Available online at www.sciencedirect.com

SCIENCE DIRECT

Journal of African Earth Sciences 45 (2006) 431–466

Journal of African Earth Sciences

www.elsevier.com/locate/jafrearsci

Stratigraphy and sedimentology of the Upper Cretaceous to Paleogene Kilwa Group, southern coastal Tanzania

Christopher J. Nicholas [a,*], Paul N. Pearson [b], Paul R. Bown [c], Tom Dunkley Jones [c], Brian T. Huber [d], Amina Karega [e], Jackie A. Lees [c], Ian K. McMillan [b], Aoife O'Halloran [a], Joyce M. Singano [e], Bridget S. Wade [f]

[a] *Department of Geology, Trinity College, University of Dublin, Dublin 2, Ireland*
[b] *School of Earth, Ocean and Planetary Sciences, Cardiff University, Main Building, Park Place, Cardiff CF10 3YE, United Kingdom*
[c] *Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, United Kingdom*
[d] *Department of Paleobiology, MRC NHB-121, P.O. Box 37012, Smithsonian National Museum of Natural History, 10th and Constitution Avenue, Washington, DC 20012-7012, USA*
[e] *Tanzania Petroleum Development Corporation, P.O. Box 2774, Dar-es-Salaam, Tanzania*
[f] *Department of Geological Sciences, Rutgers, The State University of New Jersey, Wright Laboratory, Busch Campus, 610 Taylor Road, Piscataway, NJ 08954-8066, USA*

Received 10 October 2005; received in revised form 13 March 2006; accepted 7 April 2006
Available online 13 June 2006

Abstract

The geology of southern coastal Tanzania has remained poorly understood since the first comments on its stratigraphy were made over 100 years ago. However, new field surveys combined with shallow drilling along the coast between Kilwa and Lindi are beginning to resolve the depositional history and structural evolution of this region over the past 85 Ma. Here we present the first attempt to synthesize the results of these studies to provide a coherent sedimentological, litho- and sequence stratigraphic framework, including new geological maps, for the Upper Cretaceous and Paleogene of the coastal zone.

Santonian to Oligocene sediments crop out along a broad coastal belt south of the Rufiji River from the Kilwa peninsula to Lindi Creek in southern Tanzania. During ~55 Ma, over 1 km of a broadly homogeneous, mid to outer shelf clay-dominated succession was deposited across the passive margin, which we define here as the Kilwa Group. This lies disconformably across the shelf on Albian marls and is itself unconformably overlain by shallow water Miocene clays and more recent limestones, sands and gravels. Four formations can be identified within the Kilwa Group on the basis of characteristic secondary lithologies and facies, described here for the first time; the Nangurukuru, Kivinje, Masoko and Pande Formations. These formations include conformable stratigraphic intervals through both the Paleocene–Eocene and Eocene–Oligocene boundaries. Within the Kilwa Group, 12 sequence stratigraphic cycles can be identified at present, demonstrating relatively uniform and continual subsidence across the margin from Santonian to Early Oligocene time. A further major bounding surface is present between the Upper Cretaceous and Paleogene, but this may become partly conformable in the Lindi area. Although the principal lithology in all formations is clay or claystone, there are more permeable intervals containing pervasive coarser siliciclastic sediments and these have yielded traces of crude oil which is likely to have migrated from lower in the succession. The Kilwa Group thus also provides important new evidence for petroleum play development in the southern coastal zone.

Keywords: Cretaceous; Paleogene; Lithostratigraphy; Kilwa; Group; Formation; Facies; Sequence stratigraphy; Petroleum

1. Introduction

The presence of Cretaceous and Paleogene sediments along the southern coast of Tanzania has been known since

* Corresponding author. Tel.: +353 1608 2176; fax: +353 1671 1199.
E-mail address: nicholyj@tcd.ie (C.J. Nicholas).

1464-343X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jafrearsci.2006.04.003

they were first mentioned by Bornhardt (1900). The geological map of southern coastal Tanzania in Kent et al. (1971) shows continuous Cretaceous outcrop along strike from south of the Rufiji River to the Tanzanian–Mozambique border. Paleogene age sediments crop out along the coastal zone from the Kilwa peninsula to Lindi, but are partly covered beneath an angular Neogene unconformity (Fig. 1a). However, no systematic attempt has previously been made to resolve the chronostratigraphy and establish a formal lithostratigraphy for this coastal region. In this paper we define four formations which together compose the clay-dominated Upper Cretaceous to Paleogene Kilwa Group. We have resolved the litho-, bio- and chrono-stratigraphy of the Kilwa Group from detailed field studies in three main areas; (1) the Kilwa peninsula and adjacent mainland, (2) the western flank of the Pande peninsula and (3) the area around Lindi Creek (Fig. 1b).

The Kilwa Group represents a near continuous stratigraphic succession from the Santonian to Lower Oligocene. The Cretaceous–Tertiary transition is faulted at both Kilwa and Pande, but may at least be conformable in part at Lindi, as basal Paleocene has previously been reported at Kitulo Hill (Blow and Banner, 1962; Blow, 1979). However, the group includes comparatively rare

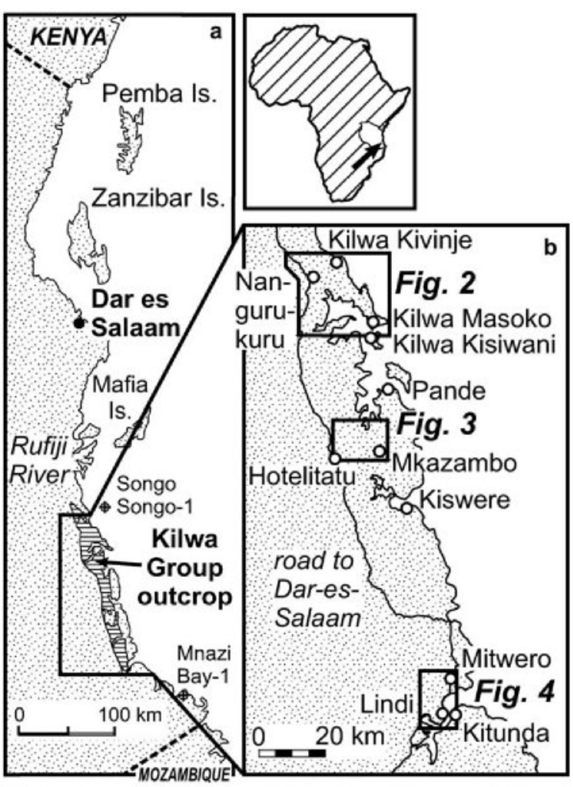


Fig. 1. Geographical setting of the Kilwa Group. (a) The current predicted extent of the Kilwa Group outcrop in southern coastal Tanzania, based partly on our field surveys and partly on Kent et al. (1971). The two shallow offshore gas production wells at Songo Songo and Mnazi Bay are also shown. (b) Location of the major towns and villages encountered in this study. The three main map areas of Kilwa (Fig. 2), Pande (Fig. 3) and Lindi (Fig. 4) are also shown.

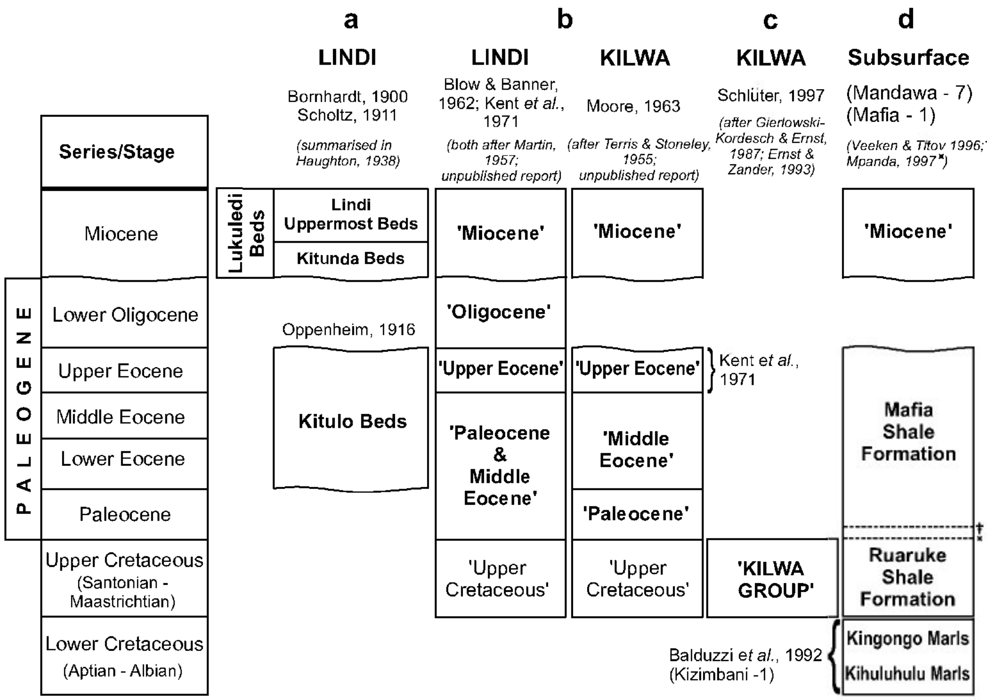
onshore sequences that span both the Paleocene–Eocene boundary, including the Paleocene–Eocene Thermal Maximum (PETM) event, and the Eocene–Oligocene boundary. The preservation of microfossils in the area is often excellent, making the group significant for palaeontological and palaeoclimate research (see Pearson et al., 2001). Also, at present, no economic accumulations of petroleum have been discovered in East Africa. Yet the Kilwa Group contains oil trapped near-surface within Paleogene clays and includes surface oil seeps along the Kilwa peninsula. In Tanzania's two shallow offshore production gas fields, the Kilwa Group also currently provides part of the seal at Songo Songo, north-east of Kilwa, and both reservoir and seal at Mnazi Bay, south of Lindi (Fig. 1a). Thus the group clearly occupies a pivotal role in understanding the hydrocarbon geology of the region.

It is intended that the results of detailed sedimentary petrography, structural and petroleum geology studies will be dealt with in future publications. The concern of this present paper is, based as far as possible on our field evidence and recent drill cores (Pearson et al., 2004, 2006), to outline a coherent lithostratigraphic and sequence stratigraphic scheme in a workable format that can be applied in future field surveys along the coastal zone of Tanzania. The lithostratigraphic scheme introduced here was constructed and tested during field work from 1998 to 2005, during which time we visited all significant exposures of the Kilwa Group between Kilwa and Lindi. It should be remembered, in the sections which follow, that this coastal zone is covered for the most part inland by thick bush, cultivations and palm groves. At the coast, mangrove swamps can also obscure much of the exposure. Tropical weathering can penetrate as much as 20 m down from the present ground surface and we have evidence of recent clay slumping around some of the hills. Field exposure is for the most part obtained where seasonal rains have temporarily stripped away the clay soil cover, for instance in drainage ditches by the roadside. In these exposures, bedding dips are rarely if ever seen.

1.1. Previous stratigraphic nomenclature

No references to either the Upper Cretaceous or Paleogene stratigraphy of the Kilwa or Pande areas exist prior to the 1950s. The earliest references to the Paleogene stratigraphy of the Lindi area were made by German geologists en route to or from the Tendaguru dinosaur excavations in south-western Tanganyika during the period from 1900 to the end of German rule in 1918. Bornhardt (1900), Scholtz (1911) and Oppenheim (1916) all informally recognised the 'Lukuledi Beds' on the southern side of the Lukuledi River at Kitunda, near Lindi (Table 1; a). These were described as 'impure greyish-yellow to reddish fossiliferous limestone, with angular to little rounded quartz pebbles and shell fragments, grey porous limestone, light grey hard coral and foraminiferal limestone' (as summarised in translation by Haughton, 1938). The 'Lukuledi Beds' were

Table 1
Previous informal stratigraphic nomenclature for the southern Tanzanian coast



(a) Early terminology suggested for the Lindi area. (b) Stratigraphic schemes for Kilwa and Lindi areas following the first field surveys by BP-Shell in the 1950s. (c) Informal introduction of the name 'Kilwa Group' by Schlüter (1997). (d) Subsurface terminology used in the closest onshore (Mandawa-7 and Kizimbani-1) and offshore (Mafia-1) wells.

subdivided into two informal units; the 'Lindi Uppermost Beds' and underlying 'Kitunda Beds'. However, the macro- and microfossil faunas listed for these two units (Haughton, 1938) suggest that they are at least partly of Neogene age. Indeed, based on our reappraisal of the Kitunda section, the general description of the 'Lukuledi Beds' suggests that what was recognised in the field was a mixture of patchy Plio–Pleistocene reef knolls, marine sands and Miocene reef limestones.

Another informal stratigraphic unit was recognised by Oppenheim (1916) exposed from Lindi Town westwards to Kitulo Hill (Table 1; a). A series of limestones were recognised and referred to as the 'Kitulo Beds' with a lower and an upper Eocene faunal assemblage. Our mapping of the Lindi area suggests this unit consists of what would now be recognised as a mixture of Paleogene limestones unconformably overlain by Miocene or younger sandy limestones, which cap the dip-slope of Kitulo Hill.

The first systematic, detailed field surveying of southern coastal Tanzania was conducted as part of a petroleum exploration programme by BP-Shell Tanganyika Ltd., during the 1950s. Aerial photo-reconnaissance produced the first topographic maps with accompanying photo-geological interpretations. These were used during subsequent land-based 'ground-truthing' in each survey area. This exploration was summarised by a series of internal reports, including stratigraphic sample lists and insert outline geological maps. Although some of these reports are now lost or have survived incomplete, those for Kilwa and Lindi still exist in the Tanzania Petroleum Development Corporation (TPDC) archives at Dar-es-Salaam. In both areas, the coastal stratigraphy was informally subdivided into chronostratigraphic units (Table 1; b). At Kilwa, A.P. Terris and R. Stoneley recognised Upper Cretaceous, Paleocene, Middle Eocene, Upper Eocene and Miocene units. They recognised for the first time that the succession was dominated by marls and clays with subordinate sandstones and fossiliferous limestones dispersed at intervals throughout. The report by Terris and Stoneley was used to produce the first published geological map of the area (Moore et al., 1963), which included notes establishing the extensive Upper Cretaceous to Neogene stratigraphic succession, but provided no further attempt to subdivide or formalise the stratigraphy.

At Lindi, F.C.R. Martin (in another unpublished BP-Shell report from 1957) also recorded a thick, clay-dominated succession but did not recognise the Lower Eocene and left the Paleocene and Middle Eocene undivided as a unit (Table 1; b). However, Martin did find Oligocene clays either side of Lindi Creek which yielded planktonic foraminifers subsequently used to define the global basal biozone of the Oligocene (Blow and Banner, 1962; Blow, 1979).

However, although intended, no corresponding Geological Survey map was published for Lindi following Martin's report. Small sketch maps based on Martin's original appeared in Blow and Banner (1962) and Kent et al. (1971) and these have remained the only published geological maps for the Lindi area. The unpublished exploration survey reports were extensively referenced in the overview of coastal southern Tanzanian geology by Kent et al. (1971) and this has remained the standard text on southern coastal Tanzanian geology.

The most recent additions to surface stratigraphic nomenclature relate to the Upper Cretaceous sequence that

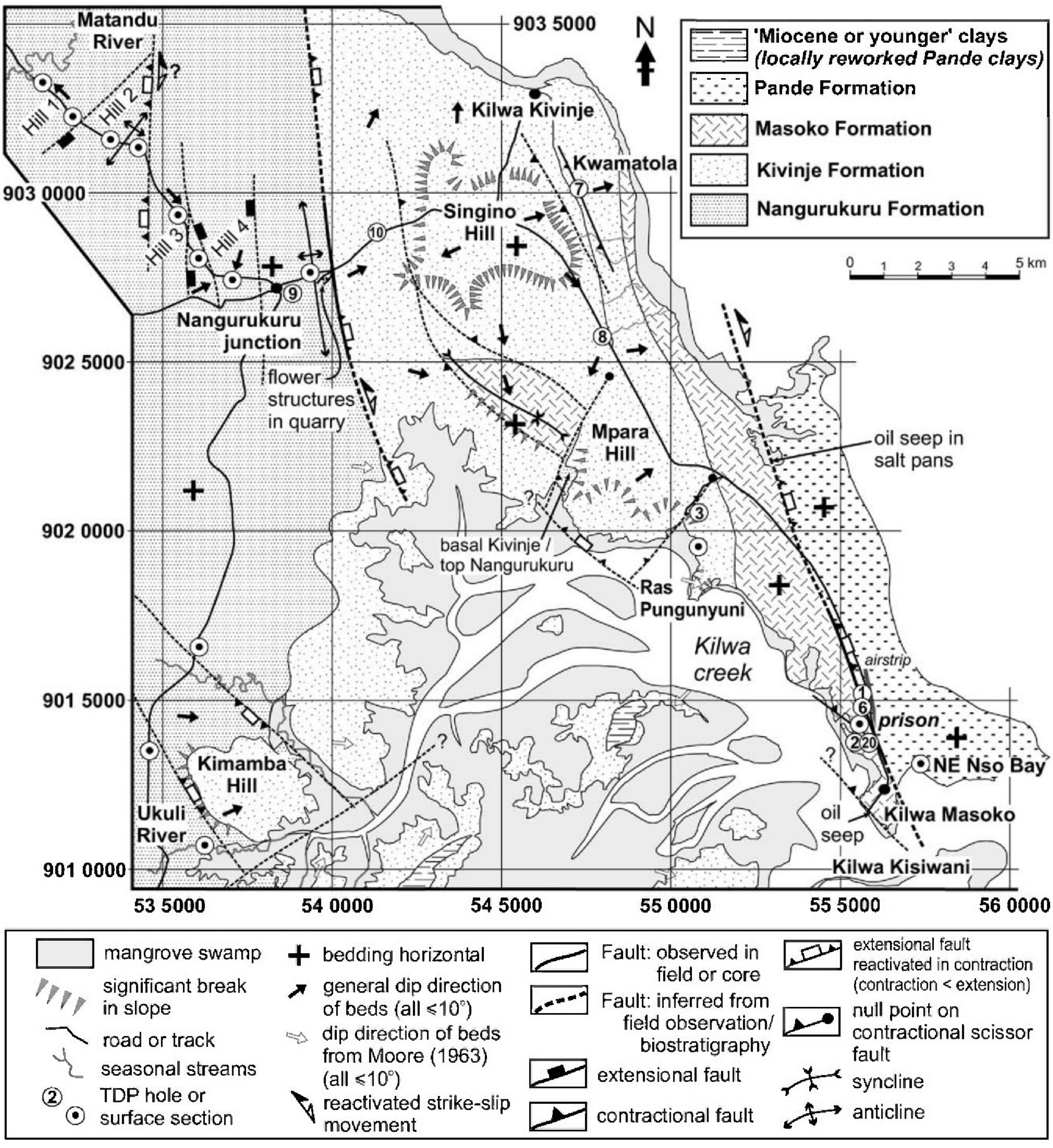


Fig. 2. Simplified geological map of the Kilwa peninsula. Faults and their trends are plotted from a combination of our field data and identification on satellite imagery. The position of all TDP sites and surface sections correlated in Figs. 6–17 are shown on this map and in Figs. 3 and 4. All dips in the Kilwa Group approximate to subhorizontal and are ⩽10° unless in the immediate vicinity of a fault zone. However, locally this can be complicated by recent slumping in the clays.

is intermittently exposed along the roadside between Matandu Bridge and Nangurukuru junction, to the north-west of the Kilwa peninsula (Fig. 2). During excavations for a new road in the mid to late 1980s, fresh sections were exposed in road cuts along the route. These were subsequently logged and described in Gierlowski-Kordesch and Ernst (1987), Ernst and Schlüter (1989), and Ernst and Zander (1993). The clays, marls and silty clays contain the characteristic deep-water flysch *Nereites* ichnofacies (Plate 1a and b). Schlüter (1997, p. 232) later named this succession the Kilwa Group, in the first use of this name for stratigraphic purposes (Table 1; c). However, the previous work by Gierlowski-Kordesch and Ernst (1987), Ernst and Schlüter (1989), and Ernst and Zander (1993) recognised no formations with which to establish a new group, and Schlüter (1997) provided no definitions for the 'Kilwa Group' as a lithostratigraphic unit in itself.

Subsurface stratigraphic nomenclature in exploration wells from the 1980s to the present day subdivides the Cretaceous to Paleogene clay-dominated sequences into four informal units (Table 1; d). The Lower Cretaceous Kihuluhulu and Kingongo Marls (Balduzzi et al., 1992; Veeken and Titov, 1996) are overlain by the Upper Cretaceous Ruaruke Shale Formation. Veeken and Titov (1996) continue the Ruaruke Shale Formation into the Paleocene, but Mpanda (1997) shows it to be exclusively Upper Cretaceous. The Paleogene is recognised as a single unit referred to as the Mafia Shale Formation (Veeken and Titov, 1996; Mpanda, 1997), overlain by Miocene and younger 'Mikindani' terrestrial clastics or 'Mafia carbonates' (Mpanda, 1997).

1.2. The Tanzania Drilling Project (TDP)

Initial reconnaissance field work by us in the Kilwa and Lindi areas between 1998 and 2000 focussed on the recovery from surface exposures of exceptionally preserved Paleogene planktonic foraminifer shells for palaeo-climatic studies (see Pearson et al., 2001; Stewart et al., 2004). During this period about 500 outcrop samples were collected, many of which yielded biostratigraphic age determinations, allowing us to begin redefining the outcrop patterns of Upper Cretaceous and Paleogene units along the coastal zone. A larger team was assembled in 2002 as the 'Tanzania Drilling Project' (TDP), to undertake shallow continuous coring at selected sites. A total of 22 holes (20 sites with 'B' holes at TDP 7 and 16) were drilled from 2002 to 2005, ranging in depths from 23 m up to 145 m (see Pearson et al., 2004, 2006). Whilst these publications detail the initial drilling results of each field season, we have not until now attempted an overall stratigraphic synthesis between all TDP holes, and integrated all this subsurface data with surface sections and localities visited since 1998. In this paper we outline such an integrated stratigraphic scheme for the Upper Cretaceous and Paleogene of southern coastal Tanzania and discuss it in context with regional facies and sedimentary sequence development along the passive margin.

2. Methods

Large scale geological sketch maps were initially prepared as a reconnaissance in areas prior to the selection of drilling sites. These were later combined with more extensive geological field mapping on a scale of 1:50 000 over a false-coloured 2001 Landsat image with superimposed 5 km Universal Trans-Mercator (UTM) grid using the WGS 84 datum. Many of the towns or villages recorded on topographic base-maps or the geological map of Moore et al. (1963) no longer exist or have changed their name. Figs. 1–4 record the major settlements and local geographical names which we encountered during our surveying. Altitudes used in cross-section construction were obtained by using a Suunto digital altimeter calibrated to changes in barometric pressure and accurate to within 1 m. The altimeter was reset before each survey at the mean high water mark by Kilwa Masoko jetty. Clay colour variations in surface exposures and core were described using the Geological Society of America rock colour chart (based on Munsell Soil colours). For analysis of bulk sediment mineralogy, samples were reduced to a fine powder, and then 5 g was loaded into a cavity mount slide for X-ray diffraction analysis. The X-ray generator used was a Phillips PW1720 with a Phillips PW1050/25 diffractometer and a Phillips PW3313/20 Cu k-alpha anode tube that was run with standard conditions of 40 kV and 20 mA at the Department of Geology, Trinity College Dublin. A soller slit and a 1° divergence slit were used on the incident X-ray beam and an anti-scatter slit followed by a 0.25° receiving slit were used on the diffracted beam, in front of the AMR detector. The detector controller was a Hilton Brooks. All measurements were taken from 2° to 40° (2θ) at a step size of 0.02°/s. Cavity slides were subsequently glycolated at 60 °C overnight and re-analysed to detect the presence of swelling clays.

The lithostratigraphic scheme presented here for the Kilwa Group was established by using high resolution microfossil biostratigraphy to correlate between TDP cores and surface sections, providing chronostratigraphic age dates for the clays and claystones. A lithostratigraphic formational scheme was then built by comparing and correlating clay or claystone facies known to be of the same age. Planktonic and benthic foraminifera, calcareous nannofossil and palynomorph assemblages and their biostratigraphy from TDP sites 1 to 10 have been described previously (Pearson et al., 2004, 2006; Bown, 2005). The microfossil assemblages from TDP sites 11 to 20 will also be described in detail in separate publications (for example, Bown and Dunkley Jones, 2006), however, the biostratigraphic zonation of sites 11–20 are given here. Additional microfossil assemblages from outcrop samples were studied according to the procedures described in Pearson et al. (2004). Cretaceous planktonic foraminifer biozonation used in this study combines the zonal concepts used by Nederbragt (1991) for heterohelicids and Robaszynski and Caron (1995) for globotruncanids, as used in Pearson et al. (2006).

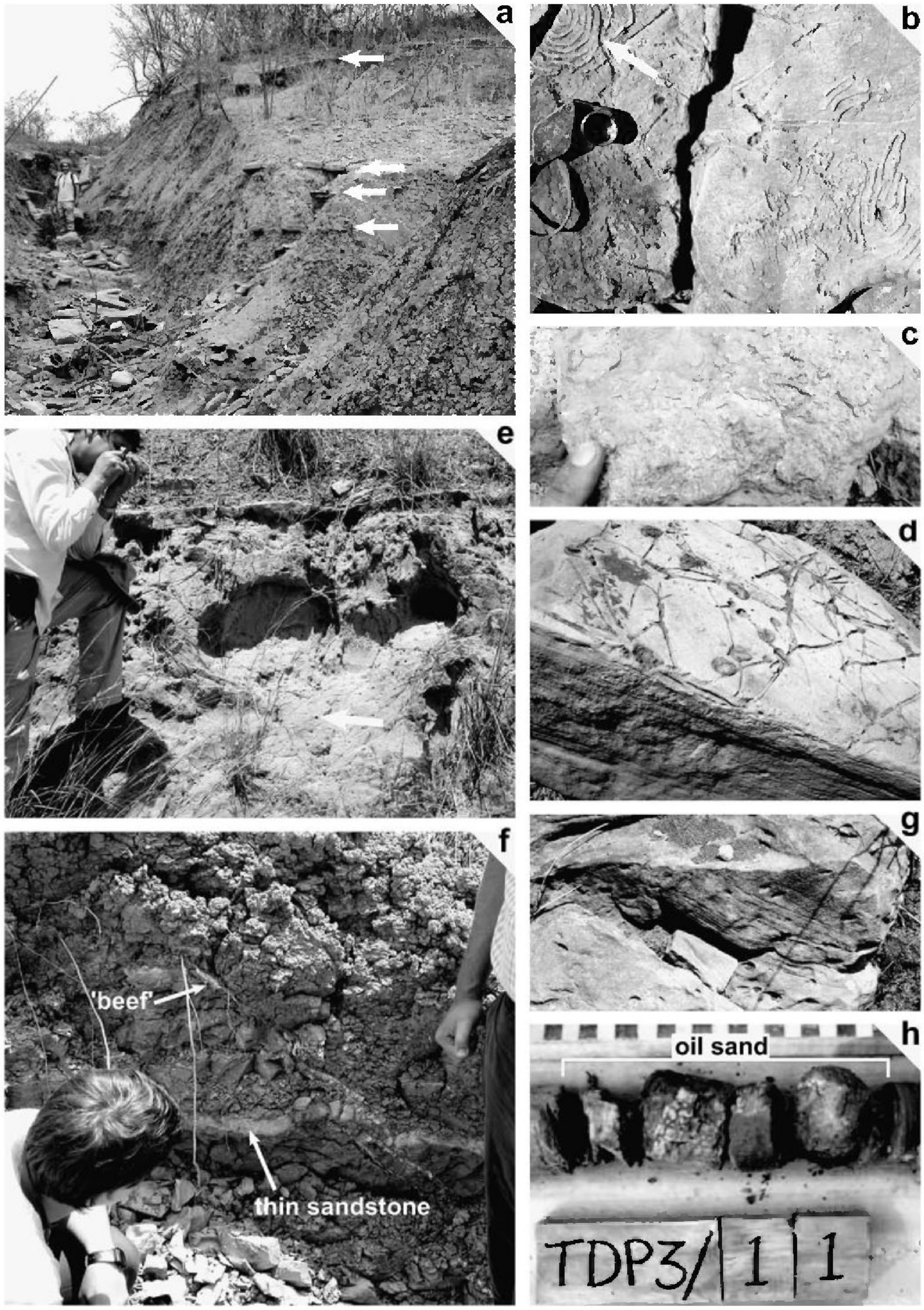


Plate 1. Nangurukuru (a–e) and Kivinje (f–h) formations in outcrop. (a) Typical roadside exposure of Nangurukuru Formation between the Matandu River and Nangurukuru junction (see Fig. 2). The arrows point to individual carbonate-cemented quartz sandstone beds, weathering proud of interbedded olive grey claystones. The figure gives the scale; (b) '*Nereites* ichnofacies' on the basal bedding surface of a thin sandstone bed close to the Ukuli River, south of Nangurukuru. The characteristic spiralled form of *Spirorhaphe* is indicated by the arrow; (c) The intensely grazed and bioturbated top surface of a loose quartz sandstone block, from south of Nangurukuru; (d) Overturned loose block of quartz sandstone by the road north of Nangurukuru. Note the planar laminations in cross-section and the burrowed base to the block. Width of view is ~50 cm; (e) The Upper Campanian limonitic sand marker horizon. A carbonate cemented *Thalassinoides* burrow, weathered proud of the surrounding sands is indicated by the arrow. (f) Typical blocky Kivinje claystone exposure just south of Singino Hill, close to site TDP 8 (see Fig. 2). A thin, poorly cemented sandstone horizon is cross-cut by a diagonal fibrous calcite ('beef') vein. (g) Roadside exposure of massive, planar and convolute laminated benthic foraminiferal sandstones at the base of the exposed Paleocene at Pande, just west of site TDP 19 (Fig. 3). These sandstones are easily distinguished from underlying Nangurukuru sands by the abundance of large benthic foraminifera. Width of view is ~50 cm; (h) An 18 cm thick, sub angular, very fine quartz sand bed in core 11, site TDP 3 at Ras Pungunyuni (Fig. 2). The sand contained residual oil, giving a characteristic smell and black to orange–brown colouration. Depth to the top of the sand is 34.43 m. The scale bar is in centimetres.

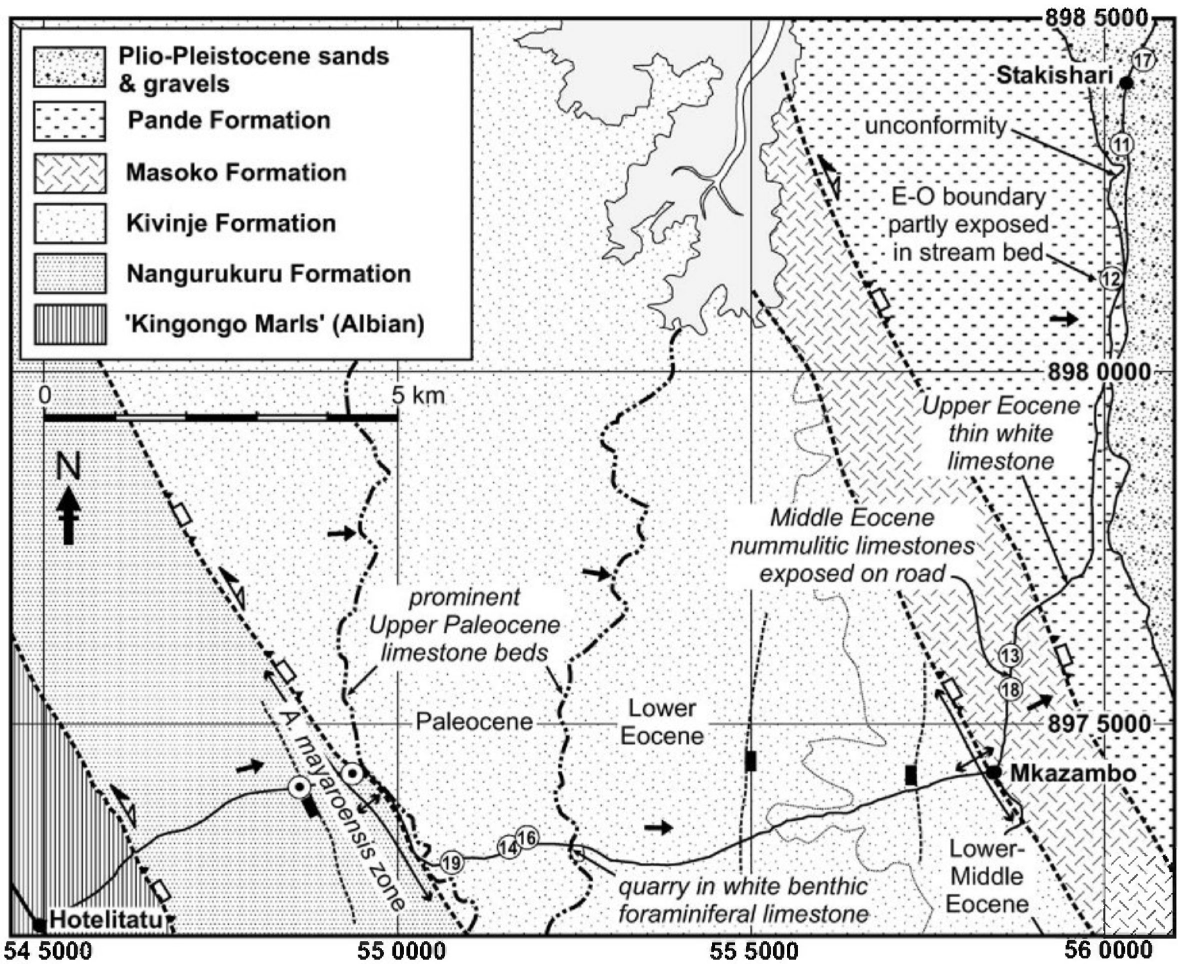


Fig. 3. Simplified geological map of the area leading to the Pande peninsula, from Hotelitatu on the main Dar-es-Salaam to Lindi road to the village of Stakishari. Map symbol key as for Fig. 2.

Paleogene planktonic foraminifer zonations are those of Berggren et al. (1995) and Berggren and Pearson (2005). Cretaceous nannofossil zones are those of Burnett (1998) and for the Paleogene follow Martini (1971). Multiple samples for biostratigraphic age determination were taken from each fresh 3 m core during drilling and as spot samples from field localities. Sample ages and subsequent correlation across the shelf between TDP sites and exposed sections were made after extensive discussion on planktonic foraminifera (Pearson, Wade, Huber, Singano) benthic foraminifera (McMillan, Singano, Karega) and calcareous nannofossil (Bown, Lees, Dunkley Jones) biozonation and constraints. Consequently, TDP sites shown in Figs. 7–17 have planktonic foraminifera biostratigraphic ages accurate to within 3 m in cored intervals, unless otherwise shown. Correlation between surface sections and subsurface TDP holes demonstrates that no single stratotype section exists for any of the four proposed formations in the Kilwa Group. Consequently, they are defined by composite stratotype sections following the International Subcommission on Stratigraphic Classification (ISSC) guidelines (1976).

3. Defining the Kilwa Group

3.1. The Kilwa Group and its lithostratigraphic units

There are three towns associated with the name 'Kilwa' (Fig. 1b). The ruins of Kilwa Kisiwani (meaning 'Kilwa on the island') are the original settlement, dating back to the ninth century (Sutton, 2000). Kilwa Kivinje, at the northern tip of the peninsula, was established as the colonial German East African administrative capital from the 1890s. Finally, Kilwa Masoko ('Kilwa market'), overlooking Kilwa Creek to the old ruins of Kisiwani, is now the main town and administrative centre for the District of Kilwa. As outlined above, the name 'Kilwa Group' was first used informally by Schlüter (1997, p. 232) but no definitions for it were provided. Rather than lose the use of the name 'Kilwa' in any further new stratigraphical nomenclature for this region, we propose to formally redefine the Kilwa Group, whilst keeping its original concept intact. We propose to keep the original roadside units referred to by Schlüter (1997) as a core part of the Kilwa Group, but these form what we would now consider as the

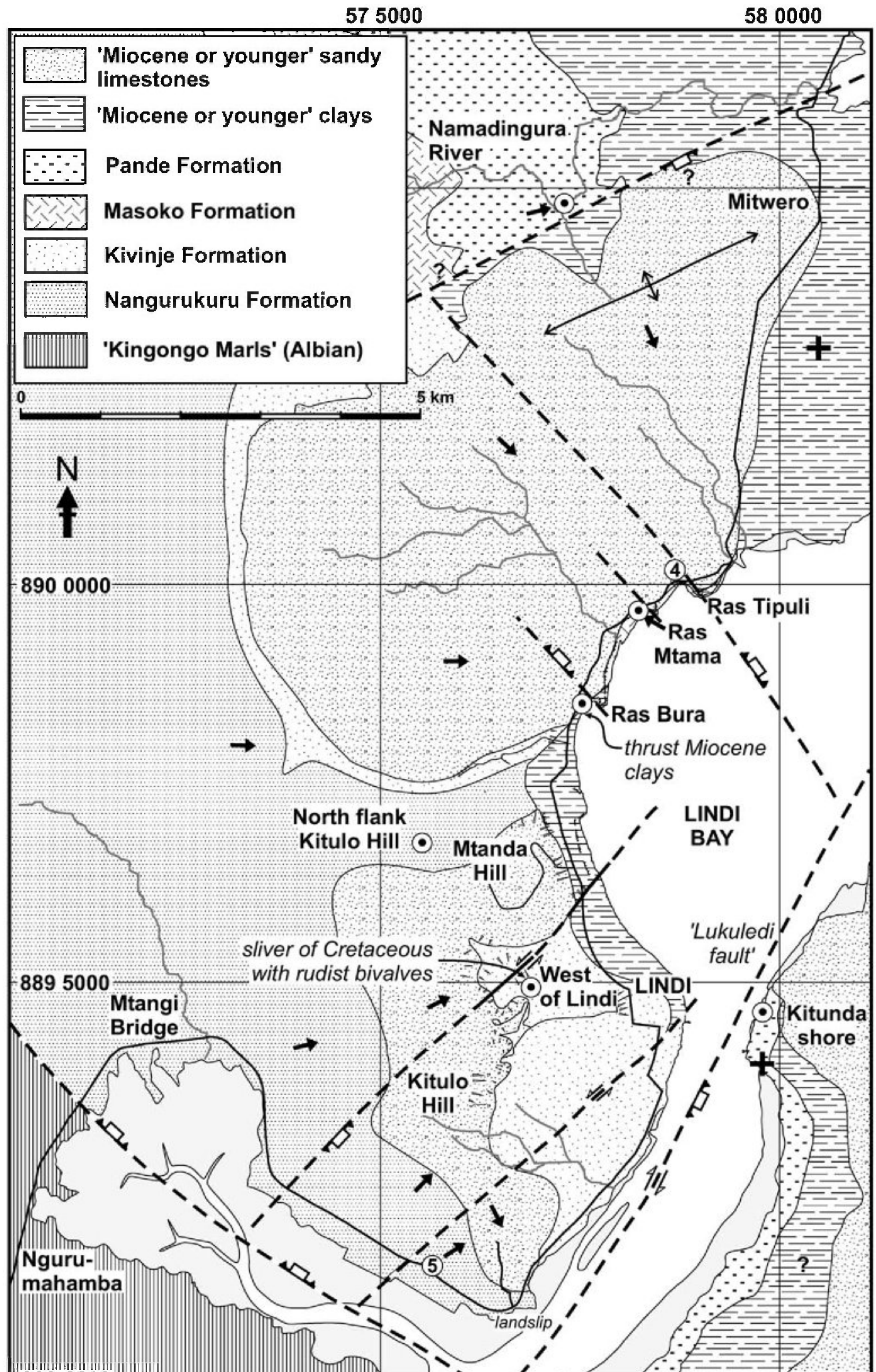
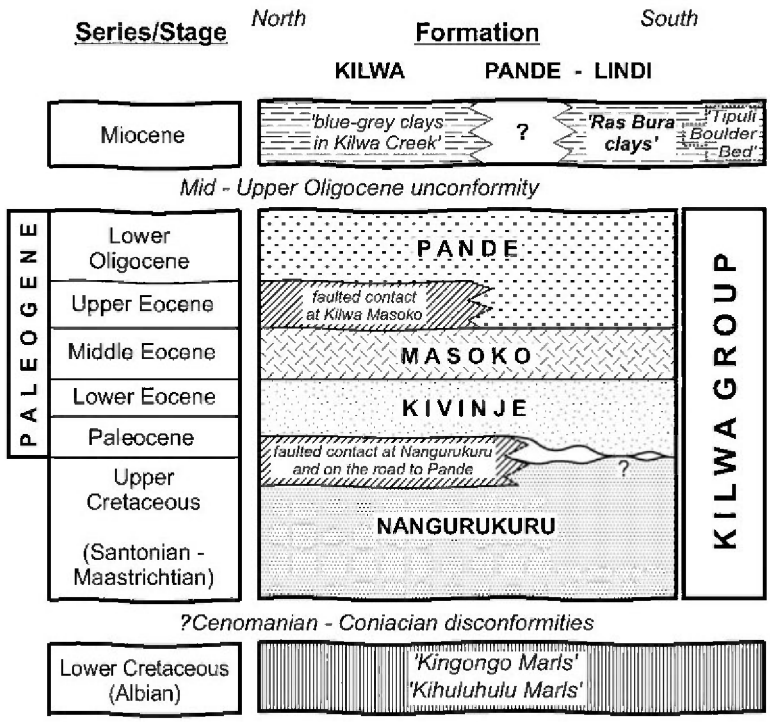


Fig. 4. Simplified geological map of the Lindi Bay area. Map symbol key as for Fig. 2.

Nangurukuru Formation. In addition, we also add to this three overlying formations that extend the original litho-stratigraphic and facies concepts of the Kilwa Group to also include the Paleogene (Table 2). It is appropriate that the group should retain the name 'Kilwa', as all four new formations are exposed on the Kilwa peninsula (Fig. 2) and this should be considered the type area. To avoid confusion between the group and new formation names erected here, we use the two more recent Kilwa town suffixes in our formation nomenclature: Masoko and Kivinje.

Table 2
Summary of the chrono- and lithostratigraphic definition of the Kilwa Group proposed in this study



Even though the base of the Kilwa Group is a faulted contact in exposures from our three main study areas, at depth the suggestion is that the stratigraphic contact is disconformable or unconformable on underlying Aptian/Albian/Cenomanian claystones.

The Kilwa Group proposed here represents a generally homogeneous sedimentary package dominated by clays and claystones to marls. These accumulated during a period of increased subsidence of the passive margin in southern coastal Tanzania from the Late Cretaceous to Paleogene. The accompanying increase in relative water depth appears to have occurred in a broadly uniform manner laterally along the shelf, at least between Kilwa where the group is defined, and Lindi about 140 km to the south–south-east. At present, four formations can be established within the Kilwa Group (in decreasing order of geological age); the Nangurukuru Formation, Kivinje Formation, Masoko Formation and Pande Formation (Table 2), which together give a combined *minimum* thickness for the Kilwa Group of just over 1 km (Table 3). Each is formally defined in the sections that follow. It is postulated that all of these formations were originally deposited along the palaeo-shelf strike from Kilwa to Pande to Lindi (Figs. 2–4). Lateral continuity and thickness uniformity of formations along shelf palaeo-strike on a passive margin is not uncommon. For instance, in the North-West Highlands of Scotland, formations and facies units less than 100 m thick can be followed along strike on the Cambro-Ordovician palaeo-shelf for nearly 240 km with no significant change (see McKie, 1993). However, despite the postulated lateral persistence of the Kilwa Group as discussed below, an Early Oligocene–Miocene unconformity may have led to partial or complete erosion of some of the formations prior to recommencement of deposition in the Neogene. Thus, at Kilwa there appears to be no surviving exposed Upper Eocene, and Miocene clays reportedly rest unconformably on the Lower Eocene in Kilwa Creek (Moore et al., 1963) (Fig. 2).

3.2. The base of the Kilwa Group

The most appropriate level at which to define the base of the Kilwa Group is the bounding surface marking the onset of increased subsidence across the shelf and the onset of laterally persistent transgressive clay deposition along the margin. However, this may have occurred twice during the transition from Lower to Upper Cretaceous. Onshore exploration wells drilled by BP-Shell in the Mandawa Basin region suggest that the Aptian–Albian 'Kihuluhulu' and 'Kingongo Marls' unconformably overlie Jurassic evaporites and shales (Balduzzi et al., 1992). In the offshore basins where subsidence rates were greater during the Early Cretaceous, the Aptian–Albian marls unconformably overlie Neocomian deltaic reservoir sands (Mpanda, 1997). Thus, the base of the Kilwa Group could be taken as the base of these marls. However, there is some evidence that a post-Albian, but pre-Santonian, disconformity may exist offshore in Songo Songo-1 well (Mpanda, 1997) and our field surveys suggest that one or more dis- or un-conformities

Table 3
Total minimum formational thicknesses in the Kilwa Group calculated from thickness data given in Figs. 6–17

Formation	Composite stratotype section	Formation thickness in section (m)	Total *minimum* formation thickness (m)
Pande	TDP 1	69.9	273.4
	TDP 17 }	91	
	TDP 12 }	103.2	
	Kitunda shore	9.3 (+)	
Masoko	TDP 4	19.8	149
	TDP 18	27.9	
	TDP 13 }	37 (+)	
	TDP 20 }	64.3	
Kivinje	TDP 2	39.5	408
	Ras Pungunyuni	1 (+)	
	TDP 3	49.5	
	TDP 8	18	
	TDP 7B	110	
	TDP 16A }	33.3	
	TDP 14 }	18	
	TDP 10	96.2	
	TDP 19	42.5	
Nangurukuru	Hotelitatu to Mkazambo	20	258
	TDP 9	84.2	
	Matandu to Nangurukuru:		
	Hill 4	7.8	
	Hill 2	29	
	Hill 3	57	
	Hill 1	60	

Note that where two holes correlate with some overlap, the maximum thickness between the upper and lower surfaces of correlation is taken from each hole. This occurs in three instances and the correlating holes are shown bracketed. See also Fig. 5.
Minimum total thickness of Kilwa Group recovered: 1088.4 m.

may be present between the Albian and Santonian onshore. We located a single outcrop of Cenomanian claystones at Maghreda swamp (UTM: 37L 528437, 9046105; north of the Kilwa map area shown in Fig. 2) and drilled this as Site TDP 15. However, we recovered 102.4 m of Lower Turonian claystones, but have so far been unable to identify any Turonian or Coniacian claystones in field exposures. This idea of post-Albian, pre-Santonian disconformities is further supported by the reported presence of thin Cenomanian and Turonian marls developed down-dip offshore in Songo Songo-1 well, suggesting a relative sea level fall (Fig. 1a). Here the Cenomanian marls and Kilwa Group form the seal to a gas pool developed immediately below them in the top of the Lower Cretaceous.

A further complication to defining the base of the Kilwa Group onshore is that Moore et al. (1963) show the geological boundary between the Upper and Lower Cretaceous striking approximately north–south about 15 km west of the Nangurukuru junction in the Kilwa area. However, our subsequent reconnaissance mapping suggests that an abrupt contact exists between the ‘Kingongo Marls’ outcropping south of the Ukuli River and the Campanian north of the River in the Kilwa area, which is most likely to be a fault. At Pande, a fault can be identified on the satellite image and our field planktonic foraminiferal biostratigraphy has shown it to bring Maastrichtian against Albian close to the village of Hotelitatu (Fig. 3). At Lindi, our field surveys have also shown that the junction between Upper and Lower Cretaceous is again sharp and suggests a fault or in this particular case, also possibly a disconformity, or a faulted disconformity (Fig. 4). Combining subsurface evidence with the scarcity of Cenomanian to Coniacian claystones in outcrop may indicate that only relict patches of pre-Santonian Upper Cretaceous have been preserved in topographic lows during a period of non-deposition and erosion, followed by onlapping of claystones during recommencement of margin-wide subsidence during the Santonian.

In summary, the base of the sedimentary package representing the Kilwa Group has not yet been cored or observed in outcrop. A basal faulted contact can be observed in two and possibly all three of our main study areas. The suggestion is, however, that where it is not faulted, the basal bounding stratigraphic surface of the Kilwa Group should lie at the lowest stratigraphic level of Santonian claystones. This surface represents the onset of regular, margin-wide subsidence and the development of a laterally uniform sedimentary package within which the four formations can be recognised and traced across the palaeo-shelf. At the surface, the oldest current exposures of Santonian Kilwa Group are found on the banks of the Matandu River in the Kilwa area (Fig. 2). This leaves the currently poorly resolved Aptian–Albian ‘Kihuluhulu’ and ‘Kingongo’ marls and a package of Turonian claystones of unknown, but possibly variable, thickness to remain as separate lithostratigraphic units below a margin-wide sequence boundary at the base of the Kilwa Group.

3.3. The top of the Kilwa Group

Post-Paleogene clay deposition also occurred in the Miocene at Kilwa and Lindi. However, when seen in outcrop, these units show a varied lateral facies and thickness variation not present in the underlying Paleogene clays. Moore et al. (1963) show two localities in Kilwa Creek where blue–grey Miocene clays rest unconformably upon Lower Eocene clays. Terris and Stoneley record a sporadic but at times abundant ostracod fauna in these Kilwa Creek clays in their BP-Shell report. These palaeontological characteristics are entirely different from those of the open marine, mid to outer shelf Paleogene clays. Also, at Kilwa, the Miocene clays are identical in weathering characteristics to the underlying Lower Oligocene Pande Formation which may suggest that they have been derived mostly or even entirely from local erosion and redeposition of these underlying clays. Further work needs to be undertaken on these younger units. However, at present, the best interpretation of the Miocene clays at Kilwa is that they were deposited in shallow water, with lateral discontinuity around topographic highs that may have been subaerially exposed. We have so far not encountered any Miocene clays in the Pande area.

At Lindi, we have identified upper Lower Miocene clays for some distance along the roadside between Mitwero village and Ras Tipuli (Fig. 4). Upper Miocene nodular clays showing structural deformation are also well exposed at Ras Bura just north of Lindi town itself (the 'Ras Bura clays'; Table 2). This more extensive Neogene cover in the Lindi area may suggest that Lindi Bay remained topographically lower than the Kilwa and Pande areas during this time, accumulating a thicker and more lithologically variable Miocene sequence.

Whilst the Lower Oligocene has been previously identified at Ras Tipuli in Lindi Bay (Blow and Banner, 1962), and by our own field surveys at Stakishari (Pande) and the Namadingura River (Lindi), no Upper Oligocene has yet been reported in the coastal zone. Thus it seems likely that a shelf-wide unconformity exists separating Lower Oligocene clays from Miocene clays laterally along strike from Kilwa to Lindi. Furthermore, there are sufficient lithological and facies differences within Miocene units along the coastal margin for them to be assigned to different formations. It is beyond the scope of this paper to formally describe these units. However, they represent a clear heterogeneous depositional style that is markedly distinct from the underlying, relatively homogeneous Lower Oligocene and older clays of the Kilwa Group. The margin-wide unconformable surface at the base of the Miocene combined with the change in style of subsequent Neogene deposition are together sufficient to use this sequence bounding surface to mark the top of the Kilwa Group (Table 2).

The absence of Upper Oligocene extends into the shallow subsurface just offshore at Mnazi Bay-1 well, south of Lindi (Fig. 1b). It suggests a significant shallowing event during the Early Oligocene and subsequent development of an unconformity to the edge of the shelf. The onset of shallowing is reflected by a coarsening-up change from interbedded silts to that of sands in the Lower Oligocene units of Mnazi Bay-1. These sands form the main reservoir to the Mnazi Bay gas field which is trapped below the Early Oligocene–Miocene unconformity.

3.4. Kilwa Group principal lithologies

Twenty-eight bulk sediment samples obtained from all four formations were analysed using XRD for their mineralogical composition (Table 4). Quantitative clay mineralogical studies are currently underway. The results presented here are preliminary studies to demonstrate the presence or absence of specific minerals. Despite the fact that the biostratigraphy demonstrates Kilwa Group sedimentation continued almost uninterrupted for ~55 Ma, the bulk composition of the sediment changed remarkably little during that time. The dominant constituent of all samples was a mixture of the clay minerals illite, montmorillonite and vermiculite. These could be detrital alteration products of feldspars and muscovite washed in from the Tanzanian gneissic basement hinterland or could be from in situ growth in marine sediments (for instance, see Singer, 1984). Kaolinite was present in all but the Pande Formation and it is tempting to speculate that the absence of this proxy for humid climatic conditions may have been due to global cooling during the Early Oligocene. A clearly detrital proportion of each sample is present in the form of quartz and albite grains. Calcite is also present as a combination of carbonate grains, including foraminifers and calcareous nannofossils and as early diagenetic cements or recent partial caliche formation within the weathering zone of TDP holes. The presence of secondary and accessory minerals is far more sporadic. Minerals such as the high temperature alkali feldspar sanidine must be detrital from the basement and occur with a variety of micas. The limited occurrence of lead sulphides such as sphalerite in the Kivinje Formation, accompanied by halite might suggest movement of brines along fractures in the formation from underlying Jurassic salt in the Mandawa basin.

Table 4
Summary of preliminary XRD results for 28 samples from the Kilwa Group

	Nangurukuru	Kivinje	Masoko	Pande	Formation
Primary minerals	X	X	X	X	Quartz
	X	X	X	X	Calcite
	X	X	X	X	Albite
	X	X	X	X	Illite
	X	X	X	X	Montmorillonite
	X	X	X	X	Vermiculite
	X	X	X		Kaolinite
	X	X	X	X	Grossular
	X	X	X	X	Wulfenite
Secondary			X	X	Sanidine
					Orthoclase
		X	X	X	Anorthoclase
	X				Microcline
		X			Micas
Accessory			X		Phlogopite
			X		Lepidolite
					Muscovite
	X		X	X	Berthierine
		X	X	X	Wurtzite
				X	Zircon
				X	Prehnite
			X		Nepheline
	X				Gypsum
	X				Alunite
	X				Hypersthene
			X		Gibbsite
		X	X	X	Sphalerite
		X			Huntite
		X			Halite
		X			Stilpnomelane

These results are not strictly quantitative but are shown broadly divided into categories indicating their general abundance. The presence (denoted by a cross) or absence (denoted by a blank space) of each mineralogical constituent is shown for the formations.

Table 5
Field identification scheme for formations within the Kilwa Group, based primarily upon the identification of characteristic secondary lithologies and facies set within clays or claystones

informal group subdivision	age range	Formation	principal lithology *(weathered colour)*	marker horizons *(in chronological order)*	characteristic secondary lithologies and facies associations *(not necessarily in chronological order)*
UPPER	Late Eocene to Early Oligocene	PANDE	soft light olive grey or blue-grey clays mottled with yellowish orange sandy clay	silty/sandy partings	• Plant fragments are common throughout; repetitive silty/fine sandy partings come on towards the top • White to cream micritic limestones and/or calcarenites are typical, often packed with assorted benthic foraminifera (<1cm in diameter) • These limestones are mostly debris flow beds also containing clay rip-up clasts, micritic balls and showing liquifaction, but not graded bedding
UPPER	Middle Eocene	MASOKO	soft light olive grey clays mottled with yellowish orange sandy clay	upper benthic foraminiferal limestones lower benthic foraminiferal limestones	• Massive, orange-brown weathering, benthic foraminiferal coquinas, typically dominated by large *Nummulites* up to 3cm in diameter • These limestones are cemented by sparry calcite and often contain well rounded coarse quartz grains • Most limestones demonstrate sedimentary structures associated with deposition from a turbulent flow;with grading, imbrication and cross-lamination in the foraminifera
LOWER	Late Paleocene to Early Eocene	KIVINJE	hard/blocky olive grey claystones mottled with yellowish orange sandy clay	*'beef' is common throughout* basal calcarenites	• Sandy partings are common throughout, occasionally developing into thin, partly cemented, calcarenites containing fine quartz sand and a subordinate clay matrix • These calcarenites typically contain small benthic foraminifera or biogenic carbonate may be absent • A series of massive, orange brown weathering sandy calcarenites are present at the base of the formation at Mpara Hill and the Mkazambo road, with graded benthic foraminifera & shell debris
LOWER	Late Cretaceous Santonian to Late Maastrichtian	NANGURUKURU	hard/blocky olive grey claystones mottled with yellowish orange sandy clay	inoceramid beds white sands limonitic sand marker bioturbated turbiditic sandstones	• At least two horizons at the top of this formation yielding abundant inoceramid fragments • An interval of repetitive, thin, white to limonitic, unconsolidated sand beds occurs in Maastrichtian below the inoceramid beds • A ~5 m thick, unconsolidated, laterally continuous limonitic sand marker horizon is present in the Upper Campanian with *Thalassinoides* burrows • Throughout this formation sporadic, massive, 10-50cm turbiditic, carbonate cemented, quartz sandstones occur, weathering to an orange-brown • Below the Maastrichtian, these sandstones possess characteristic, intensely grazed tops, burrowed / fluted bases and *Nereites* ichnofacies

Although clays are the dominant mineralogy in the Kilwa Group, there appears to be a distinct difference in hardness between the younger Masoko and pande formations and the older Kivinge and Nangurukuru formations. This seems to reflect the proportion of inorganic carbonate present, which can be observed in the field and in fresh cores, and which tends to develop a 'sugary' texture in the clays. The younger formations remain as unconsolidated, maleable clays, whilst the older two are stiffened or hardened into claystones. We do not use the term 'claystone' here to mean that the clays have been 'indurated by heat' in any way, as is sometimes implied by its use. It simply refers to the fact that the clays have become more lithified as a result of compaction, water loss and partial carbonate precipitation to become more of a 'clay-stone' in its most literal sense. However, all samples taken from within the Kilwa Group were still able to be broken down by hand and dispersed in a beaker of water for sieving and foraminiferal study. The degree of carbonate cementation thus appears to reflect subtle changes in secondary grain size within the clays and the overall difference between clay and claystone lithology is most likely to reflect burial depth. No principal lithology samples contained a greater than 40% carbonate content and so we refrain from using the term 'marl' in our lithological descriptions (typical carbonate percentages are 1–20%; Pearson et al., 2006).

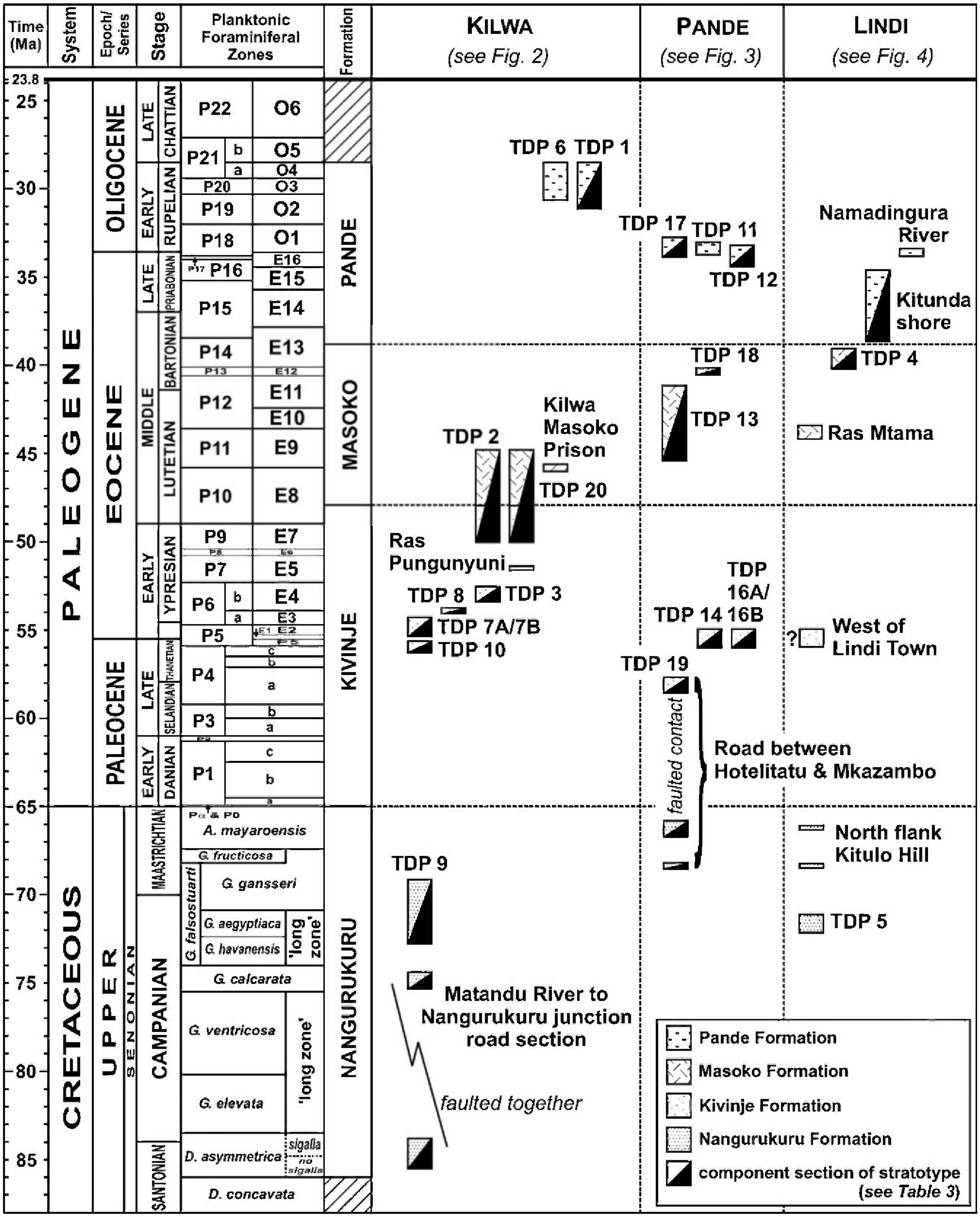


Fig. 5. Chronostratigraphy of logged sections within the Kilwa Group. The location of individual TDP holes and named surface sections are shown in Figs. 2–4. Upper Cretaceous time scale and planktonic foraminiferal biozones follow Gradstein et al. (1995), Nederbragt (1991) and Robaszynski and Caron (1995). In addition, our own observations concerning the presence or absence of *Sigalia deflaensis* in the *Dicarinella asymmetrica* zone and indeterminate 'long zones' along the Matandu to Nangurukuru road section are also shown. Paleogene time scale and planktonic foraminiferal 'P' zones are after Berggren et al. (1995); 'E' and 'O' zones after Berggren and Pearson (2005).

Detailed descriptions of the bio- and lithostratigraphy in each TDP hole from 1 to 10 are provided by Pearson et al. (2004) and Pearson et al. (2006). Sites 11–20 will also be described in a further combined results paper and thus will not be described individually in detail here. However, this contribution for the first time correlates all previous TDP holes with each other and with surface sections from Kilwa to Lindi (Fig. 5). The logs presented here show TDP holes subdivided into units of homogeneous principal lithology with corresponding thicknesses that reveal a subtle change in coarser clastic influx over time throughout deposition of the Kilwa Group. This can only be identified in fresh cores from below the weathering oxidation front. Weathered clays can display a variety of mottled colours which cannot be used to discriminate between formations in the field. Formations can be recognised in the field, however, by

Table 6
The origin of formational names in the Kilwa Group and a summary of the current known geographical distribution of formations along the coast from Kilwa and Lindi

	Origin of Name	Geographical Distribution
Pande Formation	After the oval-shaped peninsula with the village of Pande at its northern tip. This area has previously been referred to in publications as the 'Pande High'; as it delineates a basement structural high apparent at depth on seismic lines (see Veeken and Titov, 1996)	On the Kilwa peninsula, this formation only outcrops east of a fault which has downthrown it against Masoko clays. It is exposed at the base of the low cliff section on the north-east shore of Nso Bay (Fig. 2; Plate 2i). The best exposures are found in stream beds draining the western flanks of the 'Pande High' (Fig. 3; Plate 2e-f). The Pande clays are poorly exposed at Lindi and have only been proven in thin surface exposures at Kitunda on the southern shores of Lindi Bay and in the bed of the Namadingura River (Fig. 4; Plate 2h).
Masoko Formation	After the market town of Kilwa Masoko, which lies at the end of the Kilwa peninsula, overlooking the ruins of Kilwa Kisiwani. Kilwa Masoko stands on clays and limestones of the Masoko Formation.	The formation is intermittently exposed in a north-north-west to south-south-east strip across the Kilwa peninsula (Fig. 2). An outlier also appears to be exposed in the area west of Mpara Hill (Plate 2a). In the Pande area, the formation is exposed in a very gently dipping, fault-bounded block, striking north-north-west to south-south-east through the village of Mkazambo (Fig. 3). At Lindi, the formation is exposed on the foreshore at Ras Mtama on the northern shore of Lindi Bay, north of Lindi Town (Fig. 4; Plate 2c).
Kivinje Formation	After the old German provincial capital of Kilwa Kivinje at the north-eastern tip of the Kilwa peninsula, which is built on Kivinje claystones.	This formation outcrops extensively across the central area of the Kilwa peninsula around Singino Hill, stretching from coast to creek on either side (Fig. 2; Plate 1f). It is also exposed on the low islands out in the creek (Moore *et al.*, 1963). At Pande, Kivinje claystones are exposed along the roadside between Hotelitatu and Mkazambo, where they are faulted against the underlying Upper Cretaceous (Fig. 3; Plate 1g). At Lindi, Paleocene Kivinje Formation is poorly exposed as a series of claystone inliers through erosion of overlying Miocene or younger sandy limestones on the dip slope of Kitulo Hill, immediately west of Lindi Town (Fig. 4). Lower Eocene are only known from roadside exposures opposite Lindi prison, south of the town.
Nangurukuru Formation	After the village and junction at Nangurukuru on the main road south from Dar-es-Salaam, which leads onto the Kilwa peninsula. Nangurukuru claystones are exposed in roadside cuttings around the junction.	In the Kilwa area, Nangurukuru claystones are exposed in cuttings and ditches along the main road from the Matandu River in the north, almost to the Mavudyi River south of Kimamba Hill (Fig. 2; Plate 1a-e). They are poorly exposed east of Nangurukuru until faulted against Paleocene Kivinje claystones. At Pande, Nangurukuru claystones are intermittently exposed along the roadside from Hotelitatu towards Mkazambo until again faulted against Paleocene Kivinje Formation (Fig. 3). The south-west flank of Kitulo Hill at Lindi is composed of the Nangurukuru Formation and stream beds provide some poor, intermittent exposure (Fig. 4).

their secondary or subordinate lithologies, their sedimentary bedforms and structure, and their macro- or microfossil assemblages. Thus, the characteristic facies associations for each formation are described in the following sections and summarised in Table 5.

4. The Nangurukuru Formation

4.1. Nangurukuru Formation Facies (Tables 5 and 6)

4.1.1. Lithology

Nangurukuru Formation claystones are typically dark greenish grey and silty when observed fresh, but are mottled olive grey claystones when weathered. These are interbedded with thin, hard, carbonate cemented fine to coarse grained quartz arenite beds, weathering to an orange–brown (Plate 1a). These weather out prominently in outcrop and have clearly defined, but irregular top and basal surfaces (Plate 1b–d). A >5 m thick marker horizon of unconsolidated, limonitic, fine to medium subrounded quartz sand occurs in the Kilwa area within the Upper Campanian (Plate 1e; Fig. 6). Although occurring in the lower composite stratotype section, it is also present at the same stratigraphic level in new road excavations south of the Ukuli River between the map areas of Figs. 2 and 3.

4.1.2. Palaeontology

Bioturbation is common throughout the claystones, however it is the bioturbation within the sandstones which is particularly characteristic. The top surfaces of sandstone beds are often intensely grazed, producing an extremely bioturbated interval within the top 1 cm (Plate 1c). This may also exhibit a deeper red haematitic colouration than the remainder of the bed. Narrow tubular burrows penetrate the bed to basal surfaces, which exhibit the *Nereites agrichnia* ichnofauna (Plate 1d) including the excellent examples of the spiral trace *Spiroraphe* (Plate 1b). This ichnofauna was suggested as indicating a varying relative water depth during deposition of the formation by Gierlowski-Kordesch and Ernst (1987) and Ernst and Zander (1993). Burrows and grazing trails are infilled and preserved in three-dimensions, producing irregular bedding planar surfaces. These '*Nereites* sandstones' have been quarried from the roadside south of Nangurukuru junction and used as decorative paving slabs in Kilwa. The limonitic sand marker contains sporadic, carbonate-filled *Thalassinoides* burrows (Gierlowski-Kordesch and Ernst, 1987) (Plate 1e). Fragmented inoceramid prisms have been identified at two stratigraphic horizons within the Maastrichtian (Figs. 7 and 8). However, intact valves ~25 cm long have been found at the lower of these two levels on the roadside east of Nangurukuru junction. Despite the presence of these inoceramid fragments, intensive searching during the past century has yielded no macrofossils (and notably no ammonites) that can provide any biostratigraphic control for the formation. In pre-Nangurukuru Formation sediments a solitary belemnite rostrum was recovered from the Middle Albian 'Kingongo Marls' at the Mavudyi River. Benthic foraminifera assemblages from throughout the Nangurukuru Formation consist of two main groups. Firstly, and usually predominant, are agglutinated benthics, referrable to the genera *Bathysiphon*, *Ammodiscus*, *Glomospira*, *Hormosina*, *Ammobaculites*, *Haplophragmoides* and *Trochammina*. Smaller numbers of *Gaudryina*, *Dorothia* and *Spiroplectinella* occur. This part of the assemblage has a typical 'flysch'-like character, and indicates a slightly dysoxic palaeoenvironment on the outer shelf to upper continental slope throughout deposition of the Nangurukuru claystones, estimated at about 300–500 m water depth. Calcareous benthics are generally much less common, being especially poor in the Santonian portion of the formation: at higher levels, species of *Praebulimina*, *Bolivinoides*, *Gavelinella*, *Lenticulina*, *Brizalina*, *Stensioeina* and *Neoflabellina* occur in the Campanian–Maastrichtian. Planktic foraminifera usually predominate in the Santonian assemblages, whereas in the Campanian and Maastrichtian there are usually about equal numbers of planktics and benthics. There is no evidence of down slope transported shoreline debris or larger benthic foraminifera derived from the inner shelf in the Nangurukuru Formation.

4.1.3. Bedforms and structure

The sandstones are usually parallel laminated where bioturbation is absent (Plate 1d). Pyrite nodules are common throughout the claystones, or disseminated pyrite can be found within burrow fills. This disseminated pyrite appears to be particularly abundant in TDP 9 below the inoceramid beds and may represent an interval of heightened dysaerobic conditions at the sediment–seawater interface (Fig. 7). The cemented '*Nereites* sandstones' are also characterised by prominent flutes, grooves and prod marks on their basal surfaces and ripple marks on their tops, consistent with emplacement from pulsing turbulent flows. The limonitic sand marker horizon is parallel bedded on a 20–30 cm scale and shows partial carbonate cementation and convolute lamination or partial sand-balling at its base.

Bituminous spots were found in Albian 'Kingongo Marls' at new road bridge excavations at the Mavudyi River in September 2005. However, no oil traces have currently been found in the Upper Cretaceous Nangurukuru Formation. This may seem a little surprising as the friable, limonitic sand marker horizon intermittently exposed along the main road between the Matandu and Ukuli Rivers retains excellent porosity and would seem to be a laterally extensive, potential reservoir sand. In contrast, carbonate cementation appears to have filled all pore space in the repetitive '*Nereites* sandstones' lower in the stratigraphy.

4.2. Formation definition

At present, exposures present a more complete section through the Nangurukuru Formation than cores from

TDP holes. The Nangurukuru Formation is best defined by a composite stratotype of three sections. It is proposed that the lower composite stratotype section be defined as the intermittent exposures along the main road from Matandu

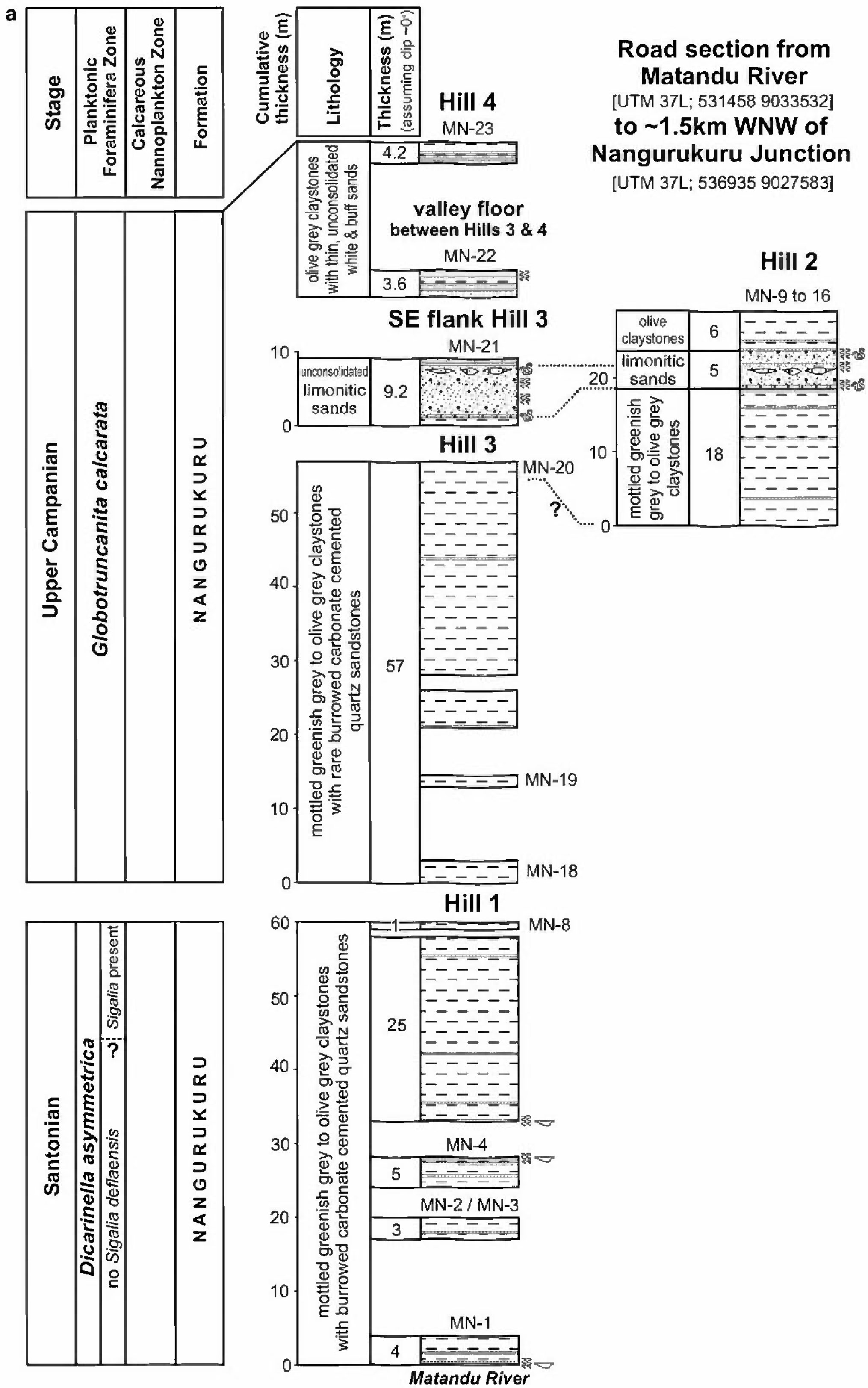


Fig. 6. Santonian–Campanian road section between Matandu River and Nangurukuru junction, Kilwa. (a) The road section of lower Nangurukuru Formation plotted in correct chronostratigraphic order. (b) Scale cross-section along the road from Matandu River to Nangurukuru showing the repetition of the limonitic sand marker unit and the sense of fault movement between blocks, plus the key to Figs. 6a, 7–17.

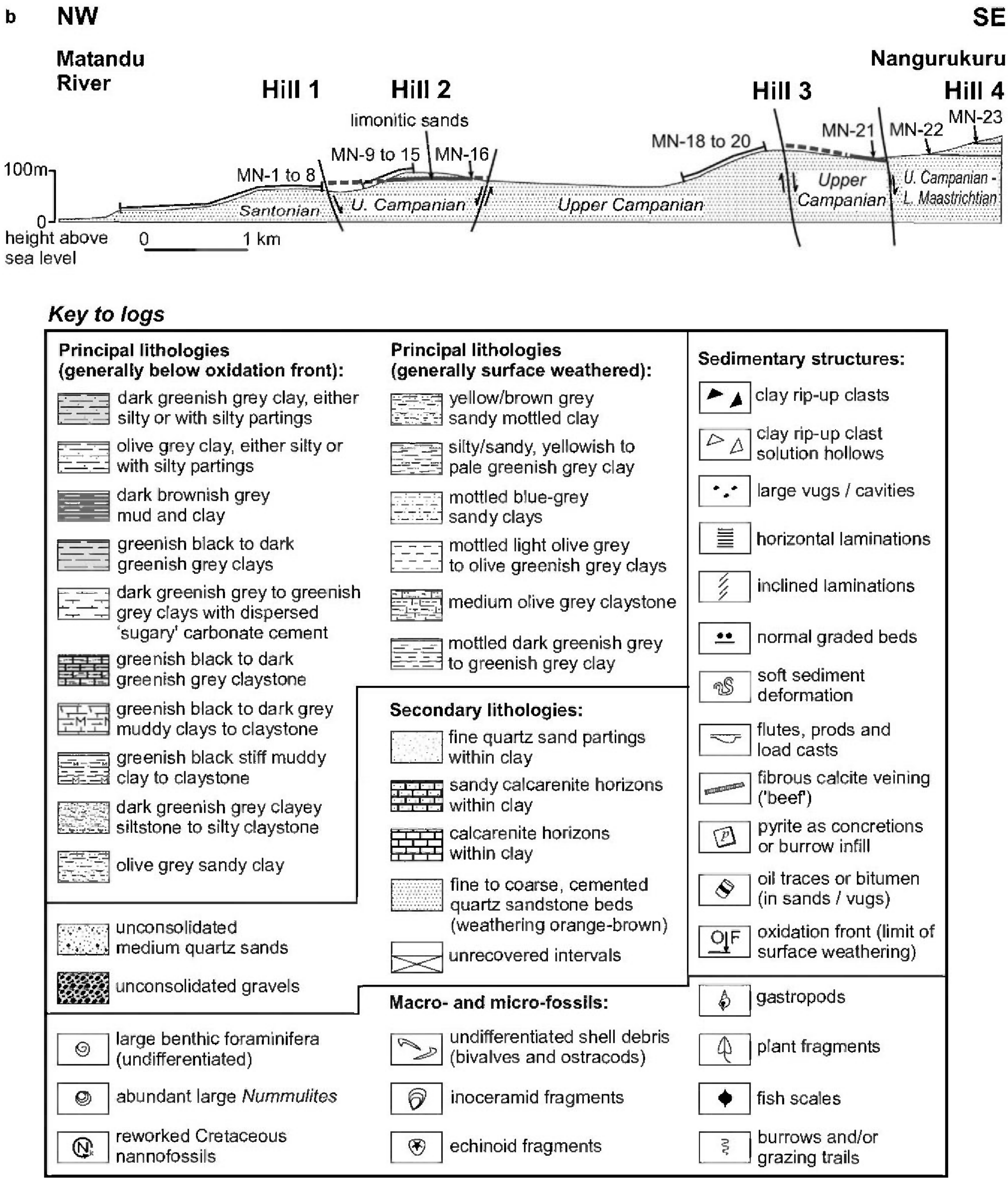


Fig. 6 (*continued*)

Bridge to Nangurukuru junction; Santonian to Upper Campanian (Figs. 2, 5 and 6a). This is the interval previously logged by Gierlowski-Kordesch and Ernst (1987) and Ernst and Zander (1993) (Plate 1a–e). However, our resolution of the structure along this roadside section suggests that the sequence is faulted out of its true stratigraphic order between four unnamed hills (Fig. 6b). The summit of 'Hill 2' correlates with the south-east flank of 'Hill 3', both containing a limonitic sand marker horizon and a younger foraminiferal assemblage than 'Hill 1'. The intervening stretch between 'Hill 2' and 'Hill 3' contains very few carbonate-cemented sandstone beds and is lithologically much more similar to 'Hill 1'. We suggest, therefore, that it should lie stratigraphically below the intervals of 'Hill 2' and 'Hill 3'. 'Hill 4' exposes claystones and sands which are younger in terms of their biostratigraphy and more coarse-clastic dominated in their lithologies than any of the previous road section. Reconstructing this succession taking fault repetition into account simplifies the stratigraphy for this lower composite stratotype section (Fig. 6a). The middle composite stratotype section (the holostratotype) is the interval recovered as TDP Site 9; Upper Campanian to Lower Maastrichtian (Figs. 2, 5 and 7). The upper few metres of this interval are exposed on the roadside from Nangurukuru to Singino Hill just east of the village (Figs. 2 and 7), where inoceramid fragments weather out from the low road cuttings. Part of the interval cored in TDP Site 9 was also recovered as TDP Site 5 in the Lindi area, demonstrating a remarkable lateral homogeneity along strike in the formation (Fig. 7). The upper composite stratotype can be observed along the road to Pande between Hotelitatu and Mkazambo and is Lower to Upper Maastrichtian (Figs. 3, 5 and 8). This upper portion of the stratigraphy is missing in the Kilwa peninsula area due to a

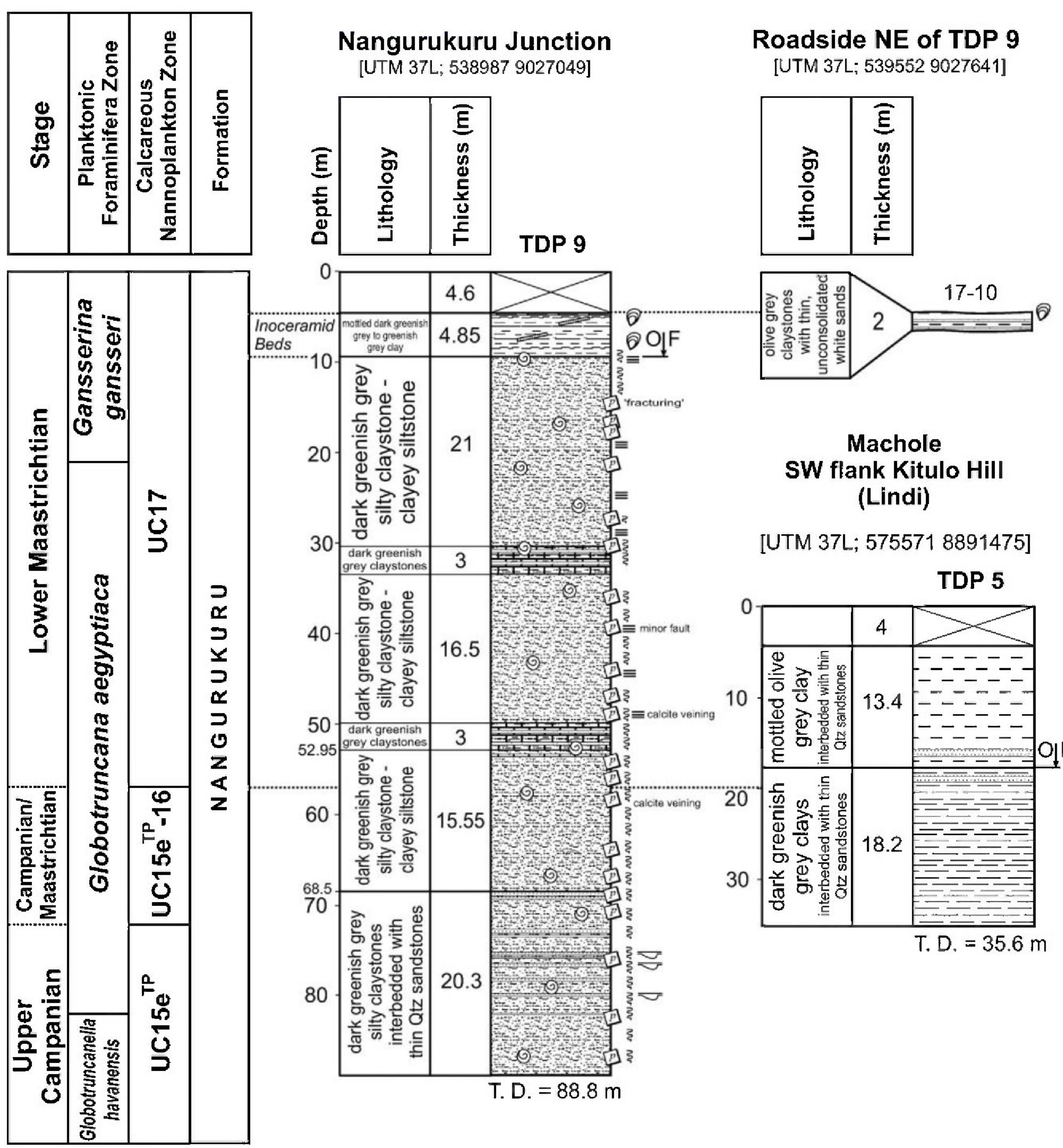


Fig. 7. Campanian–Maastrichtian upper Nangurukuru Formation at Kilwa (TDP 9 and surface exposure) and Lindi (TDP 5). See Fig. 6b for key.

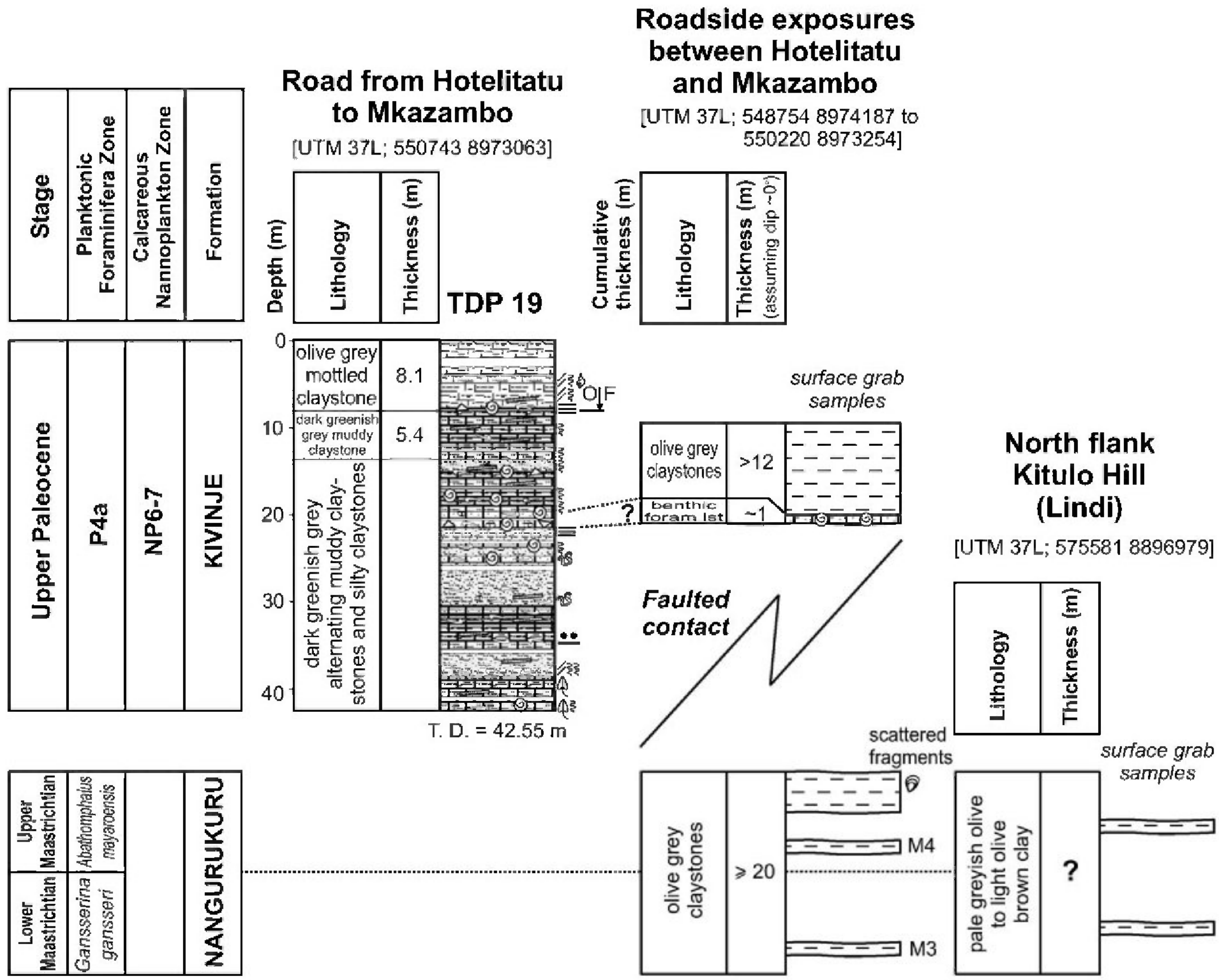


Fig. 8. Cretaceous–Tertiary transition between the upper Nangurukuru Formation and Kivinje Formation at Pande and Lindi. Roadside exposures between Hotelitatu and Mkazambo at Pande allowed the Cretaceous–Paleocene boundary to be located within a 10 m zone at the surface. Subsequent drilling of site TDP 19 on the Paleocene side of this zone recovered 42 m of Upper Paleocene and the trace of the Cretaceous–Paleocene contact at the surface in this area is thus most likely to be a high angle fault. Grab samples from the north flank of Kitulo Hill also demonstrate that Upper Maastrichtian upper Nangurukuru claystones are present at Lindi. See Fig. 6b for key.

fault. The Pande road section is the most complete exposed section of similar age to TDP Site 9 and has a second inoceramid interval at its top which appears to be younger than that exposed east of Nangurukuru. This inoceramid bed or beds are in faulted contact with the oldest exposed foraminiferal limestones and claystones of the overlying Kivinje Formation, which were cored at site TDP 19 (Figs. 3 and 8). Fragments of this upper interval are also exposed to the north of Kitulo Hill at Lindi (Figs. 4 and 8).

5. The Kivinje Formation

5.1. Kivinje Formation Facies (Tables 5 and 6)

5.1.1. Lithology

When fresh, the two principal lithologies of the Kivinje Formation are a greenish black to dark greenish grey claystone with fine quartz sandy partings, and a dark greenish grey silty claystone to clayey siltstone. Essentially, the distinction is in the pervasive nature and grain size of the secondary siliciclastics, rather than a difference in the dominant claystone. The fine to very fine quartz sands form sandy partings that can range in thickness from a few millimetres to ~10 cm at most (Plate 1f), whereas in the silty intervals the quartz is disseminated thoughout the clay. When fresh in core, these claystones have a characteristic, waxy lustre and crumbly texture. There are minor intervals within the formation which appear to be of a more muddy claystone, having lost the visible pervasive silt-sized fraction and developed a mild shaly parting. When weathered, the claystones degenerate into medium olive grey, blocky claystones (needing a hammer to sample easily) or mottled greenish grey clays probably equivalent to the muddy claystones (Plate 1f). There are occasional, individual, poorly developed calcarenite beds distributed within the claystones. However, on closer inspection, these contain a variable proportion of medium to fine quartz sands and can be packed with macrofossil debris such as benthic foraminifers (~1–5 mm in diameter) and bivalve fragments.

5.1.2. Palaeontology

Large benthic foraminifers and bivalve fragments are generally concentrated into the poorly cemented sandstone beds. However, gastropods, echinoid test fragments or spines, fish scales and plant fragments can occur at intermittent intervals throughout the formation. Bioturbation is generally common as single infilled burrows throughout the claystones. In terms of its faunal assemblage, this formation shows many of the same features as the underlying Nangurukuru Formation. There is again a remarkable scarcity of macrofossils throughout the Kivinje Formation. Benthic foraminiferal assemblages again consist of a well-developed, usually predominant agglutinated benthic portion (*Bathysiphon*, *Haplophragmoides*, *Ammodiscus*, *Triplasia*, *Flabellammina*, *Ammobaculites*, *Clavulina* and *Vulvulina*), with fewer calcareous benthics (*Stensioeina*, *Coleites*, *Globobulimina*, *Cibicidoides*, *Anomalinoides*, *Eponides*, *Gavelinella*, *Alabamina*, *Chilostomelloides* and *Nodogenerina*). These species indicate a rather dysoxic palaeoenvironment, again with a water depth of about 300–500 m on the outer shelf to upper continental slope. Unlike the Cretaceous, there are variable numbers of larger

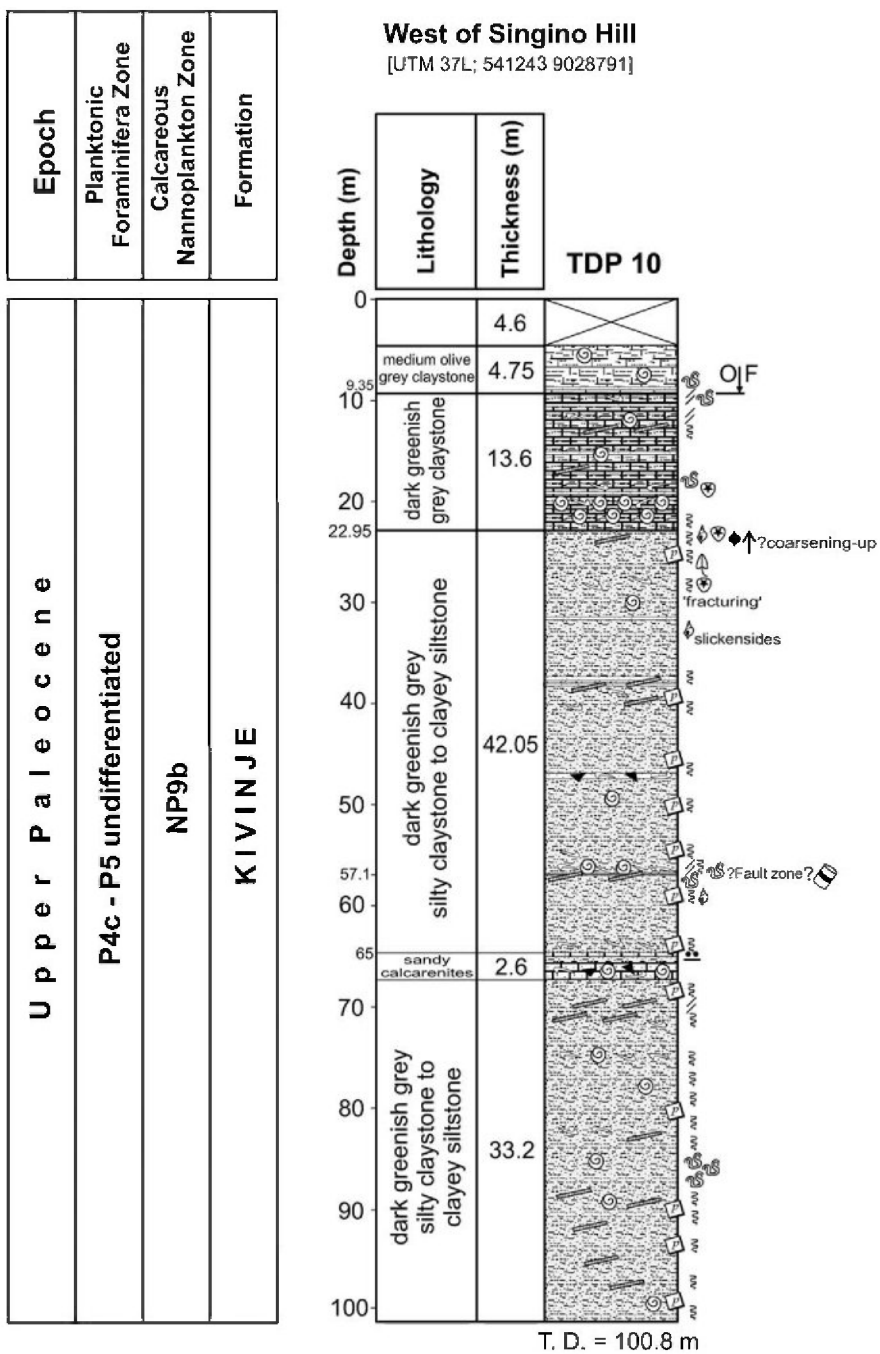


Fig. 9. The Paleocene Kivinje claystones cored in TDP 10, west of Singino Hill, Kilwa. See Fig. 6b for key.

foraminifera (chiefly *Discocyclina* and *Nummulites*, and, in the Lower Eocene, *Asterocyclina* and *Alveolina*) transported into deep water from the inner shelf. The orange–brown weathering sandy limestone which appears to be the oldest exposed Kivinje Formation at Pande and Mpara Hill contains numbers of the larger foraminifera *Discocyclina* and evolute nummulitids and planktonic foraminifera of the enclosing clays suggest an age of P4a (Plate 1g). Also comprising a small proportion of the benthic assemblage in the Kivinje Formation are small numbers of miliolids (chiefly smooth-walled *Quinqueloculina*), derived from the innermost shelf, and indicative of coastal hypersaline water. Transported intertidal foraminifera such as *Rotalia* and *Pararotalia* also occur, as well as occasional microscopic fragments of coral, echinoid shell and spines. Large fragments of *Hydnophora* corals (J. Pandolfi, pers. comm.) also occur in loose blocks on the roadside just west of site TDP 19.

5.1.3. Bedforms and structure

Sandy partings within the claystones can occasionally show cross-lamination and soft sediment deformation, although the bedding lamination commonly appears inclined to some degree in all TDP holes. Several minor, clearly compressional, slip surfaces were encountered, particularly at TDP 7A and 7B. Later structural deformation may therefore be responsible for the general, inclined lamination observed. A particular characteristic of the Kivinje claystones which may be associated with this deformation is the pervasive presence of thick fibrous calcite veining, or 'beef'. This was observed to be present in all Kivinje claystone holes in and around the Singino Hill area and was also seen in outcrop by the main road on the southern flank of the hill (Plate 1f). However, it does not appear to be present in the underlying Nangurukuru claystones below the inoceramid beds. Pyrite in the form of nodules or burrow infills is common throughout the Kivinje claystones.

Several stratigraphic intervals within the Kivinje Formation yielded traces of oil during TDP coring. Thin, fine quartz sand horizons, such as that illustrated in Plate 1f, were found to contain oil in the Upper Paleocene (P4c-P5) of TDP 10 (Fig. 9), lowermost Eocene (P5/E1-E2) in TDP 16B (Fig. 10) and two horizons were discovered in the Lower Eocene (P6b/E4) of TDP 3 (Fig. 12; Plate 1h). A fault zone near the base of TDP 7A also contained traces of oil. However, this fault and associated oil was not present in TDP 7B, drilled only 5 m to the south-east of TDP 7A, perhaps suggesting petroleum migration along a small high angle reverse fault.

5.2. Formation definition

As with the Nangurukuru Formation, no single stratotype section exists for the Kivinje Formation. Instead, biostratigraphic correlation suggests that we have recovered a series of slivers of Kivinje claystone stratigraphy in TDP holes, many of which do not overlap (Fig. 5). Thus each must define a small portion of the formation stratigraphy and stack together as part of a component stratotype. The base of the formation is not present at Kilwa, as the uppermost Paleocene is downthrown against the Cretaceous by a fault. Therefore, the base of the formation must be defined elsewhere and currently the oldest Paleocene we have recovered is zone P4a in TDP 19 on the road to Pande between Hotelitatu and Mkazambo (Figs. 3, 5 and 8). On

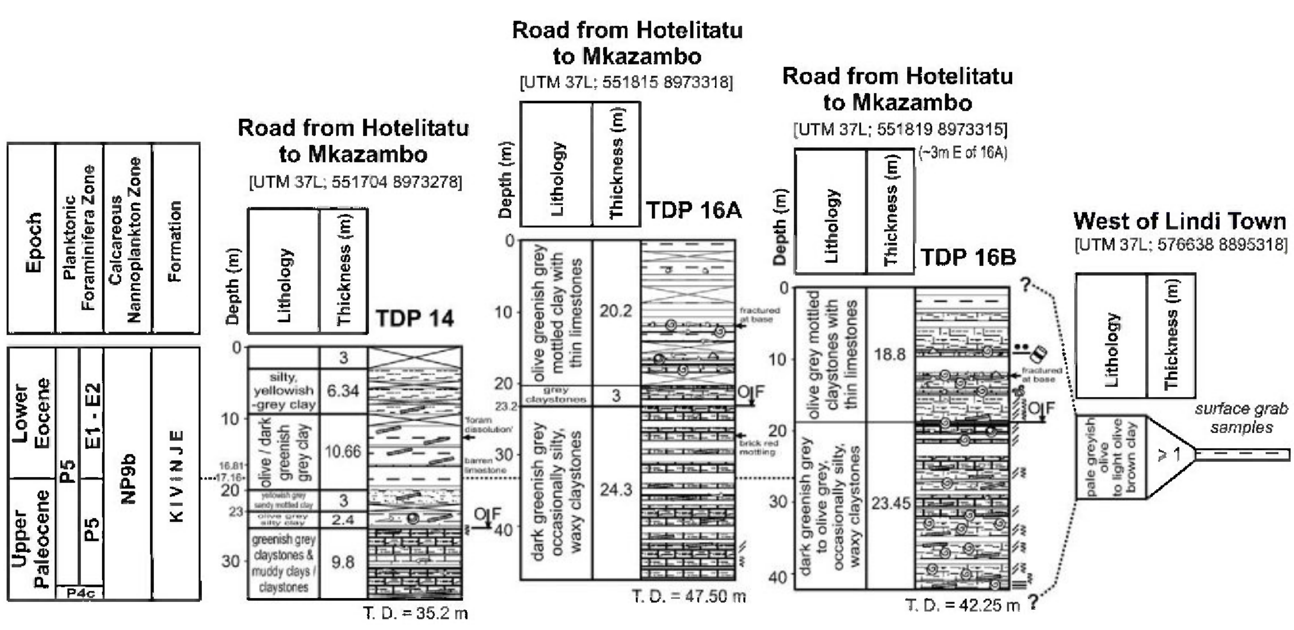


Fig. 10. Triple TDP holes across the Paleocene–Eocene boundary at Pande. Site TDP 14 was located about 100 m west of TDP 16A. TDP 16B was drilled only 3 m east of 16A in an attempt to re-core the interval with optimal recovery. All three holes yielded characteristic planktonic foraminiferal excursion taxa from the Paleocene–Eocene Thermal Maximum event. A fragment of this part of the stratigraphic succession has also been identified in the field as 'P5 clays' west of Lindi Town. See Fig. 6b for key.

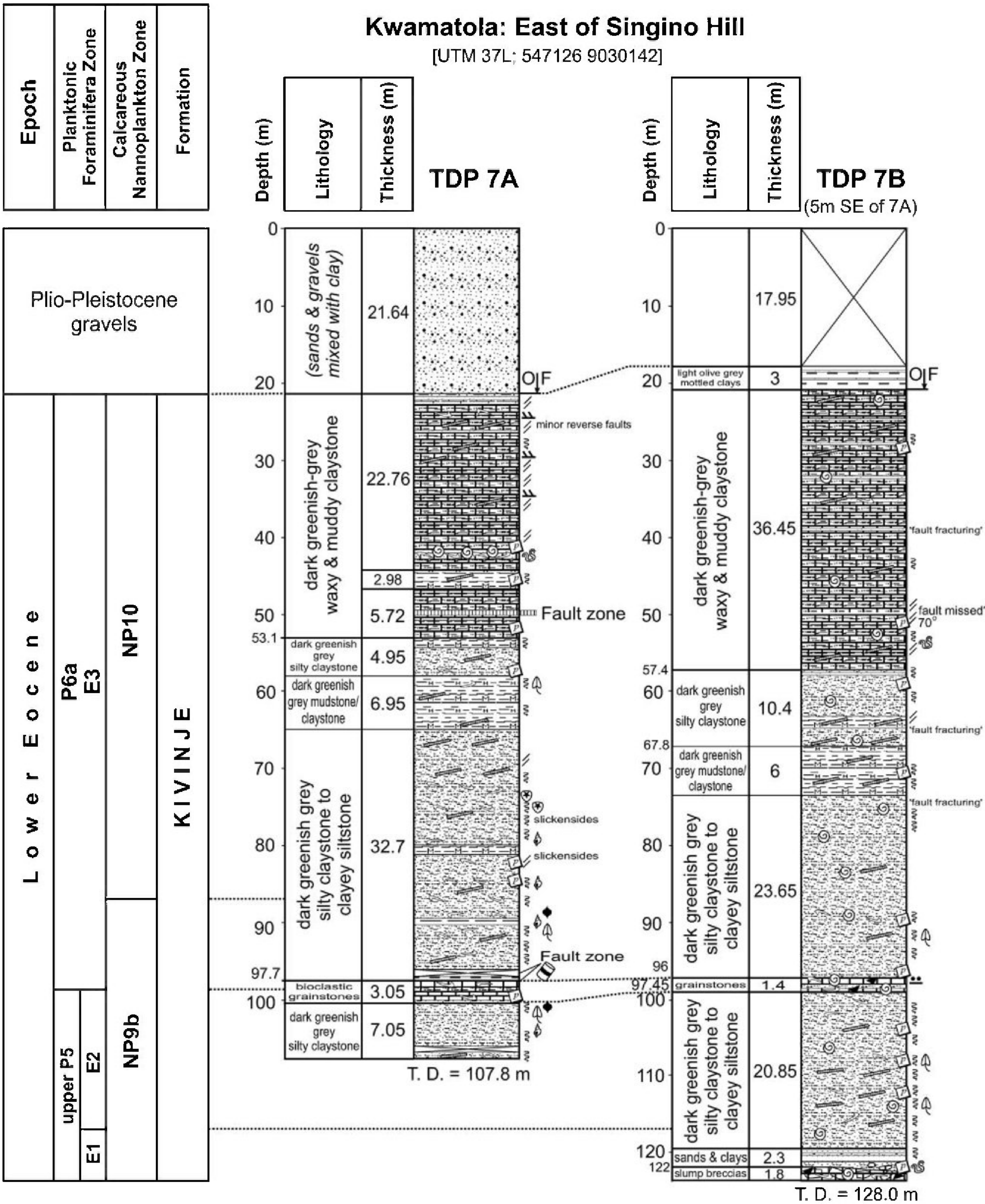


Fig. 11. TDP 7A and B holes drilled in Lower Eocene Kivinje claystones at Kwamatola, Kilwa area. The very base of TDP 7B may correlate with the top of TDP 16A. See Fig. 6b for key.

the roadside immediately west of site TDP 19, large benthic foraminiferal limestones are exposed adjacent to inocer-amid-bearing claystones. We attempted to core this interval to potentially recover a K–T boundary section, but instead drilled 42 m of Upper Paleocene. Thus the sharp contact on the roadside is also likely to be a fault. In fact, we have not been able to recover any Lower Paleocene claystones in core, nor have we confirmed their presence in surface exposures anywhere along the coastal zone. Consequently, it is possible that the Kivinje Formation lies disconformably or unconformably upon the underlying Nangurukuru claystones, but this cannot be confirmed without further drilling. The definition of the base of the Kivinje claystones is therefore the lowest stratigraphic occurrence of large benthic foraminiferal limestones in the succession; currently at the base of TDP 19 and exposed on the roadside just west of this site (Plate 1g). This boundary also corresponds to the disappearance of

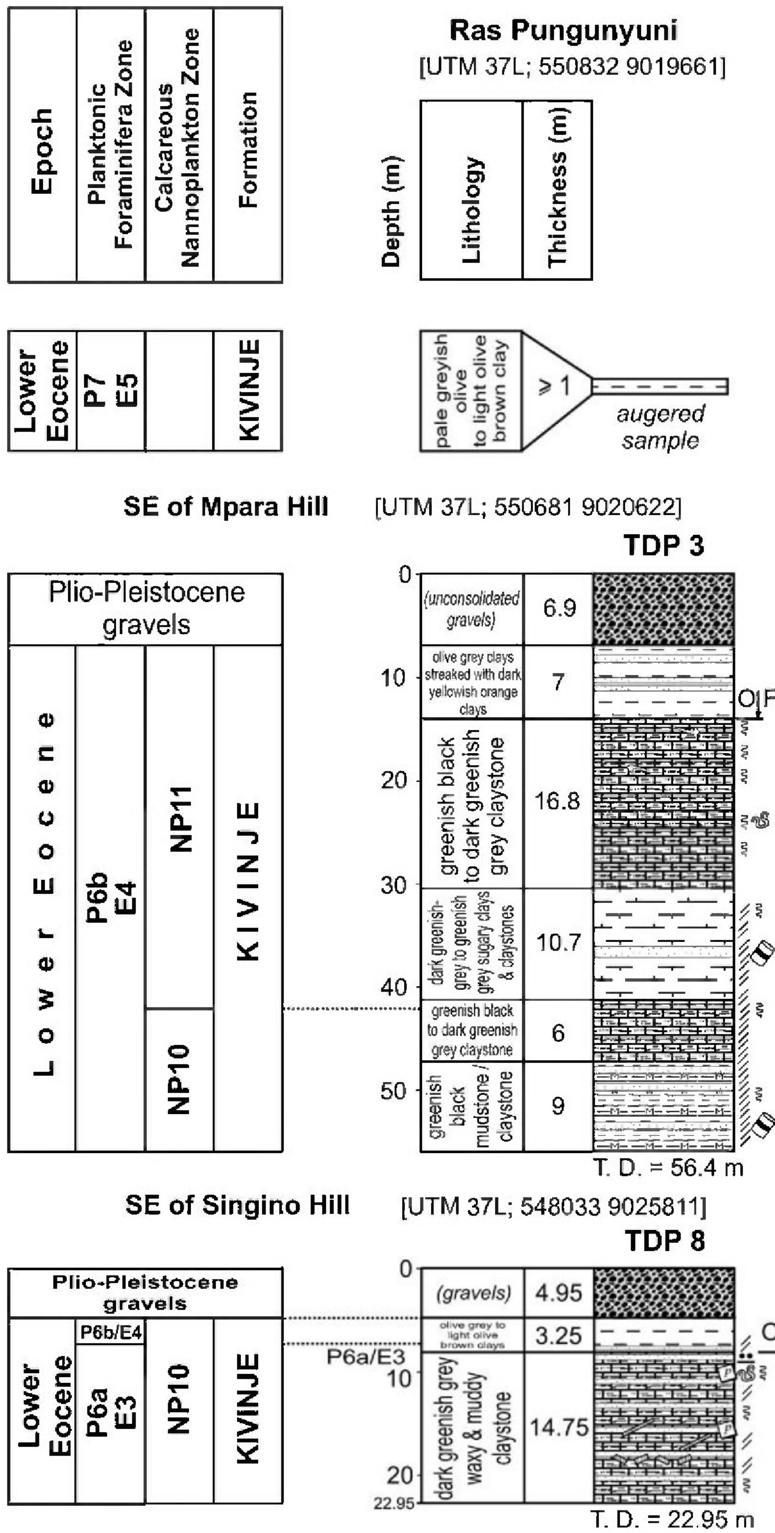


Fig. 12. Three short sections through the Kivinje claystones on the Kilwa peninsula. These stack stratigraphically on top of each other, but with short unrecovered intervals between them. See Fig. 6b for key.

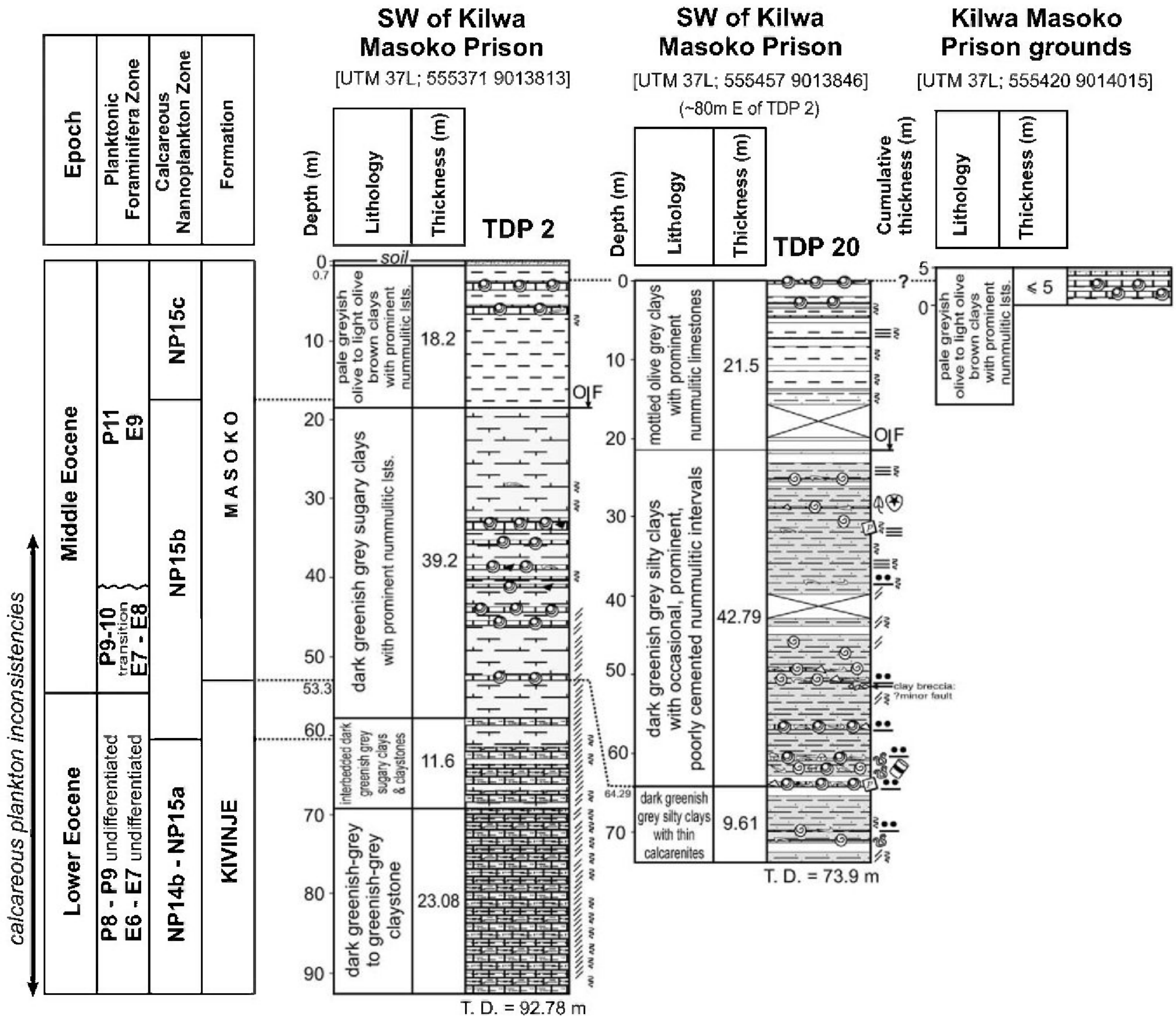


Fig. 13. The Kivinje Formation Masoko Formation boundary in TDP 2 and TDP 20, showing the correlation between subsurface and exposures in the grounds of Kilwa Masoko prison ~300 m to the north of TDP 20. The lower benthic foraminiferal limestones interval (see Table 5) is clearly present in both holes at the base of the Masoko Formation, although in TDP 20 the coquinas are less well cemented. See Fig. 6b for key.

the highly bioturbated '*Nereites* sandstones' characteristic of the underlying Upper Cretaceous. Above TDP 19, the only other TDP hole which continuously cored Paleocene throughout its length was TDP Site 10 (Fig. 9). The hole recovered just over 100 m of this formation and it exhibits the characteristic Kivinje claystone facies (Table 5). As such it should be considered as the principal parastratotype for Paleocene Kivinje claystones. About 2.5 km further east along the road to Mkazambo from the basal limestones present in TDP 19, TDP holes 14, 16A and 16B cored Paleocene and Eocene claystones (Figs. 3, 5 and 10). The remainder of the formation can be defined by a series of TDP holes or short surface sections on the Kilwa peninsula itself, which stacked in chronological order are TDP 7A/7B, TDP 8, TDP 3, Ras Pungunyuni and the lower third of TDP 2 and 20 (Figs. 5, 11–13). TDP 7B at Kwamatola remains the best recovered interval of Lower Eocene Kivinje claystones and we propose it as the holostratotype for this unit (Fig. 11). The top of the Kivinje Formation can be placed within the interval 53–62 m in TDP 2 (Fig. 13). This marks the gradational change over a ~10 m transition from underlying claystones to overlying clays and the onset of large benthic foraminiferal coquinas which are characteristic of the Masoko Formation. The top of the Kivinje claystones could therefore be taken as the highest stratigraphic occurrence of claystone, the lowest occurrence of clay, or the lowest occurrence of foraminiferal coquinas. Since the change in clay hardness is gradual, we define the top of the Kivinje claystones at the base of the stratigraphically lowest foraminiferal coquina, which is at ~53 m depth in TDP 2 (Fig. 13). This is clearly shown in TDP 20, located only ~80 m east of TDP 2, where the fine calcarenites below 64.29 m contrast with the coarse nummulitic coquinas above.

6. The Masoko Formation

6.1. Masoko Formation Facies (Tables 5 and 6)

6.1.1. Lithology

Masoko Formation clays are mottled light olive grey to greyish olive grey clays when observed weathered in exposures. However, when fresh, these occur as dark greenish grey clays. These clays can also contain a pervasive granular calcite dispersed within the clay itself, giving them a characteristic 'sugary' texture when fresh. The grains do not appear to be bioclastic debris, but are small rhombs of calcite often markedly increasing the porosity of the clays. This carbonate does not cement the clays and they remain soft and pliable. Indeed, even in weathered outcrop, the Masoko clays can often be sampled with the hand rather than a hammer and it clearly distinguishes this formation from the underlying harder, more lithified Kivinje and Nangurukuru claystones. However, it is the secondary lithologies which are the most diagnostic feature of the Masoko Formation both subsurface and in exposure. Clay intervals are punctuated by occasional, massive, hard, sparry calcite cemented, limestone beds packed with great numbers of large *Nummulites* (Plate 2a–c). The density of these foraminifera often precludes any intervening matrix being present and warrants them being described as coquinas. However, where less densely packed, the beds can contain dispersed, but coarse and rounded, quartz grains and some clay balls as rip-up clasts (Plate 2b). At the surface the limestones weather to an orange–brown colour and can often be recognised at a distance weathered in situ to stand proud of the surrounding clays (Plate 2a and c). Two intervals can be recognised in the formation where several of these nummulitic limestone beds occur repetitively; the first towards the base of the formation in TDP 2 and 20 at Kilwa (Fig. 13), and the second in the top third of TDP 13 at Pande (Fig. 14). Our biostratigraphic age constraints indicate that this upper interval of nummulitic limestones can also be traced south to the foreshore at Ras Mtama, Lindi (Fig. 14; Plate 2c).

6.1.2. Palaeontology

Nummulites in the limestone beds typically range in size from ~0.5 cm up to 3 cm in diameter (Plate 2b) and the limestones tend towards being monospecific. In TDP 2 and 20, there are few macroscopic fossils visible between the limestone beds, but dispersed shelly debris is present throughout the clays of TDP 13. Bioturbation is uncommon to rare in the Masoko clays. However, this formation exhibits distinct differences from the two underlying formations in the composition of its benthic foraminifera assemblage. This is particularly marked by the decline of the 'flysch'-style agglutinated benthic assemblage, which is scarcely represented in the Masoko Formation. 'Flysch'-style agglutinated benthics do occur (mostly *Bathysiphon*), but only in small numbers. Instead, benthic foraminifera assemblages are much more dominated by calcareous genera such as *Globobulimina*, *Uvigerina*, *Osangularia*, *Oridorsalis*, *Stilostomella*, *Nodogenerina*, *Fontbotia*, *Chilostomelloides*, *Globocassidulina* and *Gavelinella*. Agglutinated benthics include species of *Karreriella*, *Vulvulina*, *Tritaxia*, *Tritaxilina*, *Clavulinoides*, *Migros*, *Gaudryina* and *Spiroplectinella*. Transported inner shelf foraminifera become increasingly numerous: *Pararotalia*, *Rotalia*, *Planorbulinella*, *Asterigerina*, *Amphistegina*, *Reussella*, *Stomatorbina*, and few miliolids (*Quinqueloculina*). The depositional environment again appears to be situated on the outer shelf to upper continental slope, with water depths from 300 to 500 m. However, the dominance of calcareous benthics, and the sparsity of 'flysch'-style agglutinated genera shows clearly that sea-floor dissolved oxygen levels were markedly higher in the Masoko Formation than in previous formations. Large foraminifera occur widely, chiefly *Nummulites*, *Assilina*, *Discocyclina* and *Asterocyclina*. However, despite the quantity of transported Middle Eocene shelfal debris in the Masoko Formation, no reworked foraminifera from older formations have been found.

6.1.3. Bedforms and structure

Nummulitic limestone beds typically display normal grading in the *Nummulites* and some may exhibit imbrication from unidirectional flow or cross-lamination at the top of the bed, particularly well-developed in the limestones of TDP 20. These features suggest the beds are deposited from turbulent pulses exclusively sourcing sediment from shallow shelf areas. This may be consistent with these being storm deposits or tempestites. Bedding laminations developed in TDP 2 were inclined towards the base of the hole. Minor faulting also seen in TDP 2 suggests that this inclination may be tectonic.

A poorly cemented, benthic foraminifera-rich clay horizon, which lies at the base of the Masoko clays in TDP 20 at Kilwa (lowermost Middle Eocene; P9-10/E7-8) contained traces of oil in the pore spaces between foraminifera (Fig. 13). Oil residues were also found in Middle Eocene (P13/E12) silty clays in TDP 18 at Pande (Fig. 14). However, a surface oil seep was also discovered by us at Kilwa Masoko jetty, which lies at the southernmost extent of the Masoko Formation outcrop on the Kilwa peninsula (Fig. 2; Plate 2d). It must be assumed that the oil-soaked sand on the foreshore has migrated along a hidden fault at this locality. Perhaps this is a minor fault associated with the large north–north-west to south–south-east trending fault just to the east in Nso Bay, which brings Pande clays against Masoko clays (see Fig. 2). The fault zone of this was cored in TDP 6 (Fig. 17).

6.2. Formation definition

The Masoko Formation is best defined by four sections in TDP holes which together form a composite stratotype (Fig. 5). The base of the formation is present in TDP 2 at 53 m and TDP 20 at 64.29 m, both at Kilwa, as described above in defining the top of the Kivinje claystones

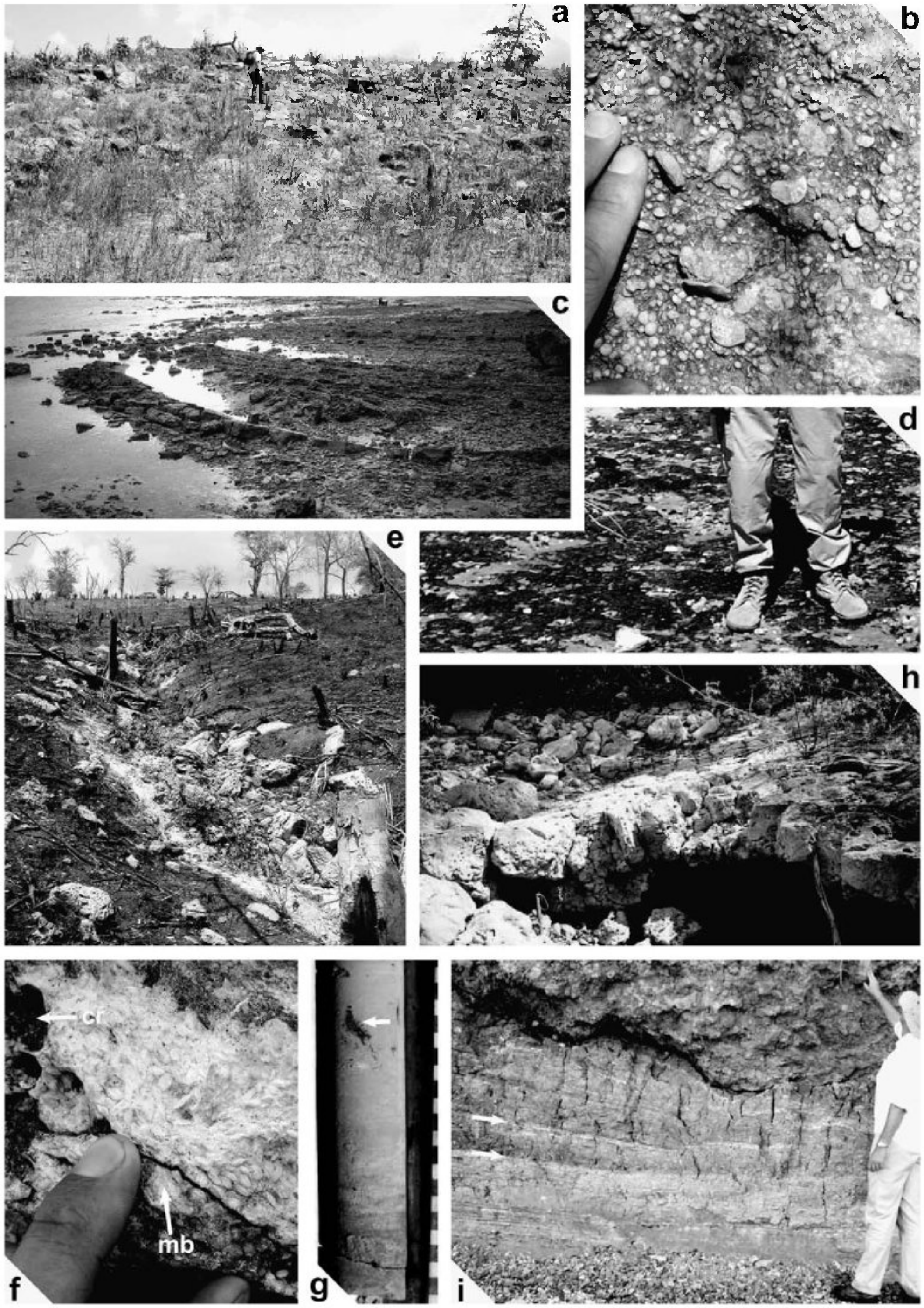


Plate 2. Masoko (a–d) and Pande (e–i) formations in outcrop. (a) A massive nummulitic limestone coquina bed in the Masoko clays exposed on the crest of a ridge north-west of Mpara Hill (Fig. 2). The figure gives the scale; (b) Close-up view of the bed in (a) showing a mixed size range of *Nummulites* specimens up to about 2 cm in diameter. (c) Similar nummulitic coquinas interbedded with olive grey clays, exposed on the foreshore at Ras Mtama, Lindi (Fig. 4). Width of view is ~30 m; (d) Surface oil seep through Masoko clays and into intertidal sands at Kilwa Masoko jetty (Fig. 2). This seep was discovered by us in 1999, but subsequently re-collected, tested and confirmed by Aminex Plc.; (e) The Eocene–Oligocene boundary exposed in a dry stream bed directly below site TDP 12 at Pande, which was drilled on the crest of the hill in the background (see Fig. 3). The Pande Formation white limestone bed shown in (f) is in the centre of the photograph underlying lowermost Oligocene clays; (f) White micritic limestone of the Pande Formation. Weathered-out clay rip-up clasts (cr) and micritic balls (mb) are surrounded by tightly packed benthic foraminifera, deformed during liquefaction; (g) Live oil oozing from a vuggy cavity near the base of a 1 m thick, fine to medium grained calcarenite in a Lower Oligocene core from site TDP 17 at Pande (see Fig. 3). Depth to the top of the calcarenite is 87.3 m, the scale bar is in centimetres; (h) Characteristic Pande Formation white limestones with weathered-out clay rip-up clasts at the Eocene–Oligocene boundary of the Namadingura River, Lindi (see Fig. 4); (i) Interbedded thin sands or silts (as indicated by the arrows) and blue–grey clays of Lower Oligocene Pande clays on the north-east cliffs of Nso bay, Kilwa (Fig. 2), similar to the cored interval in TDP 1 and 6 (Fig. 17). These are the youngest beds so far identified in the Kilwa Group and are seen here below the erosive contact with overlying Plio–Pleistocene reef debris and shallow marine sands at shoulder level.

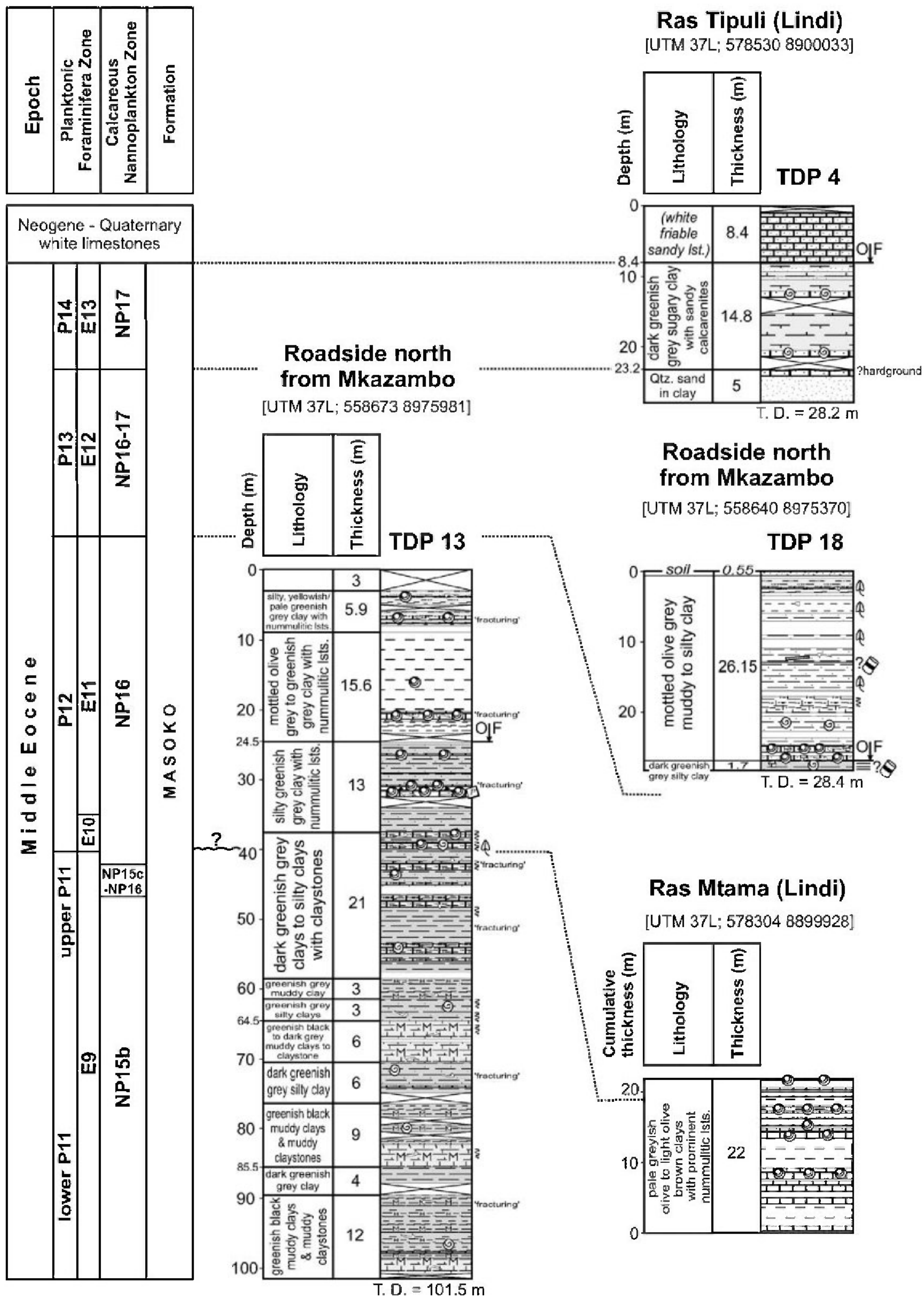


Fig. 14. Upper Masoko Formation in TDP 13 and TDP 18 at Pande, with a lateral equivalent section exposed at Ras Mtama, Lindi. Uppermost Masoko clays were recovered in TDP 4 at Ras Tipuli, Lindi. See Fig. 6b for key.

(Fig. 13). TDP 2 and 20 also cored a typical interval of Masoko clays and part of this stratigraphy can be seen close by, exposed in the grounds of Kilwa Masoko prison down to the salt pans at the creek (Fig. 2). It is therefore proposed that the interval in TDP 2 from 0.7 m down to 53 m depth and TDP 20 from 0 m to 64.29 m are considered holostratotype sections for the formation (Fig. 13) and form the lower of three intervals in the composite stratotype. TDP 13, on the track north from Mkazambo to Pande (Fig. 3), cored just over 100 m of Masoko clays and the planktonic foraminiferal biostratigraphy suggests that the very base of the hole may overlap in part with the top of TDP 2. This is proposed as the next section of the composite stratotype. Lateral age-equivalent beds of this interval of TDP 13 are exposed on the foreshore at Ras Mtama on the north side of Lindi Bay. These exhibit the same characteristic Masoko clay facies as at Pande and Kilwa, demonstrating the high degree of lateral homogeneity within each formation along the entire coastal zone. The short hole at site TDP 18 cored the interval of zone P13 (E12 of Berggren and Pearson, 2005) and stacks stratigraphically on top of TDP 13. TDP 4 was drilled ~1 km north-east of Ras Mtama and recovered the youngest interval of Masoko clays (Fig. 14), and may in part overlap with the top of TDP 18. This is the upper composite stratotype section for the formation. The top of the Masoko clays can be defined as the top surface of the highest large nummulitic or benthic foraminiferal coquina in the stratigraphy. This currently resides at a depth of 13 m in TDP 4, but may be shown with further drilling to be higher in the sequence as the top of the Masoko clays in TDP 4 are unconformably overlain by Miocene or younger units. Thus, the complete interval below the unconformable surface in TDP 4 is assumed to be Masoko clays and the top of the formation is currently defined by this erosional surface.

7. The Pande Formation

7.1. Pande Formation Facies (Tables 5 and 6)

7.1.1. Lithology

When observed fresh from the subsurface, the Pande Formation (Plate 2e–i) is uniformly composed of characteristic greenish black to dark greenish grey clay, or muddy clays developing a mild shaly parting. Thus, the overall clay colour in fresh Pande clays is a shade darker than underlying formations. In addition, fine to very fine, angular, quartz sandy partings occur throughout the clays in the upper horizons and these have occasionally developed a carbonate cement to produce very thin, sandy calcarenite beds with poorly cemented tops and bases. In the Kilwa area these clays exhibit a mottled blue–grey colour in the oxidised weathered zone and this can be used to distinguish them from underlying Masoko clays which tend to weather to an olive grey colour. This blue–grey colour is particularly well displayed in the cliff section at Nso Bay (Figs. 2 and 17; Plate 2i). In TDP 1, organic rich partings throughout the clay were also common. In addition to a difference in clay colour, the Pande clays also exhibit a difference in secondary lithologies. The formation is best recognised in the field by the occurrence of intermittent, 10–50 cm thick white or cream micritic limestones (Plate 2e, f and h). These are distinctly different in facies from the foraminiferal coquinas of the underlying Masoko clays (see below) and have been identified in roadside exposures north of Mkazambo on the road to Pande (Fig. 3; Plate 2e) and also in the bed of the Namadingura River at Lindi (Figs. 4

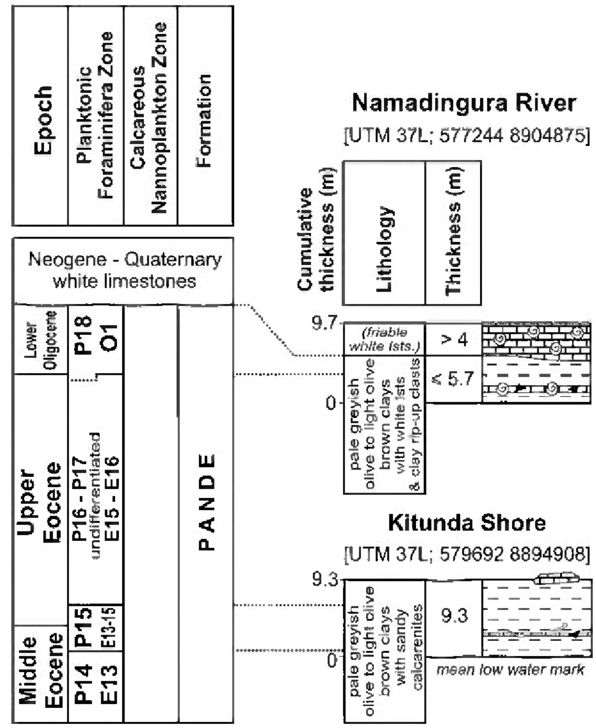


Fig. 15. Poorly exposed surface sections through the lower Pande clays at Lindi. The Upper Eocene beach section at Kitunda shore appears to be highly condensed, representing ~3 Ma through zone P15 in only 10 m of section and may represent sediment starvation on the mid to outer shelf during maximum flooding (see Fig. 18). See Fig. 6b for key.

and 15; Plate 2h). The limestones are typically composed of a mix between micrite and a fine to medium, sand-sized, carbonate grain matrix. The matrix can dominate or in some beds can be subordinate to tightly packed benthic foraminiferans (0.5 cm to 1 cm in diameter) (Plate 2f). Clay rip-up clasts can be common up to 5 cm in size within these limestones and preferentially weather out to leave the limestones with hollows and a pitted surface (for instance at the Namadingura River; Plate 2h). Balls of micrite can also occur which suggest they were semi-lithified at the time of transport (Plate 2f).

7.1.2. Palaeontology

The large benthic foraminifers which compose the limestone beds can include *Nummulites* but the overall average size of these is less than the coquina limestones of the Masoko clays. Dispersed bivalve fragments and benthic foraminifers are present throughout the clays and plant macrofossil debris was identified both in TDP 11 at Pande and TDP 1 at Kilwa, but is particularly abundant in the top half of TDP 17 at Pande. It also appears that reworked Late Cretaceous nannofossils occur in TDP 11, 12, 17 and 6. This may suggest local erosion and re-deposition of Nangurukuru claystones as Pande clays during the Late Eocene to Oligocene. However, it is not possible at present to determine whether this is from submarine erosion or due to subaerial weathering. Microscopic shelly debris transported out from the innermost shelf is abundant, and often dominates foraminiferal assemblages. Again, macrofossils in the Pande Formation are extremely rare, but oysters (transported downslope) have been found in the vicinity of site TDP 12. 'Flysch'-style agglutinated benthic foraminifera (chiefly *Bathysiphon*) occur in small numbers especially in the Late Eocene portion of the succession. Other deep-water agglutinated foraminifera include *Migros*, *Karreriella*, *Vulvulina* and *Haplophragmoides*. Transported larger benthic foraminifera are more diverse than in underlying formations, and include *Biplanispira* and *Nummulites*, and, in the Late Eocene only, *Heterostegina*, *Spiroclypeus*, *Operculina*, *Discocyclina* and *Asterocyclina*. Deep-water calcareous benthics include *Chilostomelloides*, *Globobulimina*, *Uvigerina*, *Rectuvigerina*, *Siphonodosaria*, *Oridorsalis*, *Anomalinulla*, *Palmula*, *Nodosarella*, *Frondicularia* and *Epistominella*: again an outer shelf to upper slope, slightly dysaerobic sea-floor environment, with water depths of between 300 and 500 m is indicated. However, planktonic foraminiferal and dinoflagellate assemblages suggest that the Pande clays may have been deposited in more shallow marine, mid to inner shelf environments than the underlying formations of the Kilwa Group (Pearson et al., 2006). There is a considerable abundance of innermost shelf foraminiferal debris, including *Reussella*, *Rotalia*, *Pararotalia*, *Ammonia*, *Patellina*, abundant miliolids (including *Spiroloculina*, *Triloculina*, *Quinqueloculina* and *Miliolinella*), *Sphaerogypsina*, *Planorbulinella*, *Baculogypsina*, *Asterigerina*, *Amphistegina*, *Rosalina*, *Lobatula* and many others, as well as abundant calcareous algal (*Corallina*) segments derived from the intertidal zone. Bioturbation is generally uncommon in the Pande Formation.

7.1.3. Bedforms and structure

Benthic foraminiferal limestones in the Pande clays can at times display normal grading, however, there are beds which lack any signs of grading, imbrication or cross-lamination. The presence of large, irregular, micritic balls and clay rip-up clasts, coupled with the lack of sorting within these beds suggests that the clasts were transported as debris flows rather than in a turbulent current, and this helps to distinguish them from Masoko Formation limestones. These limestones also frequently show liquefaction and soft sediment deformation. The associated convolute laminae can be highlighted by the 'swirled' orientation of benthic foraminifera (Plate 2f). Pyrite nodules are uncommon but present sporadically throughout the formation. Distinct intervals of soft sediment deformation in the clays at TDP 1 at Kilwa might suggest syn-depositional slumping or structural deformation against the fault at Kilwa Masoko (Fig. 2).

A thin interval of clayey sand between two Lower Oligocene (P18/O1) benthic foraminiferal limestones at only ~20 m depth in TDP 17 at Pande contained oil residue (Fig. 16). This was particularly developed along the top and basal clayey sand–limestone contacts and suggests oil migration along the limestone bedding surfaces. This occurrence was well within the weathered, oxidation zone close to the surface and we have found in most TDP holes that bedrock clays in this zone are frequently mixed with a proportion of what we assume to be younger quartz sand grains. This partial mixing of lithologies is probably due to a mixture of partial slumping and reworking at the surface, groundwater flow and transport of sands during flash flooding and tropical soil development. However, in this particular case it has important implications for petroleum migration as it suggests that the relict oil residue present at the top of TDP 17 is a relatively recent feature.

At a depth of ~88 m in TDP 17 at Pande, liquid oil was encountered trapped in an ~1 cm wide vuggy cavity within a thin, Lower Oligocene (P18/O1) calcarenite bed (Plate 2g; Fig. 16). Other calcarenite beds within this hole also showed partial dissolution and reprecipitation of secondary cements along the base of limestones beds. The development of internal secondary vuggy porosity could in some cases be seen to be linked by veins to this recrystallization at the base of beds. Together they suggest that petroleum has migrated along the basal bedding surfaces of secondary lithologies within the formation, allowing it to pass through a formation which is clay-dominated and might otherwise be thought of as an ideal seal.

7.2. Formation definition

The Pande Formation stratotype section is a composite of the succession at three localities. The base of the formation can be defined as the top of the highest occurrence of nummulitic limestones characteristic of the Masoko clays. As indicated above, this is likely to lie in reality at a stratigraphic level higher than the youngest nummulitic limestone cored in TDP 4 at Lindi (Fig. 14). However, the ~10 m of clays logged on the foreshore at Kitunda shore on the south-eastern side of Lindi Bay contain white to buff coloured sandy calcarenites which are not typical of the Masoko clays and should be considered as belonging to the overlying Pande Formation (Fig. 15). We have not at present recovered the missing stratigraphic interval between TDP 4 and the Kitunda section, but it clearly should include the Masoko clay–Pande clay boundary. It is difficult to assess the thickness of strata missing between the two localities because, although they face each other across Lindi Bay, there is a postulated fault, the 'Lukuledi Fault', which trends north-east to south-west through the bay between them (Kent et al., 1971). Thus, at present, the base of the Pande Formation is defined at the base of the Kitunda Shore section and this ~10 m interval defines the lower third of the composite stratotype section (Fig. 5). There is then likely to be a stratigraphic gap between the Kitunda section and the middle composite section composed of sites TDP 12, 11 and 17 on the road north from Mkazambo near a village called Stakishari (Fig. 3). Site TDP 12 cored ~145 m of Pande clays and is considered here as the holostratotype for this formation (Fig. 16). Strata from the central interval cored in TDP 12 across the Eocene–Oligocene boundary can also be found exposed

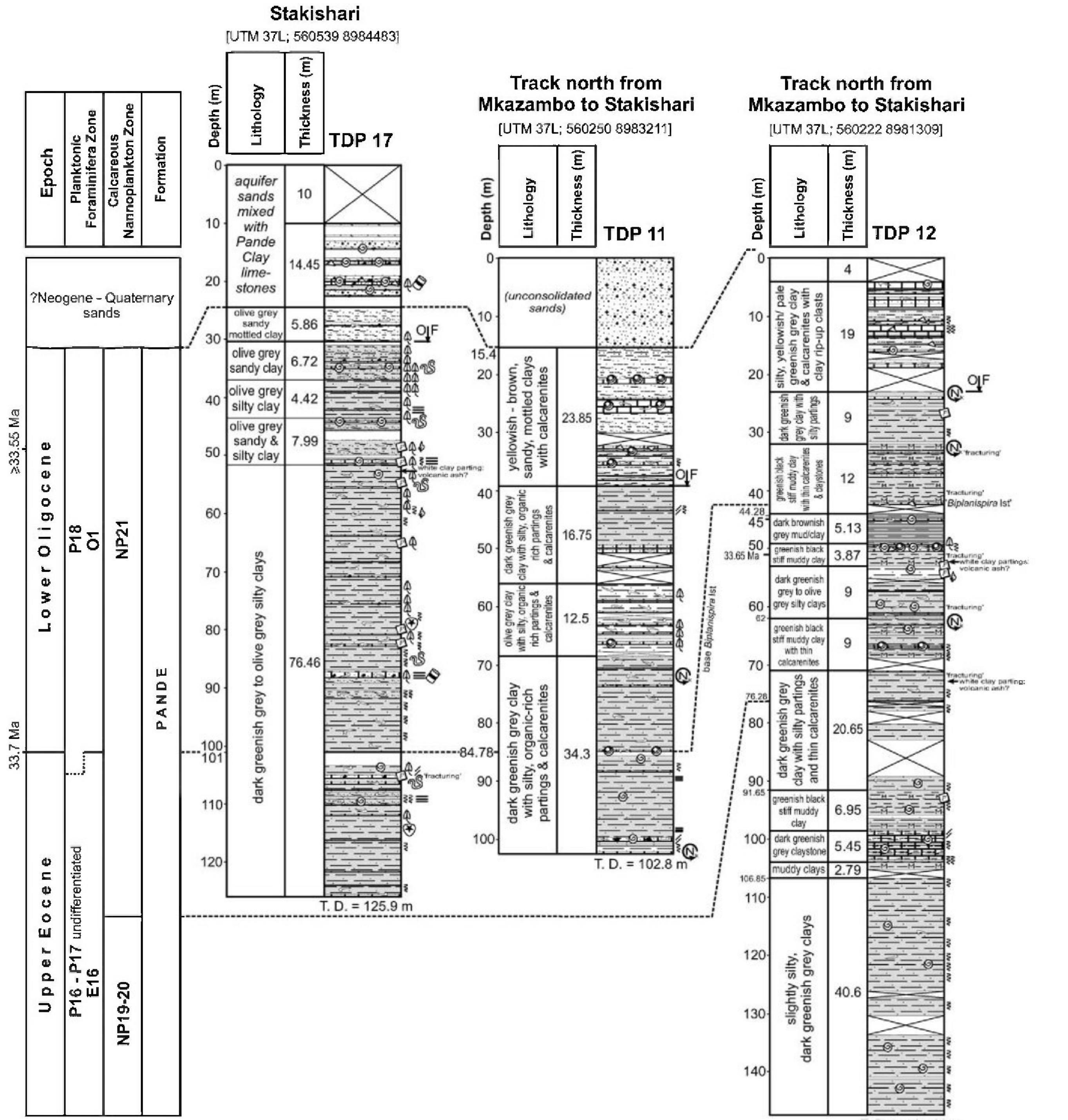


Fig. 16. The Eocene–Oligocene boundary in the Stakishari area at Pande. TDP 11, 12 and 17 all cored the boundary interval, with TDP 17 demonstrating marked shallowing and influx of terrestrial plant debris in the Lower Oligocene towards the top of the hole. The Eocene–Oligocene boundary interval of TDP 12 is exposed on the hillside below the rig site (see Plate 2e). See Fig. 6b for key.

in dry seasonal streambeds on the slopes below the rig site (Plate 2e and f). Much of the equivalent stratigraphic interval of TDP 12 was also recovered in TDP 11 and TDP 17, giving three holes with stratigraphic coverage across the Eocene–Oligocene transition. The upper of the three composite sections of the Pande clays is the interval cored in TDP 1, opposite the airstrip just north of Kilwa Masoko (Figs. 2 and 17). Here the clays are younger than at Pande but are exposed faulted against the Masoko clays which cuts out the lower Pande clay stratigraphy. The fault zone itself was cored in neighbouring TDP 6 only ~300 m south of TDP 1 (Fig. 2). These Pande clays have characteristic principal clay and secondary limestone lithologies (see above) and the top of the formation can be defined as

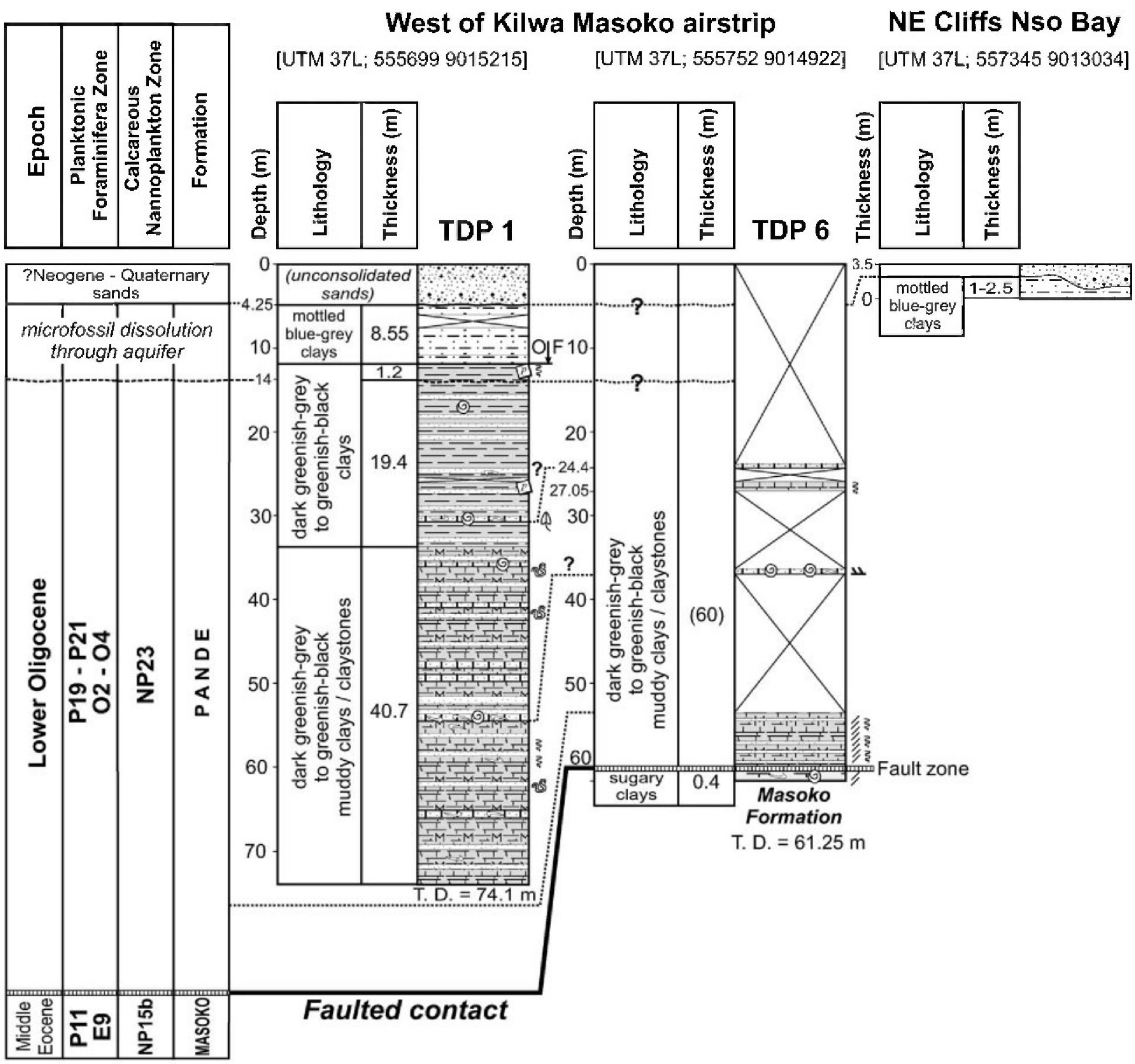


Fig. 17. Lower Oligocene Pande clays of TDP 1 and TDP 6 (~300 m to the south), drilled opposite the airstrip at Kilwa Masoko. A ~0.5 m wide fault zone was cored towards the base of TDP 6, below which were Middle Eocene Masoko clays. This 'Masoko fault' strikes north–north-west to south–south-east across the tip of the Kilwa peninsula (see Fig. 2). See Fig. 6b for key.

the highest stratigraphic occurrence of the white micritic limestones or fresh greenish black (or weathered blue–grey) clays. This is currently taken at the top of TDP 1 at Kilwa, where the Pande clays are capped by unconsolidated Plio–Pleistocene sands (Fig. 17; see also Plate 2i). These sands have acted as an aquifer and groundwater percolating along the sand/clay interface has dissolved away most of the microfossils in the clays making biostratigraphic age determinations difficult. However, whilst the Pande clays are unconformably overlain by unconsolidated sands at Kilwa, at Lindi they are unconformably overlain by Miocene or younger sandy limestones. The Miocene along the northern shores of Lindi Bay is clearly unconformable on the Kilwa Group and, as such, it should be noted that the top of the Pande clays is an irregular, sequence-bounding erosional surface.

8. Sequence development and architecture in the Kilwa Group

Planktonic to benthic foraminiferal ratios in TDP sites 1–10 suggest a dominantly mid or outer shelf to upper slope setting throughout deposition of the Kilwa Group clays and claystones (Pearson et al., 2004, 2006). There are, however, some intra-formational variations in fine clastic component and pulsed delivery of shallow water sediment and fossil material in the form of turbidity and debris flows. By making certain assumptions concerning facies development, missing stratigraphy and margin subsidence, it is possible to construct a predictive sequence stratigraphic framework for the evolution of the Kilwa Group from Santonian to Oligocene. The mid or outer shelf to upper slope depositional setting, combined with the composite nature of stratotype sections together mean that the sequence stratigraphic model that best applies to the Kilwa Group at present is that outlined as Depositional Sequence IV in Catuneanu (2002). This recognises sequence bounding surfaces at the end of base level fall, between Falling Stage and Lowstand Systems Tracts. Using the facies assumptions outlined below, fragments of Transgressive, Highstand, Falling Stage and Lowstand Systems Tracts can all be recognised in field sections or TDP cores. These are stitched together to construct a basic sequence model for the Kilwa Group based on our current field evidence which more detailed studies in the future can refine.

8.1. Facies assumptions

Whilst the entire succession of the Kilwa Group is broadly homogeneous, there are subtle cyclical changes in both the bulk clay and claystone compositions over time and the appearance or disappearance of characteristic secondary lithologies (Figs. 6–17). In the case of bulk clay and claystone composition, the Kivinje claystones for instance typically exhibit two lithological varieties; a hard waxy claystone and a silty claystone. The waxy claystones tend to have less evidence of bioturbation and shallow water macrofossil debris than the silty claystones. When sections are examined in chronostratigraphic order (Fig. 5) a cyclical change between these two principal lithologies can be observed. Using the assumption that delivery of a coarser siliciclastic component indicates a marginally closer proximity to palaeo-shoreline from a normal regression, the silty claystones are likely to represent prograding highstand units, whereas the waxy claystones accumulated during transgressive back-stepping of the claystones shoreward.

In contrast, the Nangurukuru claystones exhibit no discernable change of principal claystone lithology in exposures, but they do show variations in secondary lithologies and trace fossil assemblages which have been used previously to predict changes in relative water depth during deposition (Gierlowski-Kordesch and Ernst, 1987; Ernst and Zander, 1993). The trace fossil-bearing, carbonate cemented sandstones, or '*Nereites* sandstones' show sedimentary structures and bedforms consistent with deposition from turbulent currents. However, they do not show typical Bouma sequence architecture and are more likely to be caused by individual storm events higher on the shelf remobilising coarser clastics and delivering them to outer shelf and slope areas. As such, they could also be indicative of relative proximity to palaeo-shoreline and consequently an indicator of a relative shallowing or deepening in the Kilwa Group depositional shelf slope zone. Where these sandstones are absent in the Nangurukuru claystone succession, it may suggest a slight transgressive deepening, with the focus of *Nereites* sandstone deposition stepping westwards (shorewards). The same processes and effects could be responsible for the presence or absence of nummulitic limestones in the Masoko clays. These are also likely to be storm-induced and there are two distinct intervals for their accumulation, which could represent minor shallowing events where the palaeo-shoreline has prograded east during normal regression. Repetitive, clustered stratigraphic occurrences of shallow water shell debris, such as echinoids or gastropods, and plant fragments or benthic foraminifera towards the top of these intervals are likely to indicate a base level fall which is outstripping sedimentation rate, to accumulate a Falling Stage Systems Tract across the shelf. The evidence for this either in exposed sections or core is patchy and in general highstand progradation and falling stage rapid progradation are left undifferentiated. Finally, it should be noted that in order to construct the following sequence model, it has to be assumed that lateral facies variation within the Kilwa Group between Kilwa and Lindi is negligible. Essentially this has already been demonstrated in establishing composite stratotypes across the shelf margin between these areas.

8.2. Sequence development (Fig. 18)

Based on the assumptions outlined above, a working model of sequence development can be constructed for the southern Tanzanian coastal margin from Late Cretaceous to Late Oligocene (Fig. 18). Twelve minor sequences can be identified (numbered and given the informal prefix abbreviation of 'KG'; 'Kilwa Group', in Fig. 18), but we cannot identify the magnitude of these sequences at this time. However, two major bounding surfaces which appear to have been accompanied by significant fall in base level, can be recognised within the Kilwa Group succession. The first is at the Cretaceous–Tertiary boundary between KG3 and KG4. Because we have so far been unable to recover any Lower Paleocene, the surface between Nangurukuru and Kivinje claystones could represent a disconformity or even an unconformity across inner to outer shelf areas. Despite this however, basal Paleocene has been reported to overlie the Upper Cretaceous at Lindi (Blow and Banner, 1962). Although we have not successfully rediscovered this sample locality, its presence is best explained by either continued clay accumulation, or subsequent preservation during lowstand, within palaeo-topographic lows on the outer shelf during the Early Paleocene. The second major bounding surface is that which defines the top of the Kilwa Group, between Early and Late Oligocene. This sequence boundary is unconformable across the outer shelf and may in part reflect a genuine eustatic fall in sea level associated with Oligocene glaciations (Wade and Pälike, 2004). Indeed, the marked shallowing up-section observed in TDP 17 suggests a Falling Stage Systems Tract and may indicate the onset of the earlier 'Oi-1' cooling event in the lowermost Oligocene (see Miller et al., 1991). It is likely that both of these significant relative sea level falls were associated with the development of lowstand fans in deeper water.

The road section between Matandu Bridge and Nangurukuru junction begins with an interval of Santonian

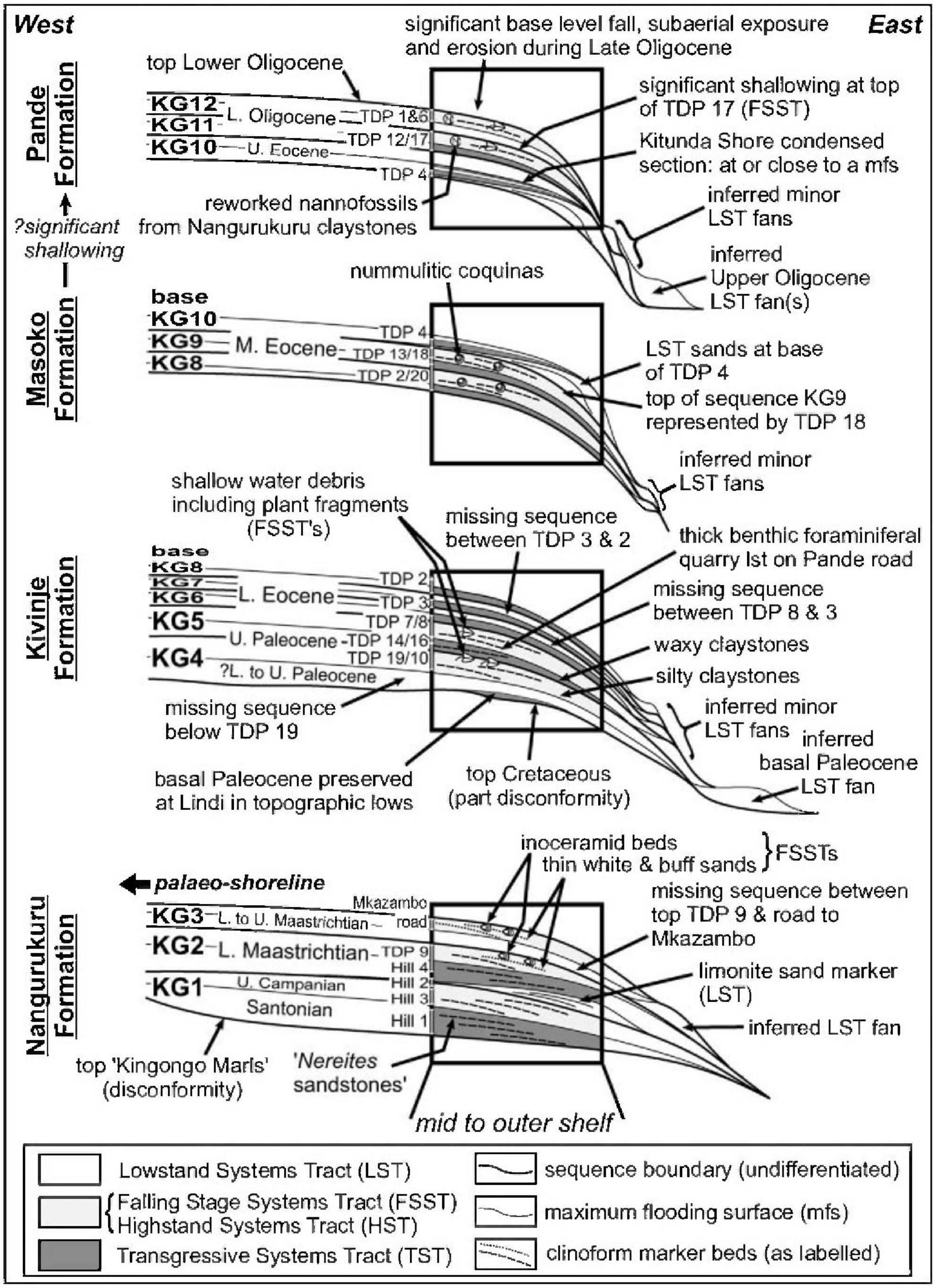


Fig. 18. Cartoon sequence stratigraphic model for the development of Kilwa Group formations from Late Cretaceous to Late Oligocene. The coastal margin is shown in cross-section west to east, with the mid shelf to upper slope zone of accumulation for the Kilwa Group shown in boxes. All stratigraphic sections (Figs. 6–17) are located within these, but no further attempt is made in this cartoon to locate them spatially relative to each other or their position in this zone. Sequences are informally numbered (e.g. 'KG1') and the age range of systems tracts indicated. The stratigraphic range of key sections used in building the model are represented in white at the edge of each box. Clinoform marker beds are schematic only, but indicate general transgression or progradation seen in the secondary lithologies of lithostratigraphic sections. Highstand Systems Tracts and Falling Stage Systems Tracts are left undifferentiated except where the presence of significant shallow water debris towards the top of a stratigraphic interval indicates that base level fall outstripped sedimentation rate and these are labelled accordingly. Note that horizontal distances and sequence thicknesses are not shown to scale.

'*Nereites* sandstone' deposition seen at 'Hill 1' (Fig. 6). This is stratigraphically overlain by the lower interval of the section on 'Hill 3', where there is only one, thin sandstone, and suggests a general deepening during transgression prior to reintroduction of these sandstones through highstand progradation. The limonitic sand marker on the summit of 'Hill 3' is likely to be significantly shallower still from its trace fossil assemblage (Gierlowski-Kordesch and Ernst, 1987; Ernst and Zander, 1993), and is best explained as the development of a thin lowstand deposit.

This would place a minor sequence bounding surface between KG1 and KG2 at the base of the limonite sand unit. The base of TDP 9 contains a thin package of '*Nereites* sandstones' overlain by an interval of few sandstones but an increased presence of pyrite (Fig. 7). This may not only indicate a deepening event, but also that the bottom waters or surface sediment layer became anoxic during this time interval. However, this is superceeded by the first of two intervals containing inoceramids, some of which are up to 25 cm long exposed in a road cut not far from TDP 9. This is taken as evidence of marked shallowing-up in the succession and is also accompanied by the increased occurrence of thin white and buff sands towards the top of KG2. Together they are likely to indicate the switch from slowing base level rise at the end of a highstand to falling stage rapid progradation of shallower clastics (see Catuneanu, 2002). A younger, similar highstand sequence on the Mkazambo road at Pande (Fig. 8) and a fragment of it at Kitulo Hill in Lindi, suggests that we have so far missed locating the basal, transgressive part of the next sequence; KG3.

The Nangurukuru–Kivinje transition (K–T boundary) and significant bounding surface has been outlined above. Following this, TDP 19 and 10 consist mostly of silty claystones, with a thin interval of shelly debris at the top of TDP 10 as it passes into waxy claystone. Thus both holes are likely to represent highstand claystones of sequence KG4 followed by the early transgressive phase of KG5, which may include syn-depositional slumping indicated by convolute bedding and inclined laminations at this level (Fig. 9). A similar sequence is recorded in the younger holes of TDP 7A/B to TDP 8. The silty claystones appear to contain derived shallow shelf shell and plant debris. However, the hard, waxy claystones towards the top contain convolute beds, inclined lamination and in this particular case, some normal grading in thin sand partings. TDP 7A/B to TDP 8 are therefore suggested to record the sequence boundary developed between a highstand and subsequent transgression, equating to the sequence boundary between KG5 and KG6. TDP 14, 16A and 16B must all therefore fit between TDP 10 and TDP 7A/B close to the maximum flooding of KG5. Overlying TDP 8, TDP 3 contains a mix of waxy claystones and sugary clays to claystones with sand partings. The occurrence of pulsed, thin sand horizons may suggest that this hole represents part of a transgressive package. TDP 3 does not overlap with underlying TDP 8 so it must be assumed that there is part of a sequence missing between the two and that TDP 3 represents the trangressive unit of the next sequence, KG7. The same is also the case between TDP 3 and overlying TDP 2 (KG8). Further work may indicate that TDP 8, TDP 3 and the lower part of TDP 2 are all part of the same transgressive sequence. However, given the facies changes seen elsewhere in the succession over this thickness of claystone, this explanation would seem less likely.

Within TDP 2 and TDP 20, waxy claystones pass up into the Masoko clays and this is taken to indicate the maximum flooding surface within KG8, followed by progradation of nummulitic coquinas present in the lower levels of the Masoko clays at TDP 2 and TDP 20 (Fig. 13). TDP 13 to TDP 18 represents a second, similar sequence (KG9) stacked on top, consisting of muddy transgressive clays passing up into more silty clays containing limestone beds and plant fragments. A sand unit at the base of TDP 4 suggests we drilled part of another thin lowstand unit overlain by transgressive clays (base of KG10). The possible presence of a hardground on the top of these sands may even represent the transgressive phase. However, the Kitunda shore section, which is younger than TDP 4, is most likely to represent the condensed sequence accumulated during maximum flooding for KG10. We currently have no record of the Upper Eocene between the Kitunda section and TDP 12, but this should correspond to a period of highstand. The lower half of TDP 12 contains no shell or plant fragments and rare benthic foraminiferal limestones. The upper half (and all TDP 11 and TDP 17) contains several limestone beds plus occasional shelly and plant material, including reworked nannofossils from the Nangurukuru claystones. Therefore, it is likely that TDP 12 represents another minor transgression-highstand sequence; KG11, which straddles the Eocene–Oligocene boundary, with the top of TDP 17 recording significant shallowing as base level fell and a Falling Stage Systems Tract developed. Finally, TDP 1 (and TDP 6 above the fault) contain silty clays with organic rich partings and plant fragments dispersed throughout, also with reworked Upper Cretaceous nannofossils. There has been no recovery of the succession between the top of TDP 17 and the base of TDP 1 but this is likely to correspond to the transgressional part of KG12. The facies of TDP 1 suggests it is part of the progradational highstand unit of KG12. This represents the youngest part of the stratigraphic succession so far identified in the Kilwa Group. The sequence-bounding surface at the top of KG12 represents the Early-Late Oligocene unconformity across the shelf.

9. Discussion

The Kilwa Group represents a clay-dominated succession that accumulated on the mid or outer shelf to upper continental slope during the Late Cretaceous to Early Oligocene. In essence, this Group equates to the most stable period of the Tanzanian passive margin, with steady, uniform subsidence across the shelf leading to lateral facies continuity along palaeo-strike. This margin stability does not seem to have existed prior to, or post-Kilwa Group deposition. Although clay deposition along the southern Tanzanian coastal zone took place prior to the Kilwa Group during the Aptian–Albian, there appear to be a series of marked dis- or un-conformities which suggest that sedimentation was at least in part tectonically controlled at this time. Whilst more detailed work still needs to be done, it could be argued that the minor fluctuations in base level recorded by Kilwa Group formations correspond to genuine eustatic sea level fluctuations. Certainly, the two bounding surfaces which correspond to the most significant fall in base level within the Kilwa Group are known intervals of global regression at the Cretaceous–Paleocene and Early–Late Oligocene boundaries (Fig. 18). The primary control on post-Kilwa Group deposition appears to be a period of Miocene extension parallel to the present day shoreline which opened most of Tanzania's shallow coastal basins (Mougenot et al., 1986). This seems to mark the end of tectonic quiescence along the southern Tanzanian margin and led to more localised, shallow water, laterally impersistent facies development in Miocene and younger units.

The delivery of detrital clays, quartz, feldspars and micas from the exposed basement hinterland of the Masasi Spur appears to have been relatively constant for ~55 Ma. There is some seismic evidence to suggest that large palaeofluvial systems existed where the present day Rufiji (to the north) and Ruvuma (to the south, marking the Tanzania–Mozambique border) rivers are situated. Such systems must have been responsible for the choking supply of clay to the shelf area caught between their large deltas. The Kilwa Group is also characterised by the high organic content of the clays. A proportion of this organic matter is terrestrial plant material also presumably flushed in by these rivers (Pearson et al., 2004, 2006). The secondary lithologies which allow recognition of the different formations within the group are essentially controlled by storm events in the shallow shelf areas. As the composition of shallow shelf faunas changed over time, this is reflected in the allochthonous benthic foraminiferal composition of Kivinje, Masoko and Pande formation limestones.

One of the most important economic aspects of the Kilwa Group is our discovery of oil and oil residues either as surface seeps or trapped at shallow depths in three out of the four formations. With such a high clay content the Kilwa Group should theoretically provide an excellent hydrocarbon seal and the excellent 'glassy' preservation of planktonic foraminifera in most clay samples indicates that for the most part it is indeed impermeable to fluid flow. However, it is clear that petroleum can migrate laterally along bedding surfaces between limestones and clays, through thin sandy clay horizons, or along fault zones. It is unlikely that the Kilwa Group is self-sourcing as the organic matter is well preserved with a very low thermal maturity (see van Dongen et al., 2006) and the most likely stratigraphic source below the Kilwa Group are the Jurassic 'Pindiro shales' (Mpanda, 1997). In either event, further research is currently underway to establish the structural evolution of the Kilwa Group and the effects this might have had on petroleum play systems along the southern Tanzanian coast.

Acknowledgements

This research was supported by Enterprise Ireland Basic Research Grant SC/2002/255 to C.J. Nicholas, Natural Environment Research Council (UK) Grants GR3/12618, NE/X509345/1 and NE/B503255/1 to P.N. Pearson and NE/C510508/1 to J.A. Lees, and UCL Graduate School funding for T. Dunkley Jones. We are grateful to the Tanzania Petroleum Development Corporation for continued logistical and scientific support and to Mike Rego of Aminex PLC., for the use of coastal satellite images and geochemical confirmation of the Kilwa Masoko oil seep.

References

Balduzzi, A., Msaky, E., Trincianti, E., Manum, S.B., 1992. Mesozoic Karoo and post-Karoo Formations in the Kilwa area, southeastern Tanzania – a stratigraphic study based on palynology, micropalaeontology and well log data from the Kizimbani Well. Journal of African Earth Sciences 15, 405–427.

Berggren, W.A., Pearson, P.N., 2005. A revised tropical to subtropical Paleogene planktonic foraminiferal zonation. Journal of Foraminiferal Research 35, 279–298.

Berggren, W.A., Kent, D.V., Swisher, C.C., Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.-P., Hardenbol, J. (Eds.), Geochronology, Time Scales and Global Stratographic Correlation. SEPM Special Publication 54, pp. 129–212.

Blow, W.H., Banner, F.T., 1962. The Mid-Tertiary (Upper Eocene to Aquitanian) Globigerinacea. In: Eames, F.T. et al. (Eds.), Fundamentals of Mid-Tertiary Stratigraphic Correlation. Cambridge University Press, London, pp. 61–151.

Blow, W.H., 1979. The Cainozoic Globigerinida: A Study of the Morphology, Taxonomy and Evolutionary Relationships and the Stratigraphical Distribution of Some Globigerinida (mainly Globigerinacea), vols. 3. E. J. Brill, Leiden, 1308 pp.

Bornhardt, W., 1900. Zur Oberflächengestaltung und Geologie Deutsch-Ostafrikas. Deutsch-Ostafrika 7, Dietrich Reimer, Berlin, pp. 1–595.

Bown, P.R., 2005. Paleogene calcareous nannofossils from the Kilwa and Lindi areas of coastal Tanzania (Tanzania Drilling Project 2003–4). Journal of Nannoplankton Research 27, 21–95.

Bown, P.R., Dunkley Jones, T., 2006. New Paleogene calcareous nannofossil taxa from coastal Tanzania: Tanzania Drilling Project Sites 11 to 14. Journal of Nannoplankton Research 28, 17–34.

Burnett, J.A. (with contributions from Gallagher, L.T., Hampton, M.J.), 1998. Upper Cretaceous. In: Bown, P. R. (Ed.), Calcareous Nannofossil Biostratigraphy. British Micropalaeontological Society Series, Chapman & Hall: Kluwer Academic Press, 132–199.

Catuneanu, O., 2002. Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. Journal of African Earth Sciences 35, 1–43.

Ernst, G., Schlüter, T., 1989. The Upper Cretaceous of the Kilwa Region, Coastal Tanzania. Workshop Geol. Tanzania Rev. Res. Progr. Univ. Köln, Abstr., Cologne, pp. 1–3.

Ernst, G., Zander, J., 1993. Stratigraphy, facies development, and trace fossils of the Upper Cretaceous of southern Tanzania (Kilwa District). Geology and mineral resources of Somalia and surrounding areas. Inst. Agron. Oltremare Firenze, Relaz. e Monogr. 113, Firenze, pp. 259–278.

Gierlowski-Kordesch, E., Ernst, G., 1987. A flysch trace assemblage from the Upper Cretaceous shelf of Tanzania. In: Matheis, G., Schandelmeier, H. (Eds.), Current Research in African Earth Sciences. Balkema, Rotterdam, pp. 217–222.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J., Huang, Z., 1995. A Triassic, Jurassic and Cretaceous time scale. In: Berggren, W.A., Kent, D.V., Aubry, M.-P., Hardenbol, J. (Eds.), Geochronology, Time Scales and Global Stratographic Correlation. SEPM Special Publication 54, pp. 95–126.

Haughton, S.H. (Ed.), 1938. Lexicon de Stratigraphie, vol. 1: Africa. Thomas Murby, London, p. 203, 229.

International Subcommission on Stratigraphic Classification (ISSC), 1976. In: Hedberg, H.D. (Ed.), International Stratigraphic Guide. Wiley, New York, 200 pp.

Kent, P.E., Hunt, J.A., Johnstone, D.W., 1971. The Geology and Geophysics of Coastal Tanzania. Institute of Geological Sciences Geophysical Paper No. 6, HMSO, London.

Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Faranacci (Ed.), Proceedings of the Second Planktonic Conference Roma 1970, vol. 2. Edizioni Tecnoscienza, Rome, pp. 739–785.

McKie, T., 1993. Relative sea-level changes and the development of a Cambrian transgression. Geological Magazine 130, 245–256.

Miller, K.G., Wright, J.D., Fairnbanks, R.G., 1991. Unlocking the ice house; Oligocene – Miocene oxygen isotopes, eustasy and margin erosion. Journal of Geophysical Research 96, 6829–6848.

Moore, W.R., McBeath, D.M., Linton, R.E., Terris, A.P., Stoneley, R., 1963. Geological Survey of Tanganyika Quarter Degree Sheet 256 & 256E. 1:125 000. Kilwa. First Edition. Geological Survey Division, Dodoma.

Mougenot, D., Recq, M., Virlogeux, P., Lepvrier, C., 1986. Seaward extension of the East African Rift. Nature 321, 599–603.

Mpanda, S., 1997. Geological development of the East African coastal basin of Tanzania. Stockholm Contributions in Geology 45, 1–121, University of Stockholm, Sweden.

Nederbragt, A.J., 1991. Late Cretaceous biostratigraphy and development of Heterohelicidae (planktic foraminifera). Micropaleontology 37, 329–372.

Oppenheim, P., 1916. Die Tertiärbildungen von Deutsch-Ostafrika. Zeitschrift der Deutschen Geologischen Gesellschaft 68B, 103–113.

Pearson, P.N., Ditchfield, P.W., Singano, S., Harcourt-Brown, K.G., Nicholas, C.J., Olsson, R.K., Shackleton, N.J., Hall, M.A., 2001. Warm tropical sea surface temperatures in the Late Cretaceous and Eocene epochs. Nature 413, 481–487.

Pearson, P.N., Nicholas, C.J., Singano, J.M., Bown, P.R., Coxall, H.K., van Dongen, B.E., Huber, B.T., Karega, A., Lees, J.A., Msaky, E., Pancost, Pearson, M., Roberts, A.P., 2004. Paleogene and Cretaceous sediment cores from the Kilwa and Lindi areas of coastal Tanzania: Tanzania Drilling Project Sites 1–5. Journal of African Earth Sciences 39, 25–62.

Pearson, P.N., Nicholas, C.J., Singano, J.M., Bown, P.R., Coxall, H.K., van Dongen, B.E., Huber, B.T., Karega, A., Lees, J.A., MacLeod, K., McMillan, I.K., Pancost, R.D., Pearson, M., Msaky, E., 2006. Further Paleogene and Cretaceous sediment cores from the Kilwa area of coastal Tanzania: Tanzania Drilling Project Sites 6–10. Journal of African Earth Sciences, in press, doi:10.1016/j.jafrearsci.2006.02.005.

Robaszynski, F., Caron, M., 1995. Foraminifères planktoniques du Crétacé: commentaire de la zonation Europe-Mediterranée. Société Géologique de France 166, 681–692.

Schlüter, T., 1997. Geology of East Africa. Gebrüder Borntraeger, Berlin, 484 pp.

Scholtz, E., 1911. Beiträge zur Kenntnis der Deutsch-Ostafrikanischen Tertiärablagerungen. Zeitschrift der Deutschen Geologischen Gesellschaft 62, 368–379.

Singer, A., 1984. The paleoclimatic interpretation of clay minerals in sediments – a review. Earth Science Reviews 21, 251–293.

Stewart, D.R.M., Pearson, P.N., Ditchfield, P.W., Singano, J.M., 2004. Miocene tropical Indian Ocean temperatures: evidence from three exceptionally preserved foraminiferal assemblages from Tanzania. Journal of African Earth Sciences 40, 173–190.

Sutton, J.E.G., 2000. Kilwa: a history of the ancient Swahili town with a guide to the monuments of Kilwa Kisiwani and adjacent islands. British Institute in East Africa, Nairobi, Kenya, 57 pp.

van Dongen, B.E., Talbot, H.M., Schouten, S., Pearson, P.N., Pancost, R.D., 2006. Well preserved Palaeogene and Cretaceous biomarkers from the Kilwa area, Tanzania. Organic Geochemistry 37, 539–557.

Veeken, P.C.H., Titov, K.V., 1996. Gravity modelling along a seismic line across the Mandawa basin, southeastern Tanzania. Journal of African Earth Sciences 22, 207–217.

Wade, B.S., Pälike, H., 2004. Oligocene climate dynamics. Paleoceanography. PA4019, doi:10.1029/2004PA001042.