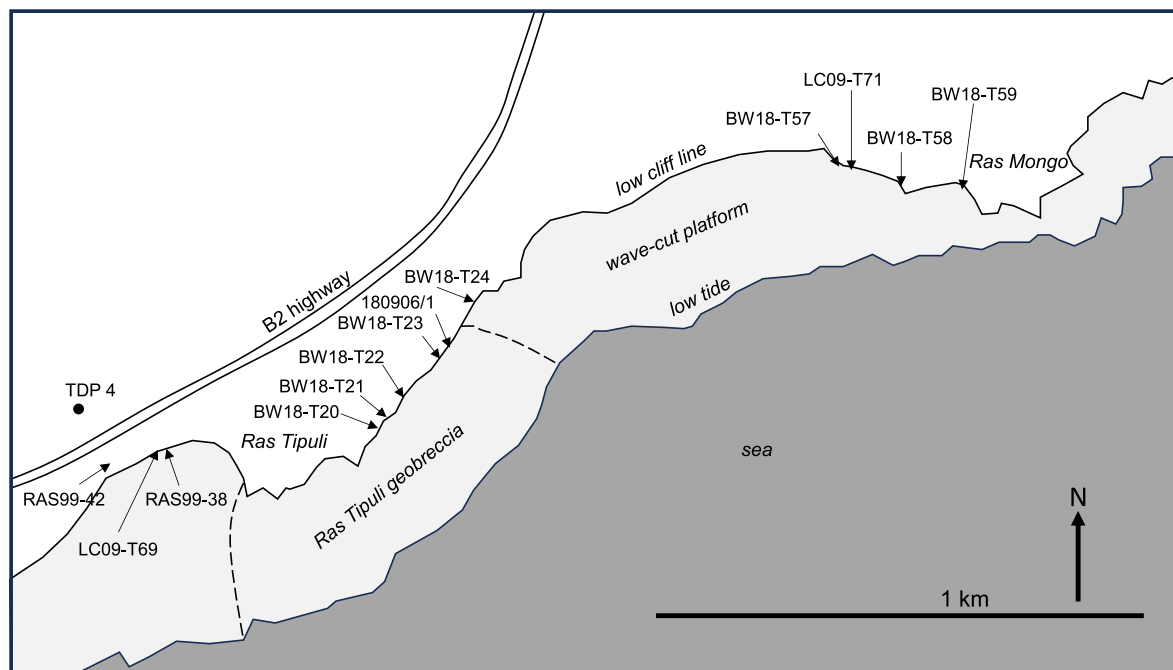


Fig. 10. Sketch map of North Lindi Bay showing the Ras Tipuli and Ras Mongo sampling localities.

discrepancies are unresolved, so the preferred age range was extended to include all these possible constraints pending further study of the area (see Table 1).

3.10. North Kitunda shore

The Kitunda district lies on the east side of the Lukuledi estuary opposite the city of Lindi (Fig. 12). It is a historically important area, first studied by Blow and Banner (1962) using samples collected by exploration geologist F.C.R. Martin in the 1950s, and used by them to typify several planktonic foraminifer biozones of the upper Eocene and lower Oligocene. Various species were named by Blow and Banner (1962) from these samples, the approximate locations of which was shown in their published map. We collected samples from the same area in 1998, 1999, 2009, and 2018. For convenience we divide the Kitunda area into the north Kitunda shore area, and the northern and southern sectors of the sloping hillside south-east of Kitunda village.

The foreshore north of the village has sporadic areas of wave-cut exposure under boulders and shifting sand and gravel. We collected samples from this area in 1998 (Sample PP98-L11; upper Eocene) and 1999 (Sample LIN99-17; middle Eocene planktonic foraminifer Zone E13; the type locality of *Acarinina mcgowrani* described in Berggren et al., 2006), for which stable isotope data was published by Pearson

et al. (2001). In 2018, we collected two more localities, Samples BW18-T55 and -T56. Both new samples yielded upper Eocene foraminifer and nannofossil assemblages. Planktonic foraminifera indicate a level in Zone E14, that is, above the top occurrences of quadrate acarininids and *Morozovelloides* (which are common in Sample LIN99-17). Strontium isotope data from Sample BW18-T56 is problematic as it suggests an Oligocene age which is definitively ruled out by the biostratigraphy.

3.11. Kitunda slope north

We collected samples in several areas south of Kitunda in the general area that Blow and Banner (1962) reported well-preserved Oligocene samples. A scrubby slope to the south of Kitunda contains sporadic exposures of weathered mudstones (see Fig. 2c) rising to a limestone plateau which we sampled in two areas, designated 'Kitunda slope north' and 'south'. Foraminifer and nannofossil biostratigraphy divide the north set into two groupings, the uppermost three of these (Samples BW18-T28, -T29, and -T50) and the lowermost five samples (BW18-T30 through -T34). The upper group all present a substantial biostratigraphic mismatch between foraminifers and nannofossils. The foraminifers are assigned to lower Oligocene Biozone O3 (29.2-30.3 Ma) based on the absence of *Turborotalia ampliapertura*, but consistent presence of

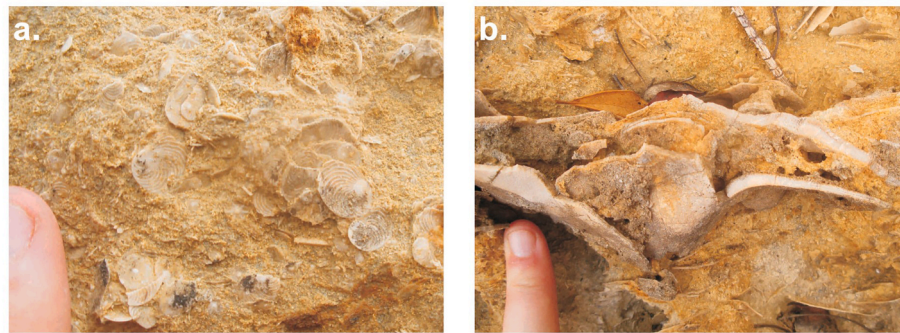


Fig. 11. Larger benthic foraminifera in field outcrop of limestone ‘geobreccia’ at Ras Tipuli. (a) large *Planostegina*. (b) very large lepidocyclinids.

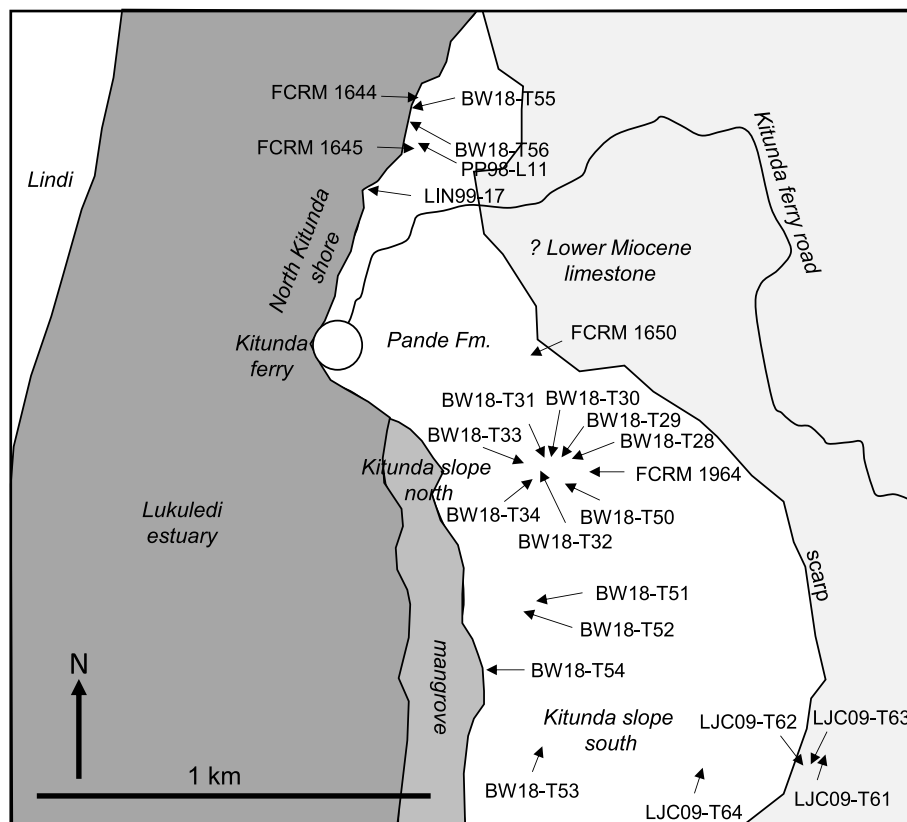


Fig. 12. Sketch map of the Kitunda area showing samples collected in 1998, 1999, 2009, and 2018. Also shown are the approximate location of historically significant Samples FCRM 1644, 1645, 1650, and 1964 studied by Blow and Banner (1962).

Chiloguembelina cubensis and *C. ototara*. In contrast the nannofossils indicate a substantially younger age in the short upper Oligocene Biozone NP24 defined by the co-occurrence of *Sphenolithus ciperoensis* and *S. distentus* (26.81–27.17 Ma). It is possible that *C. cubensis* persists above its last common occurrence (Leckie et al., 1993; King and Wade, 2017), hence the nannofossil age determination is preferred here, pending more detailed study of the succession. The lower group of samples are certainly older, but here there is also a slight biostratigraphic discrepancy. The planktonic foraminifers indicate Biozone O1 (33.1–33.9 Ma) based on the presence of *Pseudohastigerina naguewichiensis*, whereas the nannofossils indicate the lower part of Zone NP23 (= Biozone CNO3) (30.0–32.02 Ma) based mainly on the absence of *Reticulofenestra umbilicus*. For these we prefer the foraminifer data as it is based on positive evidence, and the extinction of *R. umbilicus* is known to be diachronous (Agnini et al., 2014) (see Table 1). The samples may well be from the upper part of Biozone O1, which would reduce the apparent diachrony.

3.12. Kitunda slope south

Samples BW18-T51, -T52, -T53, and -T54 from ‘Kitunda slope south’ have nannofossil and foraminifer ages in good agreement. Nannofossils place them in the lower part of Biozone NP23 (= Biozone CNO3) (30.00–32.02 Ma). The uppermost sample, Sample BW18-T51, is assigned to planktonic foraminifer Biozone O3 (29.2–30.3) based on the absence of *Turborotalia ampliapertura*, whereas Samples BW18-T52, -T53, and -T54 all contain *T. ampliapertura* and are assigned to Biozone O2 (30.3–32.1 Ma). Strontium isotope ages from both *Cibicidoides* and *Lenticulina* from Sample BW18-T53 are also in good agreement (see Table 1).

Weathered sandy claystones are exposed a little further inland up the slope leading to a water well where the topography flattens out and limestones crop out. These were sampled in 2009. Sample LJC09-T64 contains poorly preserved foraminifera including *Globoturborotalita woodi* sp., *Tenuitella*, *Ciperoella ciperoensis*, *Globigerina*

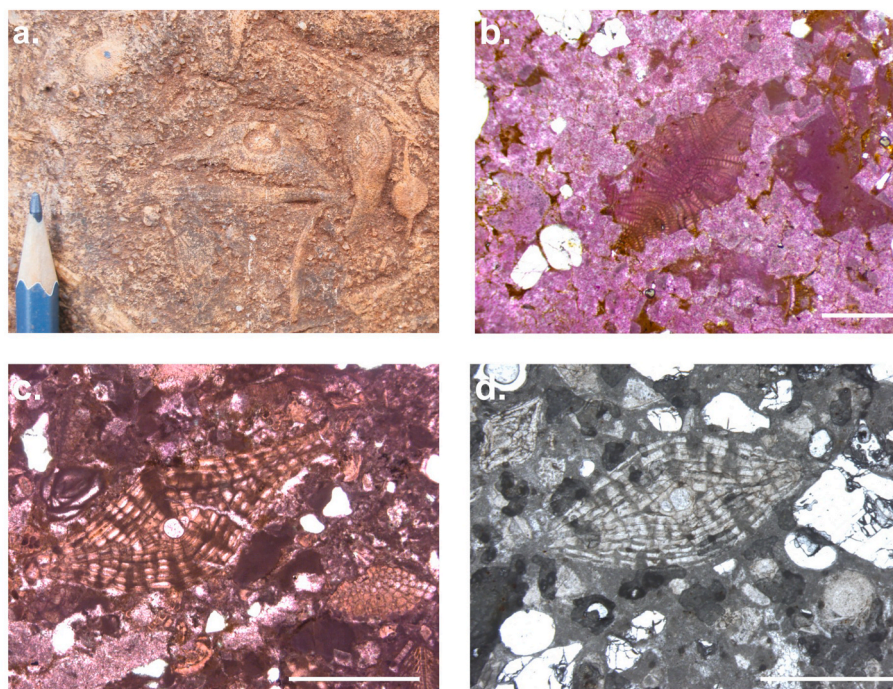


Fig. 13. Larger benthic foraminifera from Kitunda section. (a) weathered surface showing large lepidocyclinids in outcrop, close to samples LJC09-T62 and T63. (b) sample LJC09-T62 showing lepidocyclinid with calcite pseudomorphs of dolomite. (c) LJC09-T62 with *Spiroclypeus*. (d) LJC09-T63 showing *Spiroclypeus* with *Amphistegina*. Scale bar 1 mm.

pseudopraebuloides, and *Globigerinella praesiphonifera* indicating a late Oligocene age (23.04–27.29 Ma). The upper part of the section comprises of a series of LBF-rich limestones dominated by lepidocyclinids and *Spiroclypeus*, with additional *Miogypsina* and an archaiasine miliolid, indicating an Oligocene to lower Miocene age (20.45–27.29 Ma). The lepidocyclinids are several centimetres in size in the lowermost limestones (Sample LJC09-T63), occurring with complete clypeasteroid echinoids. The upper beds (Samples LJC09-T61 and -T62) contain smaller more inflated lepidocyclinids with algal fragments and oncoids (Fig. 13).

4. Organic matter preservation

Organic matter preservation can be evaluated using a wide range of molecular maturity parameters among which bacterial-derived hopanoids are an especially useful group (Mackenzie et al., 1980). These undergo many structural transformations during diagenesis, including modification and subsequent loss of the polyfunctionalised side chain. With increasing maturation, the biological isomer ($17\beta,21\beta$; $\beta\beta$ hereafter) is gradually transformed into the more stable $17\beta,21\alpha$ ($\beta\alpha$ hereafter) and then $17\alpha,21\beta$ ($\alpha\beta$ hereafter) isomer. Hopane $\beta\beta/(\alpha\beta + \beta\beta)$ indices are frequently used to assess organic matter preservation in sedimentary rocks (Mackenzie et al., 1980; Ourisson and Albrecht, 1992) whereby lower values indicate higher thermal maturation.

We detected a range of C_{27} – C_{31} hopanes and C_{30} hopenes in 23 out of 33 samples analysed (see Supplementary Information 1). The dominant hopanoid in the hydrocarbon fraction was typically hop-22(29)-ene (diploptene). Diploptene is synthesized by a wide variety of bacteria and is found in diverse terrestrial (Inglis et al., 2025) and marine environments (Prah et al., 1994; Kim et al., 2025). Various diploptene degradation products were also detected, including neohop-13(18)-ene (C_{30}) and hop-17(21)-ene (C_{30}). Collectively, this suggests that organic matter has undergone minimal diagenetic alteration (Inglis et al., 2025).

In a subset of samples (BW18-T54, BW18-T55 and BW18-T56), the hopanoid assemblage was dominated by biologically-derived $17\beta,21\beta$ (H)-hopanes and thermally stable $17\beta,21\alpha$ (H) and $17\alpha,21\beta$ (H)-

stereoisomers. The assemblage included 17α (H)- and 17β (H)-trisnorhopane (C_{27}), $17\alpha,21\beta$ (H), $17\beta,21\alpha$ (H)- and $17\beta,21\beta$ (H)-norhopane (C_{29}), $17\alpha,21\beta$ (H)- and $17\beta,21\beta$ (H)-hopane (C_{30}), and (22R)- $17\alpha,21\beta$ (H)-, (22R)- $17\beta,21\alpha$ (H)- and $17\beta,21\beta$ (H)-homohopane (C_{31}). To quantify the degree of hopane isomerisation, we used the C_{27} – C_{31} hopane $\beta\beta/(\alpha\beta + \beta\beta)$ index (following Mackenzie et al., 1980). In our samples, C_{27} – C_{31} hopane $\beta\beta/(\alpha\beta + \beta\beta)$ indices range from 0.62 to 0.87. These results are similar to previously studied Paleogene and Cretaceous sediments from the Kilwa area, Tanzania (van Dongen et al., 2006) and confirm that the sediments are thermally immature and have not been deeply buried.

5. Carbonate preservation

As described above, the value of the Kilwa Group for palaeoclimatology depends in a large part on the carbonate preservation, which is often excellent. This has been attributed to the high clay content, which inhibits recrystallization, and low thermal maturity (e.g., Pearson et al., 2001; Bown et al., 2008). Despite that, calcite infilling of foraminifer tests is frequently encountered in drill-cores, occurring patchily throughout the succession. While infills can be removed by crushing and manual picking, previous work has generally avoided such samples and focused instead on samples that lack significant infilling (e.g., Pearson et al., 2007; Ando et al., 2015).

A separate issue of particular relevance to outcrop samples is surface weathering and oxidation. Drill-sites frequently show a pronounced transition from fresh dark greenish-grey clays at depth to light greenish grey clays with orange and white concretionary spots near the surface. The transition can be fairly abrupt, generally at around 10–20 m bore-hole depth (e.g., Pearson et al., 2004; Nicholas et al., 2006). This indicates that clays near the surface must have been subjected to prolonged weathering. At the surface itself, clays are further affected by vegetation and pedogenic processes. In general, the best preservation is found in more rapidly eroding areas, but even unpromising exposures such as in roadside ditches can yield excellent preservation.

While the white concretionary mottling is easily identified as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), we were uncertain as to the mineralogy of the orange mineral which frequently causes discolouration and minute spots and stains on foraminifera (Fig. 14). In geochemical analysis, its presence can be mitigated to some extent by selecting the better-preserved specimens and cleaning them manually to remove orange-stained adhesions and infillings, but it is generally impossible to remove completely. We investigated several specimens with SEM and Energy Dispersive X-Ray Spectroscopy (EDS). The crystals exhibit the typical size and habit of siderite (FeCO_3) formed by bacterial reduction of ferrihydrite ($\text{Fe}_8\text{HO}_8 \cdot 4\text{H}_2\text{O}$) (Chistyakova et al., 2023). This suggest that the sediment typically passes through a microbially catalysed oxidation process involving pyrite oxidation and calcite dissolution, producing ferrihydrite and ultimately siderite and gypsum (e.g., Nordstrom, 1982; Czerewko and Cripps, 2023). Despite the dissolution of calcite, it is evident that calcite microfossils survive the process because the same samples contain well-preserved foraminifera and nannofossils.

The presence of siderite staining in outcrop samples is not considered a major problem for oxygen and carbon stable isotope analyses of foraminifera when it is volumetrically insignificant. Moreover, it is unlikely to affect strontium isotope age dating because Sr^{2+} does not readily exchange with Fe^{2+} in the siderite lattice because of its much greater ionic radius.

6. Samples with excellent carbonate preservation

Of the various samples studied, seven were found to have excellent foraminifer preservation which were deemed potentially useful for future geochemical analysis. These samples were studied in detail for

their benthic foraminifer assemblages and are the samples for which strontium isotope data were obtained. We describe them in more detail in this section from oldest to youngest, with details of the micro-palaeontology, preservation, and palaeoenvironment.

6.1. Sample BW18-T56 (upper Eocene, 35.96 ± 0.17 Ma, Kitunda shore)

This sample is a new locality from the Kitunda shore area, approximately 200m north of Sample LIN99-17, the type locality of *Acarinina mcgowrani* Wade and Pearson, in Berggren et al. (2006), which is middle Eocene (Pearson et al., 2001). Sample BW18-T56 lacks quadrate *Acarinina* and *Morozovelloides* and so post-dates the extinction of those forms which approximates the division between the Bartonian (middle Eocene) and Priabonian (upper Eocene) stages (Wade et al., 2012; Agnini et al., 2021). We examined rock chip surfaces of Sample BW18-T56. These confirm the excellent preservation of carbonate microfossils despite siderite concretions in the sediment (Fig. 15). This underlines the potential of the Kitunda area as an excellent site for future drilling of the middle Eocene through to the Oligocene, including intervals not so far recovered by coring.

Planktonic foraminifera show a full assemblage of species from surface mixed-layer dwellers (Fig. 16) to thermocline and sub-thermocline deep-dwellers (Fig. 17). An interesting aspect of the assemblage is the frequent presence of an apparently undescribed relatively large, high-spired, form with well-separated spherical chambers, recorded here as *Globoturborotalita* sp. (Fig. 16.20–24) Also noteworthy are occurrences of *Globigerinathea tropicalis* (Fig. 16.26–30). This species was originally described by Blow and Banner (1962) from Sample FCRM 1645, which judging from the old field maps, may be the exact same locality, but if

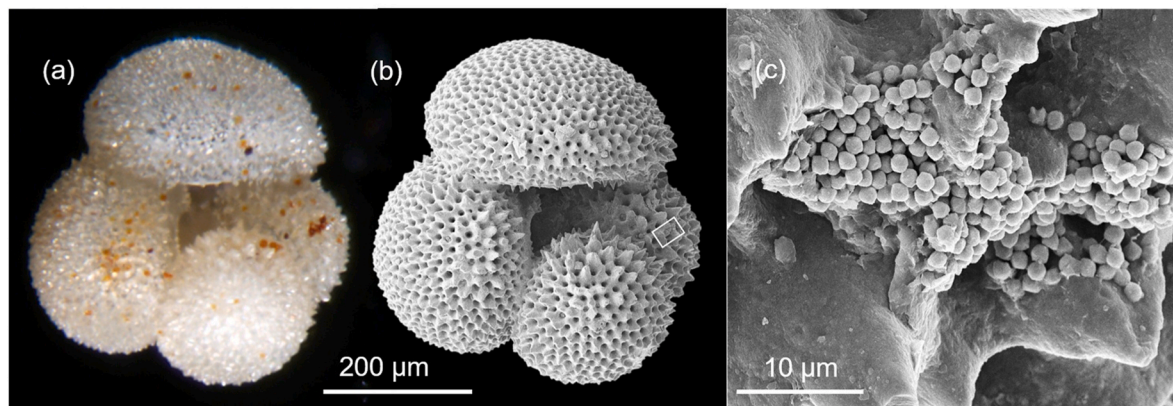


Fig. 14. Investigation of the orange oxidation mineral on a specimen of *Dentoglobigerina prasaepis* from Sample BW18-T53 (Kitunda Slope south). (a) light microscope image. (b) Scanning electron micrograph, with highlighted box. (c) detail of highlighted box area showing the habit of the orange mineral siderite.

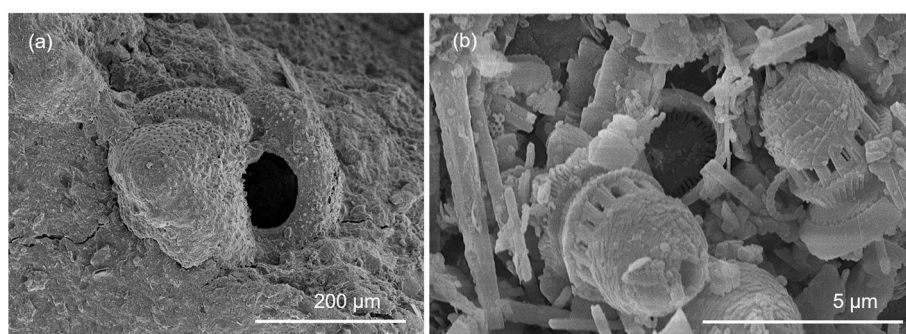


Fig. 15. Scanning electron micrographs of rock chip surface from Sample BW18-T56. (a) example of a planktonic foraminifer *Turborotalia cerroazulensis* embedded in the claystone, showing the empty void space within the test. (b) high magnification detail of the rock chip surface showing excellent preservation of nannofossils *Blackites* sp. (liths shaped like a classical rotunda).

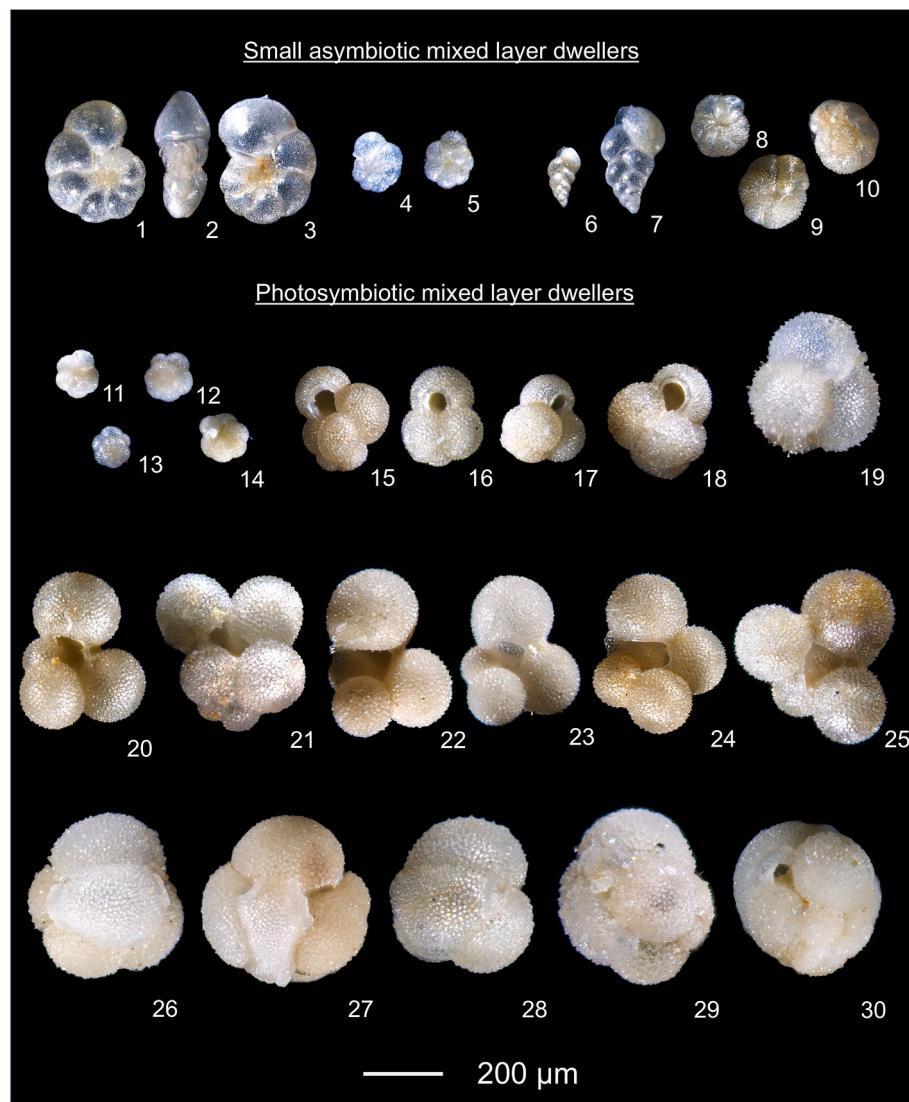


Fig. 16. Light microscope images of planktonic foraminifera from the upper water column from Sample BW18-T56. 1-3, *Pseudohastigerina micra*. 4-5, *Pseudohastigerina nagewichiensis*. 6-7, *Streptochilus martini*. 8-10, *Planorotalites capdevilensis*. 11-14, *Acarinina collactea*. 15-18, *Globoturborotalita barbula*. 19, *Acarinina echinata*. 20-25, *Globoturborotalita* sp. 26-30, *Globigerinatheka tropicalis*.

not is certainly very close. Also described by Blow and Banner (1962) from the same sample was '*Globigerinatheka lindiensis*'. These two species were regarded as synonyms by Premoli Silva et al. (2006) but both variants are present in our sample.

Scanning electron microscopy (Fig. 18) reveals other details of interest, including the often excellently preserved wall texture on specimens where siderite growth is minimal. True spines are preserved within the apertural region of *Globigerinatheka tropicalis* (Fig 18.3) as also seen in other excellently preserved material from Croatia, Trinidad and Tanzania (Premoli Silva et al., 2006). Spine-like projections occur in *Acarinina meddizai* (Fig 18.6 7) and apparently broken-off spine-like objects were observed within the centres of muricae (Fig 18.9), supporting the view that muricae served as the bases for spine-like projections similar to, but not homologous with, the true spines of *Globigerinatheka* and many other taxa (Pearson et al., 2022).

Benthic foraminifera are relatively rare in Sample BW18-T56 (~490 forams/gm). The assemblage is dominated by bolivinids (~30% of the benthic assemblage) with lesser amounts of *Uvigerina* spp., *Cibicoides* spp. and *Cassidulina* spp. Planktonic foraminifera are common (33% of the total assemblage). The foraminiferal assemblage is typical of the reduced oxygen conditions in an outer shelf to upper slope environment.

Palaeodepths may have been as deep as 230 m (based on the % planktonic minus low oxygen benthic foraminiferal calculation of van Hinsbergen et al., 2005). Minor (<10%) reworked shallow-water taxa are present in this sample including: *Cibicides* spp., *Asterigerina* spp. and *Neorotalia* spp.

Nannofossil preservation is excellent with very high diversity (>80 taxa) and frequent fragile taxa, such as *Blackites*, *Syracosphaera* and holococcoliths. The assemblage includes several taxa that are indicative of the upper Eocene and disappear in the Eocene–Oligocene transition interval, e.g., heliodiscoasters (*Discoaster barbadiensis*, *D. saipanensis*), *Hayella situliformis*, *Reticulofenestra reticulata*, *R. isabellae*, *Umbilicosphaera bramlettei*, and *U. protoannula*. *Pemma* is present in BW18-T56 but not in BW18-T53. Both samples contain abundant *Gladiolithus*.

6.2. Sample BW18-T53 (lower Oligocene, 31.46 ± 0.56 Ma, Kitunda slope south)

The preservation of samples from Kitunda slope south was variable. They all showed obvious orange siderite nodules and staining of foraminifer tests and most had variable amounts of gypsum and/or sugary calcite, often filling voids and overgrowing surfaces. The least affected

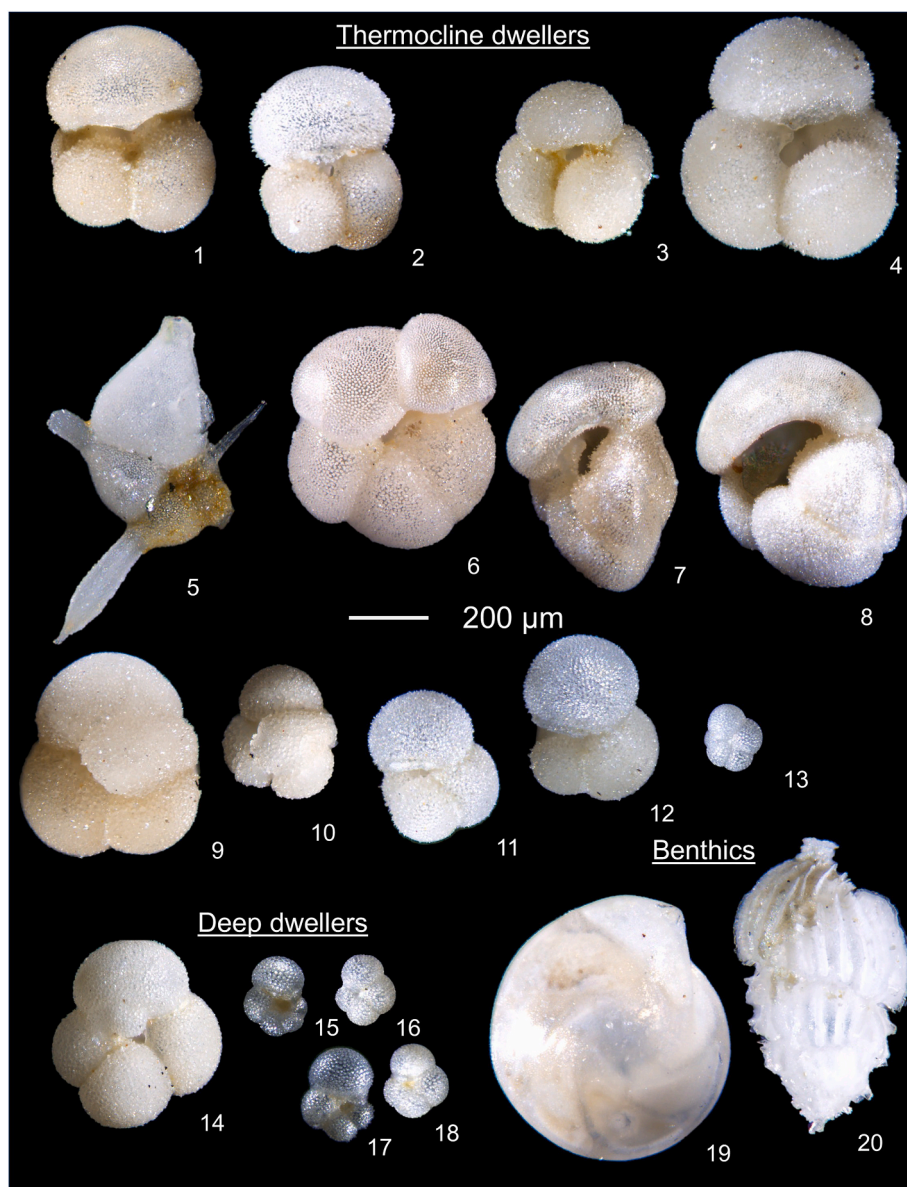


Fig. 17. Light microscope images of deeper-dwelling planktonic foraminifera and benthic foraminifera from Sample BW18-T56. 1-2, *Dentoglobigerina eotripartita*. 3, *Dentoglobigerina venezuelana*. 4, *Dentoglobigerina galavisi*. 5, *Hantkenina alabamensis*. 6-7, *Turborotalia cerroazulensis*. 8, *Turborotalia pomeroli*. 9-10, *Catapsydrax unicus*. 11-12, *Subbotina utilisindex*. 13, *Paragloborotalia* sp. 14, *Subbotina* cf. *yeguaensis*. 15-18 *Globorotaloides* spp. 19, *Lenticulina* sp. 20, *Uvigerina* asp.

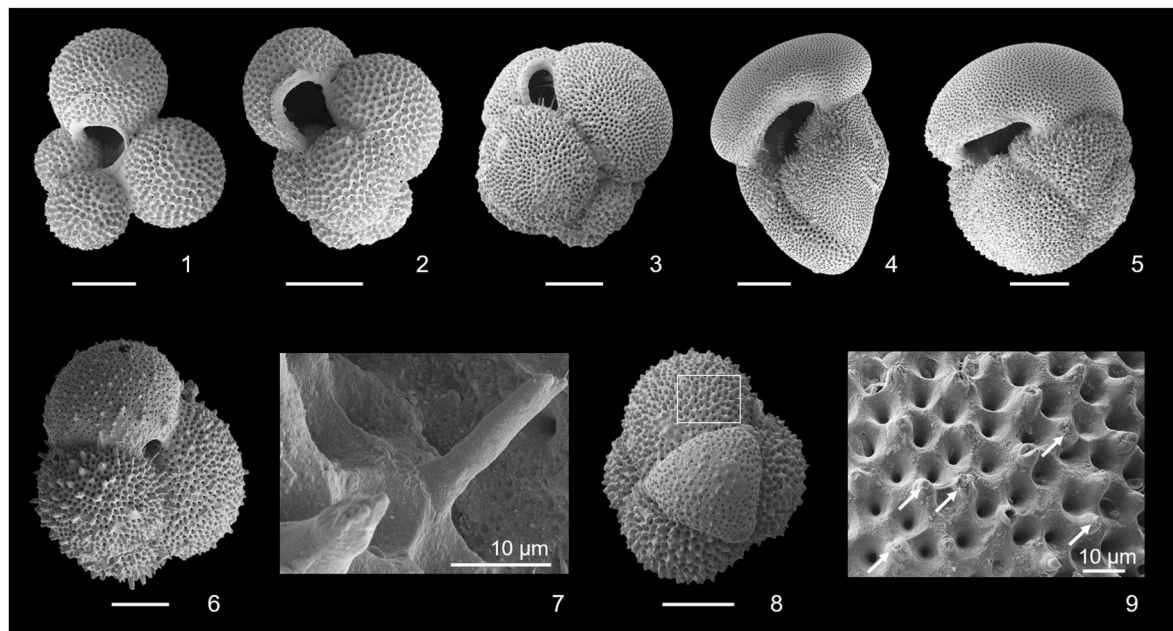


Fig. 18. SEM images of planktonic foraminifera from Sample BW18-T56. 1, *Globoturborotalita* sp. 2, same specimen as Fig. 16.20. *Globoturborotalita barbula*, same specimen as Fig. 16.15.3, *Globigerinatella tropicalis* with true spines preserved in the aperture. 4, *Turborotalia cerroazulensis*, same specimen as Fig. 16.7.5, *Turborotalia pomeroli*. *Acarinina echinata*, same specimen as Fig. 16.19, showing long muricae and spine-like projections. 7, detail of apertural region with spine-like projection. 8, *Acarinina echinata*, detail of highlighted area of final chamber showing broken muricae with central spine-like objects.

of the samples is Sample BW18-T53 which has many well-preserved foraminifera, despite frequent siderite spots (see Fig. 14).

Foraminifera are abundant in Sample BW18-T53 (>4600 forams/gm). The benthic assemblage is dominated by bolivinids (~54% of the benthic assemblage) with lesser *Anomalinoidea* spp., *Uvigerina* spp., *Cibicides* spp. and *Globocassidulina* spp. Planktonic foraminifera are common (30% of the total assemblage). The assemblage is typical of the low-oxygen conditions in an outer shelf to upper slope environment. The presence of abundant bolivinids suggest conditions were more dysoxic than Sample BW18-T56. Palaeodepths may have been up to 400 m. Over 23% of the benthic foraminifera are interpreted to be reworked in this sample with common shallow taxa such as: *Glabratellina* spp., *Cibicides* spp. and *Neorotalia* spp.

Sample BW18-T53 also yields excellent nannofossil preservation with very high diversity (>50 taxa) and frequent fragile taxa, such as *Syracosphaera* and holococcoliths. The sample is above the extinction level of *Coccolithus formosus* and *Reticulofenestra umbilicus* but below the appearance of *Sphenolithus distentus*. The sample include abundant *Gladiolithus*. Discoasters and medium to large reticulofenestrids are rare. Reworked Upper Cretaceous taxa are frequent.

6.3. Sample BW18-T18 (lower Oligocene, 31.25 ± 0.15 Ma, Rushungi approach)

The area southwest of Rushungi is a newly discovered area of Kilwa Group outcrop, although exposures are scrappy on a vegetated slope. The best of the samples from this area is BW18-T18 which contains 'glassy' foraminifera from a variety of habitats in the water column (Fig. 19). We illustrate a few of the significant species for local biostratigraphy by SEM in Fig. 20. Foraminifera are abundant (>8600 forams/gm). Nannofossil preservation is good with high diversity (>40 taxa) and common fragile taxa, especially *Syracosphaera* and holococcoliths. The benthic assemblage is primarily bolivinids (~65%), with common *Angulogerina* spp. and rarer *Cibicides* spp. and *Anomalinoidea* spp. The assemblage suggests strongly dysoxic conditions in an outer shelf to upper slope environment. Palaeodepths may have been up to 380 m. Around 25% of the benthic foraminifera are interpreted to be

reworked with common shallow taxa including: *Glabratellina* spp. and *Neorotalia* spp.

6.4. Sample BW18-T7 (lower Oligocene, 29.25 ± 0.05 Ma, Rushungi Road section)

Of the three samples collected from the Rushungi road section, Sample BW18-T7 has the best preservation, the others having many foraminifera infilled with crumbly mineralization, probably gypsum or calcite or both. Fig. 20.1a and b shows an example of an excellently preserved benthic foraminifer from this sample. Foraminifera are common (>2000 forams/gm) with a benthic assemblage similar to BW18-T18, dominated by bolivinids (~65%) with common *Uvigerina* spp. and rarer *Cancris* spp. and *Anomalinoidea* spp. Planktonic foraminifera are also common (~30%). The assemblage is typical of strongly dysoxic conditions in an outer shelf to upper slope environment, with palaeodepths up to 440 m. Nearly 10% of the benthic foraminifera are reworked with shallow taxa including: *Cibicides* spp., and *Elphidium* spp. Nannofossil preservation is good with high diversity (>40 taxa) and common fragile taxa, especially *Syracosphaera* and holococcoliths.

6.5. Sample BW18-T26 (middle Miocene, 15.42 ± 0.03 Ma, Mchinga turn)

Sample BW18-T26 contains very well preserved 'glassy' foraminifera (Fig. 21), many of them showing fine features such as spines on *Globigerinoides*, but there is also a volumetrically small amount of calcite overgrowth on external and internal surfaces, probably as a result of burial diagenesis. Many specimens show siderite staining and there is also gypsum mineralization associated with surface oxidation. Among the notable foraminifera present are common *Trilobatus bisphericus*, the ancestral form of the *Praeorbulina* – *Orbulina* lineage (see Fig. 21.8.10). *Mutabellia mirabilis* is frequent in this and other Tanzanian middle Miocene samples (see Fig. 21.15a and b). Other useful marker species are *Fohsella peripheroronda* and *Globigerinatella insueta*.

Foraminifera are abundant in (>3700 forams/gm) with the benthic assemblage comprising common bolivinids (~45%) with common

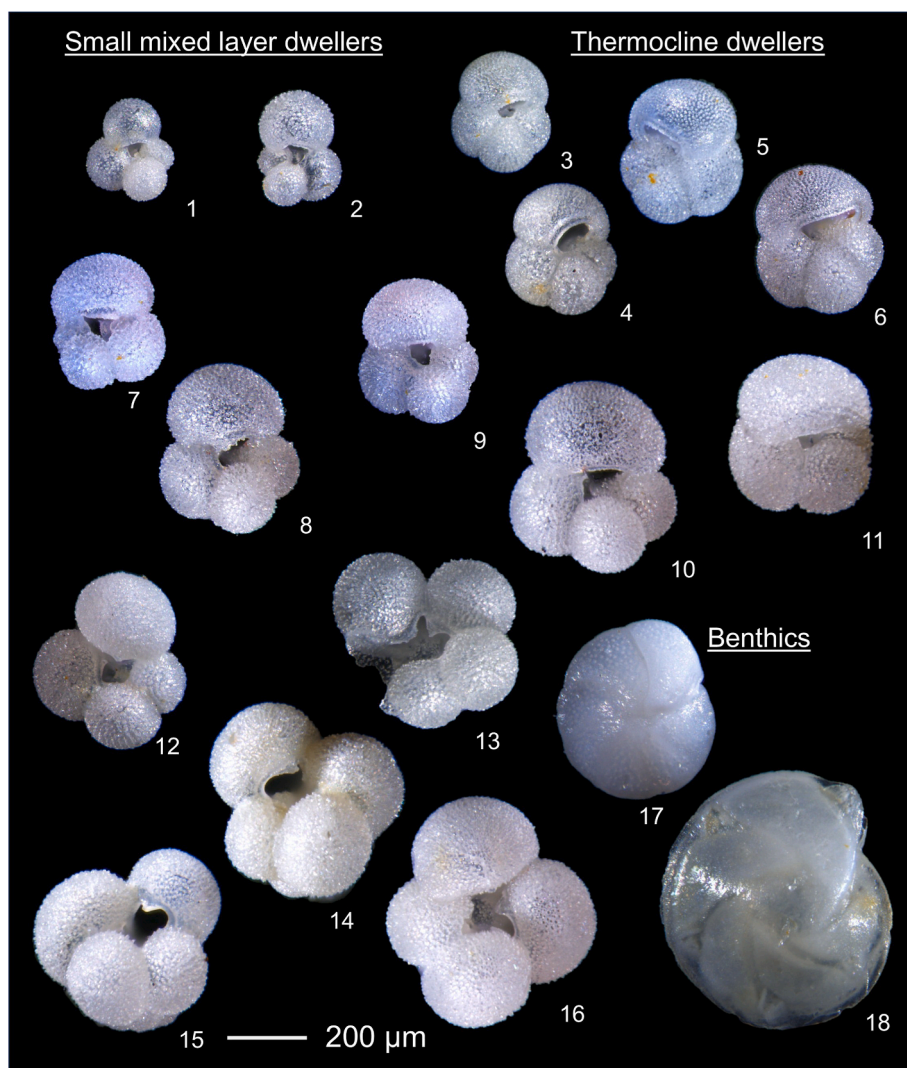


Fig. 19. Light microscope images of foraminifera from Sample BW18-T18 showing mixed layer, thermocline, and benthic species with 'glassy' preservation. 1, *Globoturborotalita ouachitaensis*. 2, *Globoturborotalita pseudopraebulloides*. 3-6, *Turborotalia ampliapertura* from a series of size fractions. 7-8, *Dentoglobigerina galavisi*. 9, *Dentoglobigerina taci*. 10, *Dentoglobigerina tapuriensis*. 11, *Dentoglobigerina prasaepis*. 12-16, *Subbotina projecta*. 17, *Cibicidoides* sp. 18, *Lenticulina* sp.

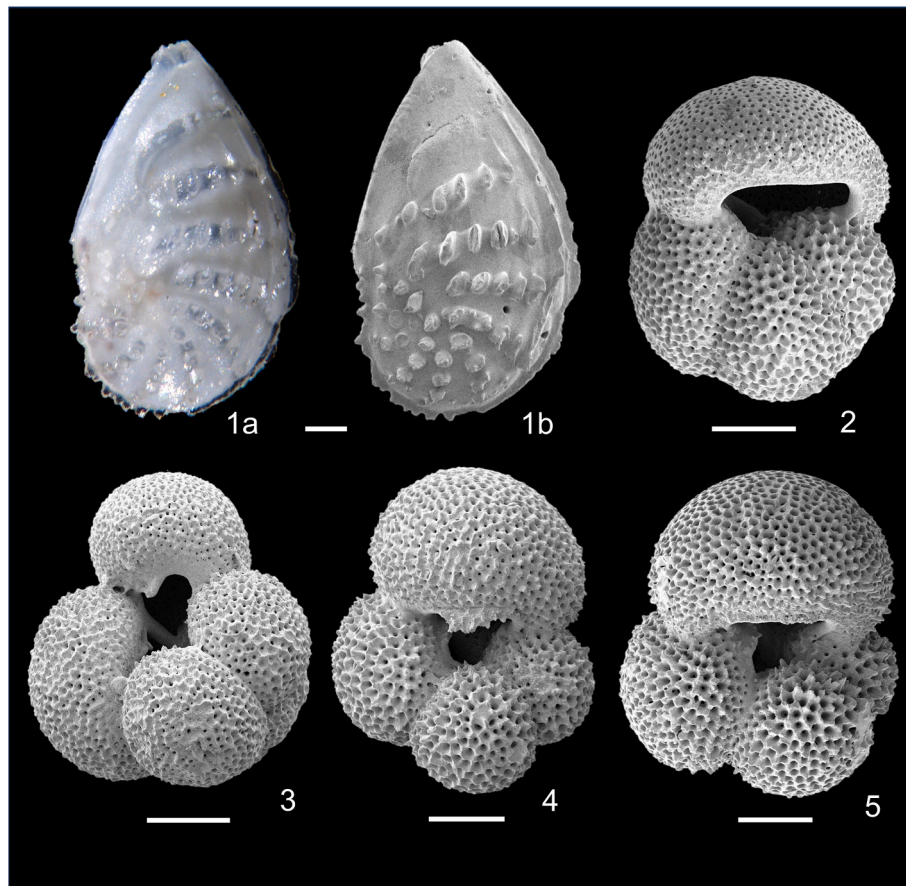


Fig. 20. Light microscope and SEM images of foraminifera from the Rushungi area. 1a-b, Sample BW18-T7, Rushungi road section, LM and SEM images, *Perulotozonaria* sp. 2-5, Sample BW18-T18, Rushungi approach, SEM images: 2, *Turborotalia ampliapertura*, same specimen as Fig. 19.6. 3, *Subbotina projecta*, same specimen as Fig. 13.15. 4, *Dentoglobigerina pseudovenezuelana*, same specimen as Fig. 19.8. 5, *Dentoglobigerina tapuriensis*, same specimen as Fig. 19.10. Scale bars = 100 µm.

Cibicidoides spp. and *Anomalinoides* spp. Planktonic foraminifera are relatively common (~22%). The assemblage is typical of a dysoxic outer shelf to upper slope shelf environment. Palaeodepths may have been as deep as 170 m. Over 20% of the benthic foraminifera are reworked, including the shallow taxa: *Cibicides* spp. and *Notorotalia* spp. Nannofossil preservation is moderate to good and is notable for containing several rarely preserved fragile taxa, including *Syracosphaera* and *Rhabdosphaera poculi*.

6.6. Sample BW18-T27 (middle Miocene, 14.89 ± 0.23 Ma, Mchinga turn)

This sample, shown in Fig. 22, has the same preservational features as Sample BW18-T26, above. Unlike that sample, which is from a little lower down in the same outcrop, it contains a good suite of *Praeorbulina* species, showing the transition from *Trilobatus bisphericus* to *Orbulina suturalis* (Fig. 22.5.9). The latter are distinguished from *Praeorbulina* by the presence of scattered enlarged pores (incipient areal apertures) positioned away from the sutures.

Another species of note is a form with rough wall texture and an aperture almost closed off by dense spines or spine bases (Fig. 22.3a and b). Although rarely described in the literature, this species is common in the Tanzanian middle Miocene. It was illustrated as '*Globoturborotalita* sp.' by Stewart et al. (2004) from Sample RAS99-38 from Ras Tipuli. We investigated it further by examining a suite of specimens from Sample LJC09-T71, a slightly younger sample from Ras Mongo (Fig. 23). The basic morphology is a small, quite high-spined globigeriniform test with a small or almost non-existent primary aperture. Larger specimens can be very high spired and irregular in chamber placement (Fig. 23.6-9).

The simpler morphology accords well with *Globigerina eamesi* of Blow (1959), originally described from the upper Miocene of Venezuela. The larger variants appear to be late ontogenetic developments of this species.

The foraminiferal assemblage is similar to BW18-T26 and is interpreted to have been deposited in a similar dysoxic outer shelf to upper slope environment at a slightly deeper palaeodepth (>230 m) where transported taxa (~9%) are not as common.

6.7. Sample BW18-T22 (middle Miocene, 11.62 ± 0.05 Ma, Ras Tipuli)

Samples from Ras Tipuli are generally well-preserved with abundant siderite nodules. This is the best-preserved of the set and so was selected for more detailed study (Fig. 24). It lacks *Praeorbulina* but includes relatively common *Orbulina suturalis* and *O. universa*. Other species of note are the zone fossils *Globorotalia archeomenardii* and *Paragloborotalia siakensis*.

The BW18-T22 foraminifera assemblage resembles BW18-T26 and T27, except it yields more common planktonic foraminifera (~37%) suggesting deeper (~370 m) palaeodepths. Foram yields are slightly lower (>2300 forams/gm). Nannofossil preservation is moderate/good and is notable for containing frequent rarely preserved fragile taxa, including *Syracosphaera* spp. and *Rhabdosphaera* spp.

7. Conclusion

Our study of outcrop samples collected in several expeditions confirms that the Paleogene sediments represent an upper slope environment, with plankton assemblages including deep-water elements from

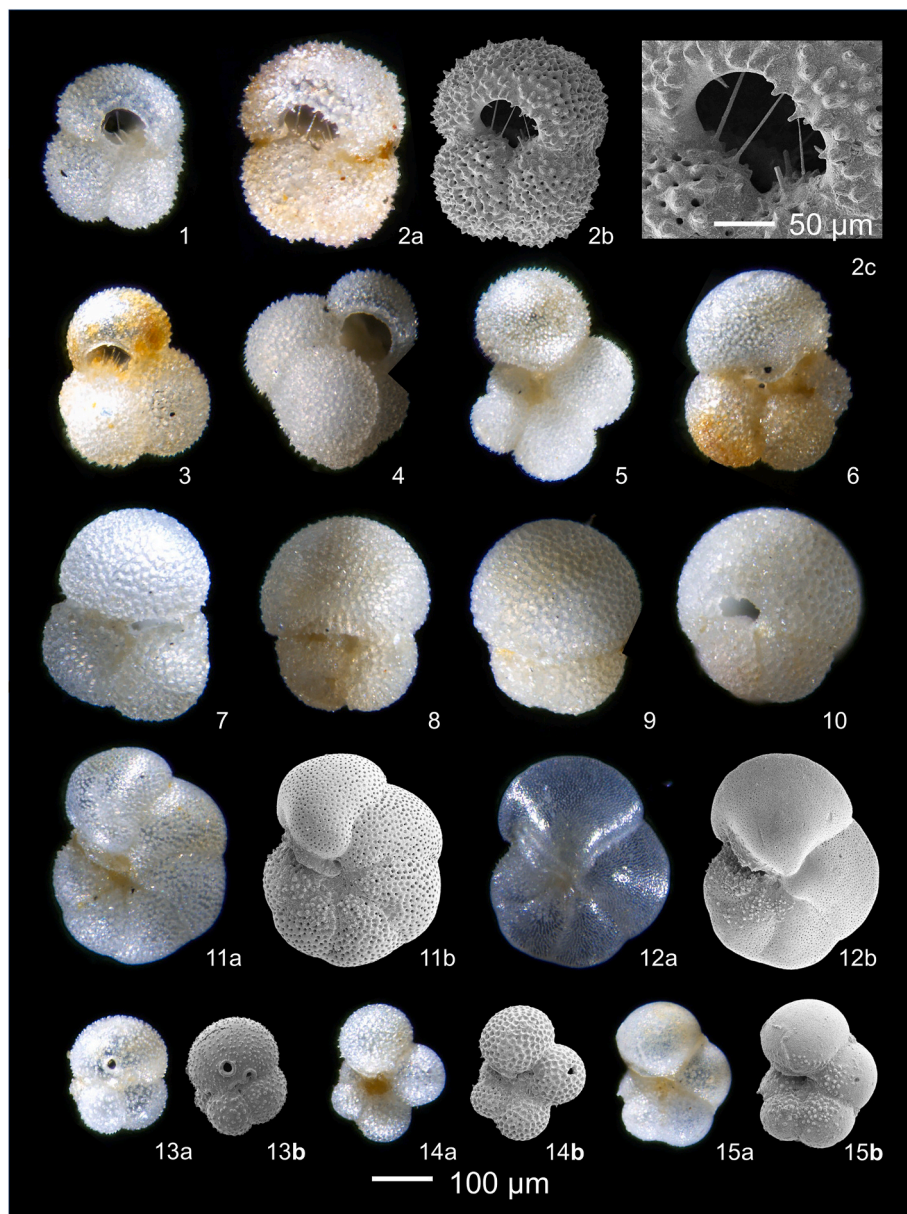


Fig. 21. Light microscope and SEM images of foraminifera from Sample BW18-T26, Mchinga turn. 1-2c, *Globigerinoides subquadratus*, with spines preserved in the aperture. 3, *Globigerinoides obliquus*, with spines preserved in the aperture. 4, *Globigerinoides mitra*. 5, *Globigerinella praesiphonifera*. 6, *Dentoglobigerina baroemoensis*. 7, *Trilobatus trilobus*. 8-10, *Trilobatus bisphericus*. 11a-b, *Fohsella peripheroronda*. 12a-b, *Globorotalia praescitula*, 13a-b, *Globigerinatella insueta* (small specimen with just two areal apertures). 14a-b, *Globorotaloides* sp. 15a-b, *Mutabella mirabilis*.

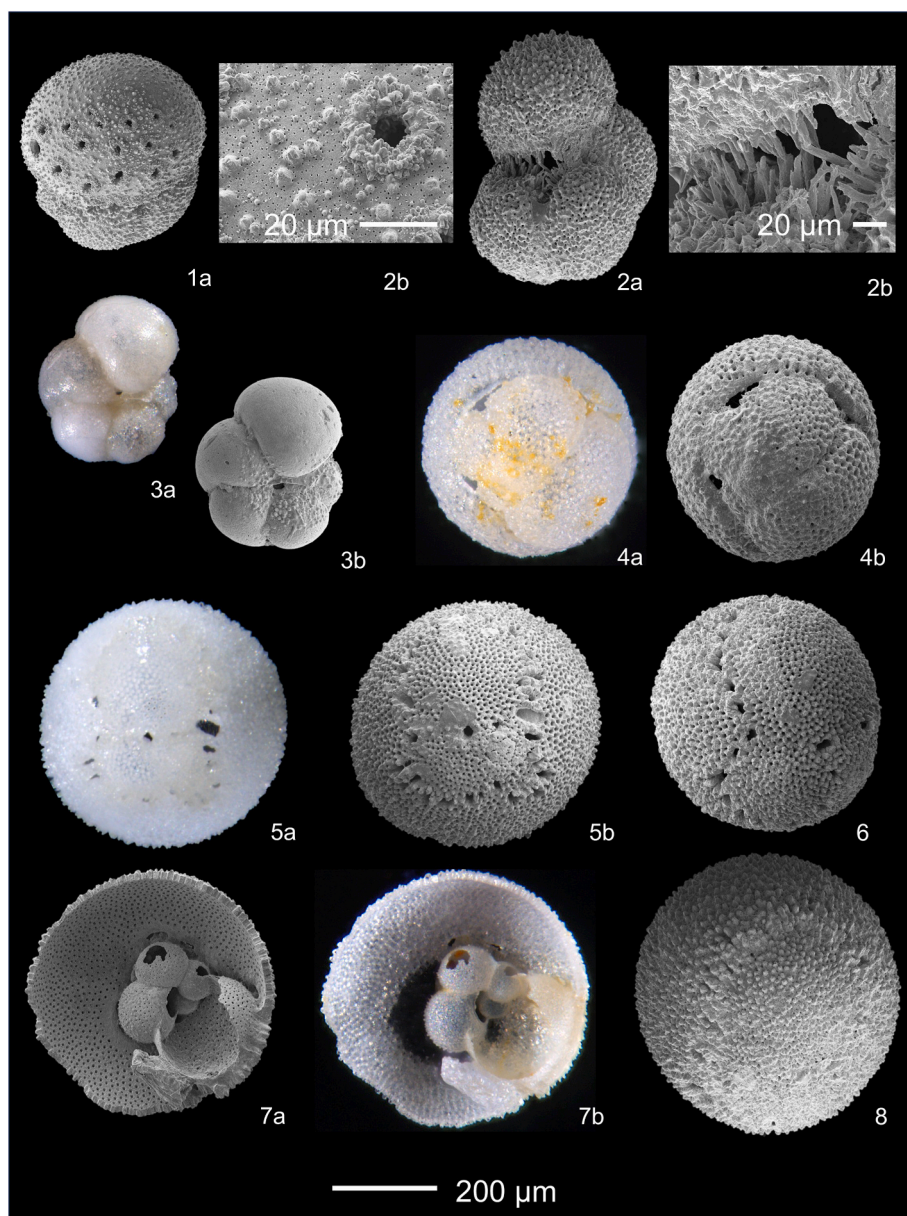


Fig. 22. Light microscope and SEM images of foraminifera from Sample BW18-T27, Mchinga turn. 1a-b, *Globigerinatella insueta*, with detail of the microperforate wall and areal aperture. 2a-b, *Globoturborotalita eamesi*, high-spined variant. 3a-b, *Mutabella mirabilis*. 4a-b, *Praeorbulina sicana* with four apertures around the base of the final chamber (three visible). 5a-7b, *Praeorbulina circularis* including broken specimen showing early whorls. 8, *Orbulina suturalis*, transitional form with scattered slightly enlarged pores.

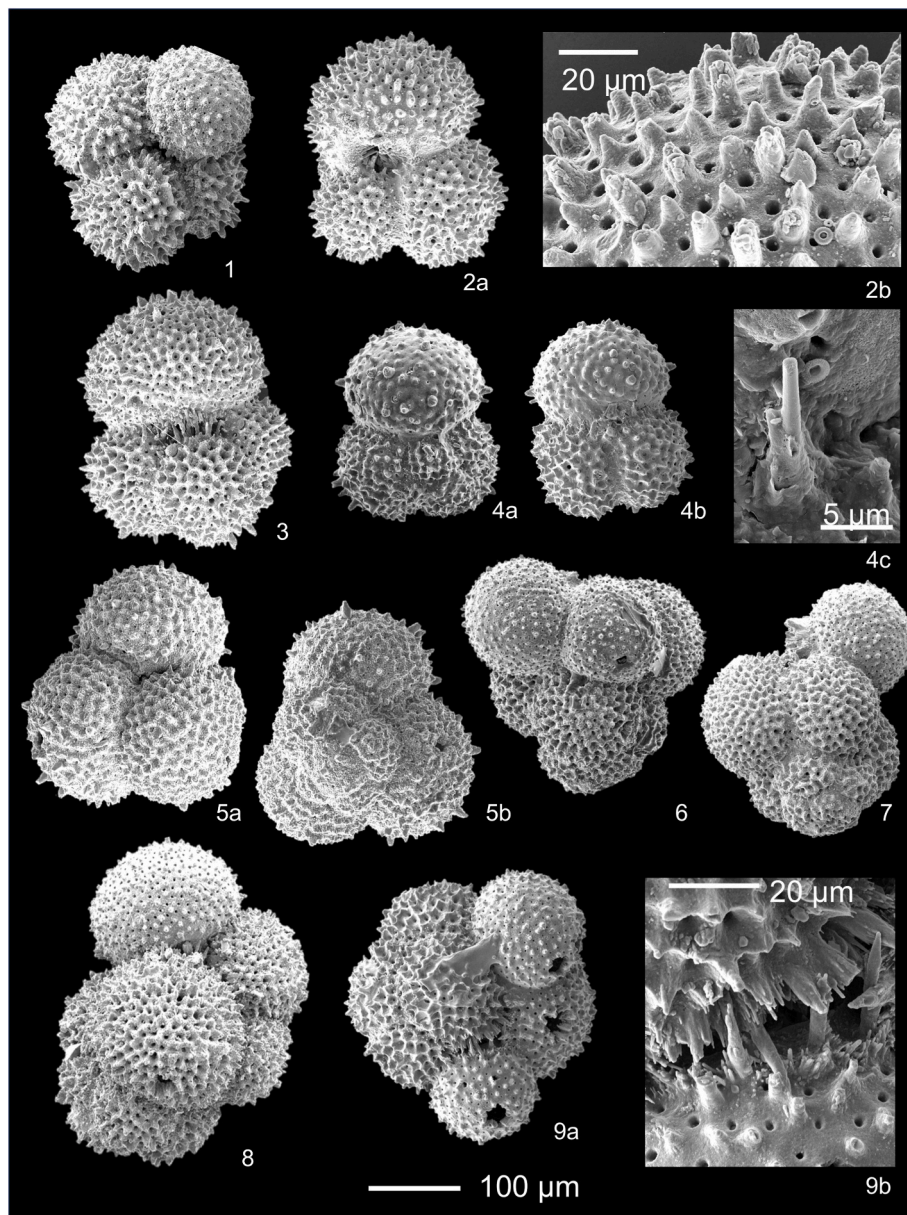


Fig. 23. SEM images of *Globoturborotalita eamesi* from Sample LJC09-T71. 1, specimen illustrating the basic form, a small, very rugose globigerini-form with a narrow umbilicus, similar to the holotype from Venezuela. 2, specimen showing the rough wall texture formed of raised spine bases, similar to the muricae seen in Paleogene *Acarinina*. 3, specimen with the aperture almost obscured by rugosities. 4a-c, umbilical, spiral and detail views of a small specimen showing what appears to be a true spine protruding from one of the rugosities in the sutural area. 5a-b, umbilical and spiral view of another specimen with an almost entirely closed primary aperture. 6-8, large, high-spired variants. 9a-b, spiral view of an aberrant specimen with two additional chamberlets and rugosities obscuring the small supplementary aperture.

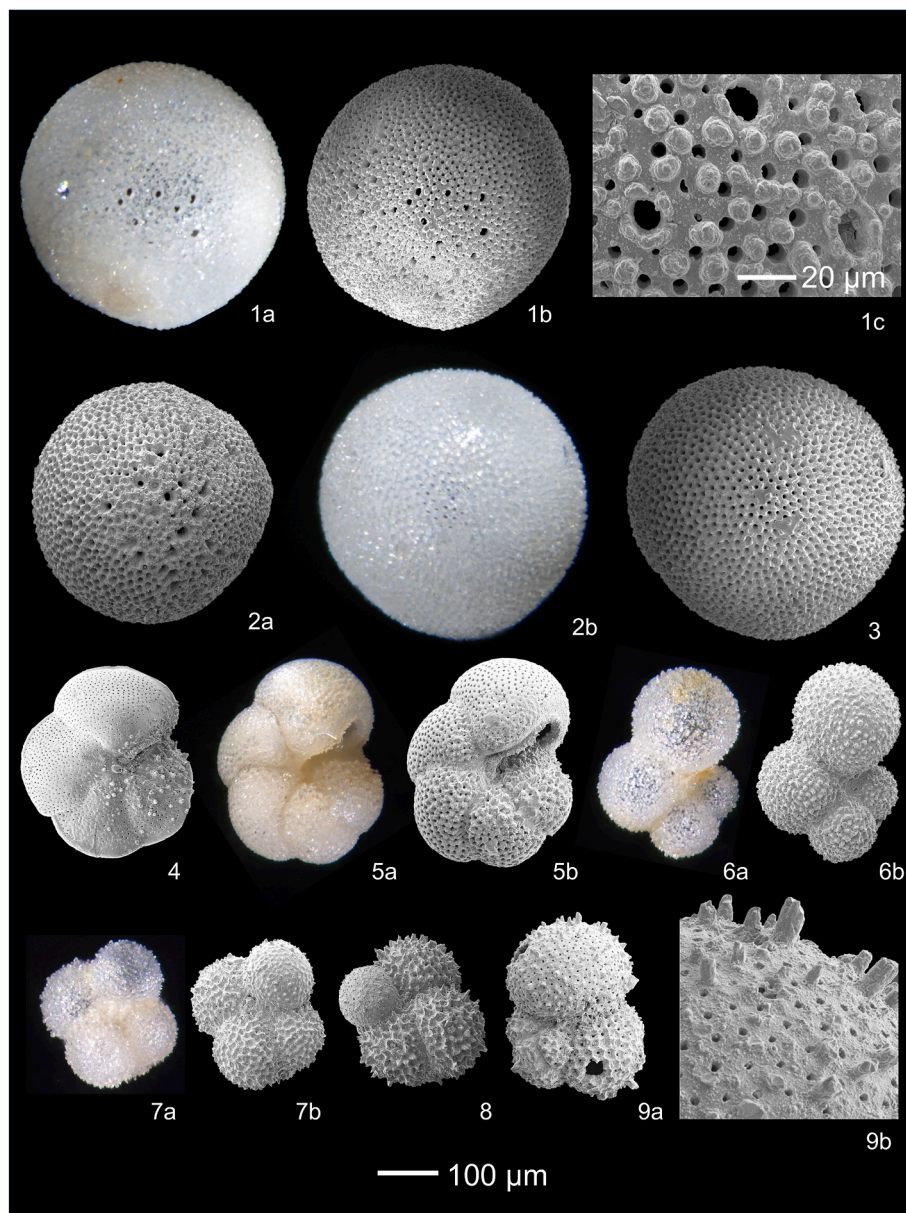


Fig. 24. Light microscope and SEM images of planktonic foraminifera from Sample BW18-T22. 1a-2b, *Orbulina suturalis*. 3, *Orbulina universa*. 4, *Globorotalia archeomenardii*. 5a-b, *Paragloborotalia siakensis*. 6a-b, *Globigerinella praesiphonifera*. 7a-9b, *Globoturbotalita eamesi*.

an open ocean environment. Limestones and sandy limestones with transported shallow-water fossil assemblages occur as occasional turbidites and debris flows through much of the Paleogene succession. The Neogene sediments appear to represent a generally shallower environment, alternating between in-situ limestones rich in larger benthic foraminifera and deeper-water clays. We have confirmed the excellent preservation potential of Kilwa Group hemipelagic sediments and Miocene claystones for further palaeontological palaeoenvironmental, and palaeoclimatic investigations. Of the outcrop samples collected, seven are particularly promising in containing excellently preserved carbonate microfossils ranging in age from upper Eocene (35.96 ± 0.17) to middle Miocene (11.62 ± 0.05 Ma). These samples will be subjected to a wide range of additional geochemical analyses, including further organic geochemistry, trace metals, carbon and oxygen stable isotopes, and boron isotopes. The samples preserve a long record of tropical biodiversity which will help fill gaps in our knowledge of the evolution of marine biodiversity hotspots through the Paleogene and Neogene.

More broadly, our results underline the potential for further

scientific drilling, which will not only improve our knowledge of the stratigraphy of the coastal regions, its geology and tectonics, but also provide new material for paleoenvironmental research not covered by previous drilling. We have confirmed that the Kilwa Group extends into at least the upper Oligocene, and excellent carbonate and organic matter preservation continues to the middle Miocene. The connection between Oligocene and Miocene strata remains unclear and could be clarified with further scientific drilling.

CRediT authorship contribution statement

P.N. Pearson: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **T. Agterhuis:** Writing – review & editing, Formal analysis, Data curation. **P.R. Bown:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. **L.J. Cotton:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **S.J. Gallagher:** Writing – review & editing,

Writing – original draft, Resources, Investigation, Formal analysis, Data curation. **G.N. Inglis:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Formal analysis. **C.J. Nicholas:** Writing – review & editing, Investigation. **E. Piga:** Writing – review & editing, Methodology, Investigation. **I. Rutta:** Writing – review & editing, Investigation. **A. Sajilo:** Writing – review & editing, Investigation. **B.S. Wade:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafrearsci.2026.106354>.

Data availability

Data are provided in the manuscript and as Supplemental Information

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