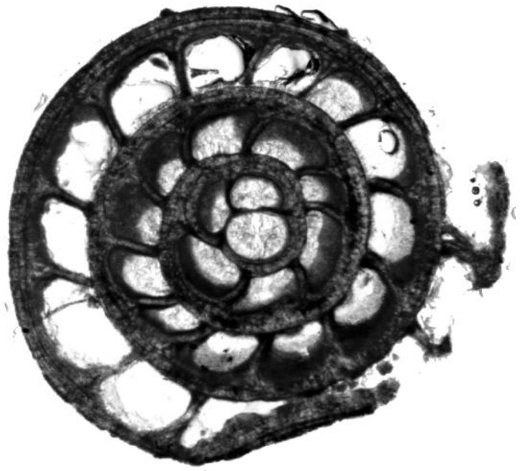
Paleogene Larger Benthic Foraminifera of Tanzania and the Eocene - Oligocene Transition

Laura J. Cotton

2012



Thesis submitted for the Degree of Doctor of Philosophy

Cardiff University

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Abstract

Mass extinctions are important events for the evolution of life on Earth but often the mechanisms behind them are poorly understood. The Eocene - Oligocene Transition (EOT) had a profound and lasting influence on global climate and, though not one of the “big 5” mass extinction events, widespread extinctions in many fossil groups have been recognised. Larger benthic foraminifera (LBF), one of the most conspicuous and widespread fossil groups during the Eocene, are known to have experienced a rapid global overturning during the EOT, including the extinction of long-ranging families such as the Discocyclinidae, Orbitoclypeidae, Pellatispiridae and a number of species in the Nummulitidae. However, detailed records through the transition are rare, and few complete sections are known; the timing and causes of extinctions therefore remain uncertain.

Extensive field samples from the southern Tanzanian coastal region along with Tanzania Drilling Project (TDP) samples are used to give an overview of Eocene to Miocene LBF and to produce high resolution stratigraphic records of LBF events across the EOT. Two further important EOT sites, Fuente Caldera, Spain and Melinau Gorge, Sarawak, both with unresolved questions relating to LBF at the EOT were studied for comparison.

The field samples combined with the TDP data cover an area of approximately 200 km from Kilwa to the Mozambique border. Initial comparisons with Tethyan and Indo-Pacific faunas show perhaps an intermediate assemblage in the Eocene and some similarities with the Indo-Pacific in the Miocene. However in both epochs there are features distinctive of an East African or western Indo-Pacific fauna. Additionally, this work identifies many previously unreported localities and provides a solid basis for future work.

Three of the TDP sites span the EOT and contain abundant LBF. Extensive calcareous micro-, nannofossil and stable isotope studies of these cores allow the LBF stratigraphy to be tied to global stratigraphy. These records show that the LBF extinction event occurs close to the Eocene/Oligocene boundary (EOB), as defined by the extinction of the planktonic foraminiferal Family Hantkeninidae, rather than at the prominent oxygen isotope excursion in the early Oligocene that signifies maximum ice growth and global sea-level fall. New bulk isotope data from the Melinau Limestone of Sarawak further support this conclusion. In Fuente Caldera, where the extinction level was previously reported to be within the Oligocene, extensive reworking means that an EOB extinction is also likely at this site. This correlation raises new questions about the cause of the extinctions and has important implications for global larger benthic foraminiferal stratigraphy.

Contents

Chapter 1:
Introduction

1.1 Introduction: the big questions

Mass extinction events have occurred periodically throughout the evolution of life on Earth, causing dramatic shifts in evolution and ecology. The largest extinction events of the Phanerozoic have been extensively studied and yet the exact mechanisms responsible remain debated. Most of the large extinction events occur during periods of pronounced climatic change or are associated with events such as meteorite impacts or large volcanic eruptions (e.g. Alvarez et al., 1980; Courtillot et al., 1986; Courtillot, 1990; Hallam and Wignall, 1997). Raup and Sepkoski (1982) identified what are referred to as the "big five" mass extinction events; the end Ordovician, the late Devonian, the Permo-Triassic, the Triassic-Jurassic and the Cretaceous-Paleogene extinction events. However, these are not the only mass extinction events, there are a number of others which although not as large as the "big five" are still globally recognised and exceptionally important in shaping the evolution of life.

Whilst mass extinction events are detrimental to life at the time, they can be extremely useful for biostratigraphy, in that they provide useful horizons for correlation. Synchronous extinctions occurring on a global scale can form "natural biozones"; a mass extinction is often followed by evolution and radiation of the surviving organisms and therefore often results in a distinct change in fossil assemblage which can be easily recognised and used for dating (see discussion in McGowran, 2005). This is one of the reasons mass extinctions are often found at stage boundaries. Additionally, certain extinction events are useful analogues for the study of future environmental perturbations.

The Eocene - Oligocene Transition (EOT) was one of the most profound episodes of lasting climate change to occur in the Cenozoic. It is an extended period of step-wise cooling occurring between 33.5 and 34 Ma, associated with the growth of the first semi-permanent ice sheets on Antarctica (Shackleton and Kennett, 1975; Coxall et al., 2005). Though not listed as one of Sepkoski's "big five" the EOT is considered a period of significant biological overturning, with rapid and widespread extinctions in many fossil groups (see reviews by Prothero, 1994; Coxall and Pearson, 2007). Planktonic and larger benthic foraminifera both show rapid extinctions within this interval (Adams et al., 1986; Molina, 1986; Coccioni et al., 1988; Wade and Pearson, 2008) and although changes in other microfossils are less dramatic, assemblage changes and overturning are still clearly visible (Baldauf, 1992; Brinkhaus, 1992; Brinkhaus and Biffi, 1993; Dunkley Jones et al., 2008). Major overturning is also seen within some molluscan records (Dockery and Lozouet, 2003). In terrestrial vegetation a strong trend to more temperate vegetation occurs (Wolfe, 1992, 1994) and in the land mammal record there is a high turnover in hoofed mammals with 60 % of taxa disappearing (Savage and Russell, 1983; Coxall and Pearson, 2007). Many of these records, particularly the macro-fossil record, remain difficult to tie exactly to the events of the EOT (e.g. Prothero and Swisher, 1992) or have a patchy distribution and although there is a general link to the cooling the exact mechanisms for their extinctions are complex and remain ambiguous. The response of the carbonate platform environment, in particular, remains poorly understood. The shallow carbonate platforms at that time, much like today, were a highly diverse and dynamic environment and a major carbonate factory. The study of this environment in particular can provide information on sea-level changes, surface run off/sedimentation changes and the response of shallow water organisms. Shallow platform dwelling organisms, such as corals, calcareous algae and larger benthic foraminifera (LBF) are highly specialised to this environment, so small changes can bring about dramatic effects. Therefore, in this thesis LBF are used to examine the changes taking place in the shallow carbonate environment through this period of rapid climate change.

1.2 LBF of the Paleogene

LBF are emblematic of the Paleogene, occurring in rock forming quantities around the tropical regions of the Tethyan, Indo-Pacific and American provinces. *Nummulites* are found in such high numbers during this period that it was once referred to as the Nummulitique (Rollier, 1923; Gradstein et al., 2004). This applies in particular to the Eocene, when some of the most well-known LBF - the *Nummulites*, became widespread and exceptionally abundant. The LBF assemblage, however, is not constant throughout the Paleogene. Several global overturning events occur within the Eocene causing extinctions of a number of important, widespread genera and dramatically altering the LBF assemblage, but these events are poorly understood. Migrations of

LBF from America to the Tethys and Indo-Pacific in the late Oligocene, coupled with extinction of the *Nummulites* and evolution of new genera result in an entirely different LBF assemblage which continues into the Neogene.

After the K/T extinction event at the end of the Cretaceous the Paleocene was a period of recovery for LBF; over 80 % of the Maastrichtian LBF suffered extinction at the boundary (BouDagher-Fadel, 2008). The carbonate platforms of the Paleocene were dominated by calcareous algae rather than LBF, which diversified rapidly after the Maastrichtian and have a peak in the Early Eocene (Figure 1.1; Zamagni et al., 2012). LBF remained small sized and relatively rare through the Early Paleocene. Their size and diversity then begins to steadily increase from the Late Paleocene and through the Early and Middle Eocene (Hottinger 1997, 1998).

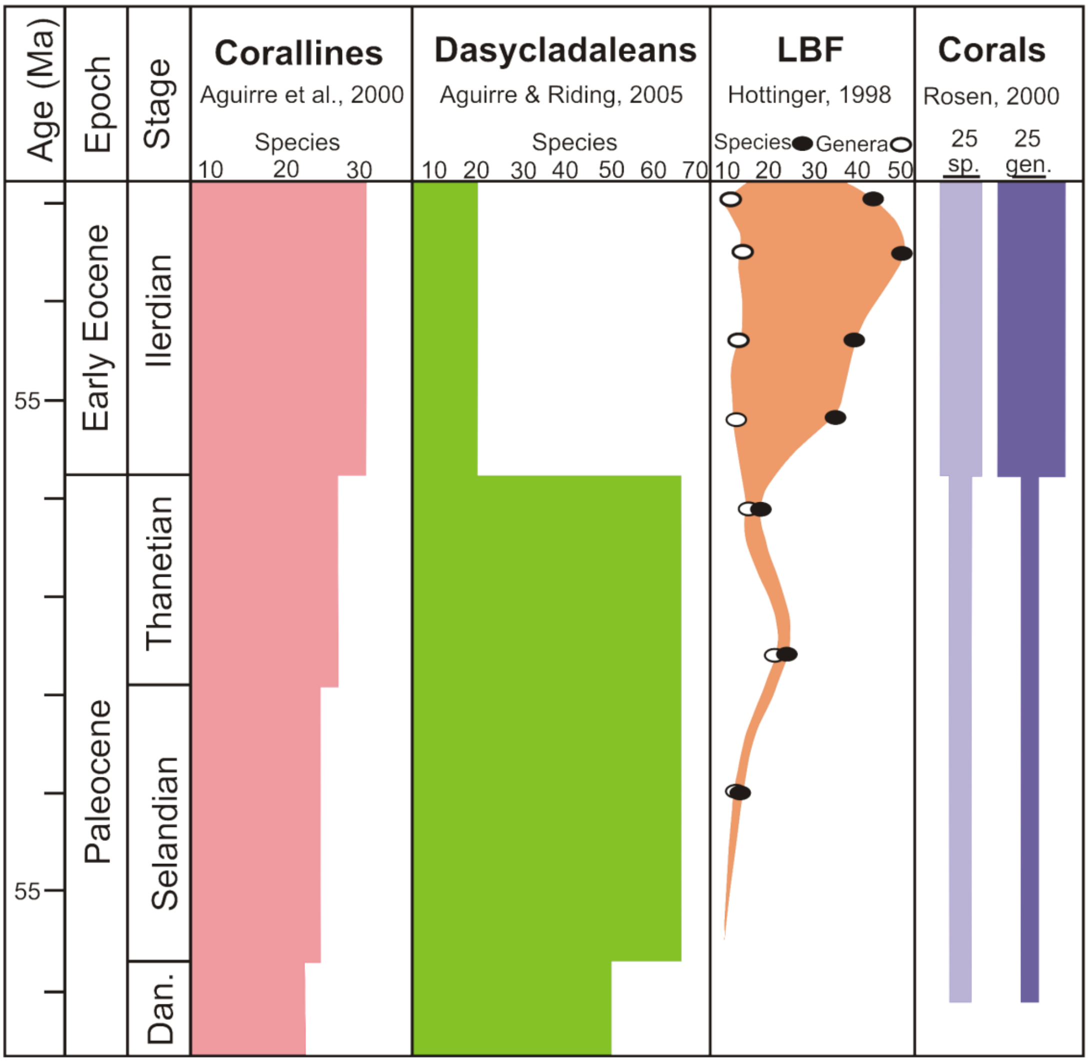


Figure 1.1. Diagram showing increase in LBF diversity through the Paleocene and Early Eocene, along with coralline, coral and dasycladalean diversity changes (modified from Zamagni et al., 2012)

Nummulites, *Assilina*, orthophragmines and *Alveolina* are among the LBF which evolved during the Late Paleocene and came to dominate the LBF assemblages of the Early and Middle Eocene. Middle Eocene *Nummulites* and *Assilina* are known to have reached exceptionally large sizes, often several centimetres in diameter and up to almost 15 cm diameter in the case of *Nummulites millicaput* (Beavington-Penney and Racey, 2004). Following this, however, were a series of global turnover events affecting the LBF (indicated on Figure 1.2). During the late Bartonian there is a rapid turnover in species of *Nummulites*, the evolution of the first reticulate *Nummulites* also occurs around this time. This is followed by the extinction of *Assilina* and shortly afterwards the extinction of *Alveolina* and large species of *Nummulites* (Hallock et al., 1991). A rapid extinction event then occurs at the EOT with the extinction of the orthophragmines, pellatispirids and some species of *Nummulites* (Adams et al., 1986). Whilst these extinction events are well known, their cause and exact timing remain uncertain. High resolution records across these intervals with means of independently dating them are rare. Additional problems arise when there are associated sea level changes such as during the EOT, which cause erosion of the interval of interest. Hallock et al. (1991) noted that there were similarities in timing between these LBF events and events within the planktonic foraminiferal record, but could not compare these two records more accurately due to problems with LBF biostratigraphy (Figure 1.2).

Following the EOT the Early Oligocene assemblages are mostly composed of small *Nummulites* and other nummulitids, until the migration of lepidocyclinids to the Tethys from America near the end of the Early Oligocene and then to the Indo-Pacific in the Early Miocene (BouDagher-Fadel and Price, 2010). The *Nummulites* become extinct near the end of the Early Oligocene and after this lepidocycinids tend to dominate assemblages. Miogypsinids then evolve close to the Oligocene/Miocene boundary and become abundant in Miocene shallow platform carbonates.

Whilst there are clearly many interesting events in LBF evolutionary history, this thesis focusses on the EOT, using recently drilled exceptionally complete records from a location little studied in terms of LBF.

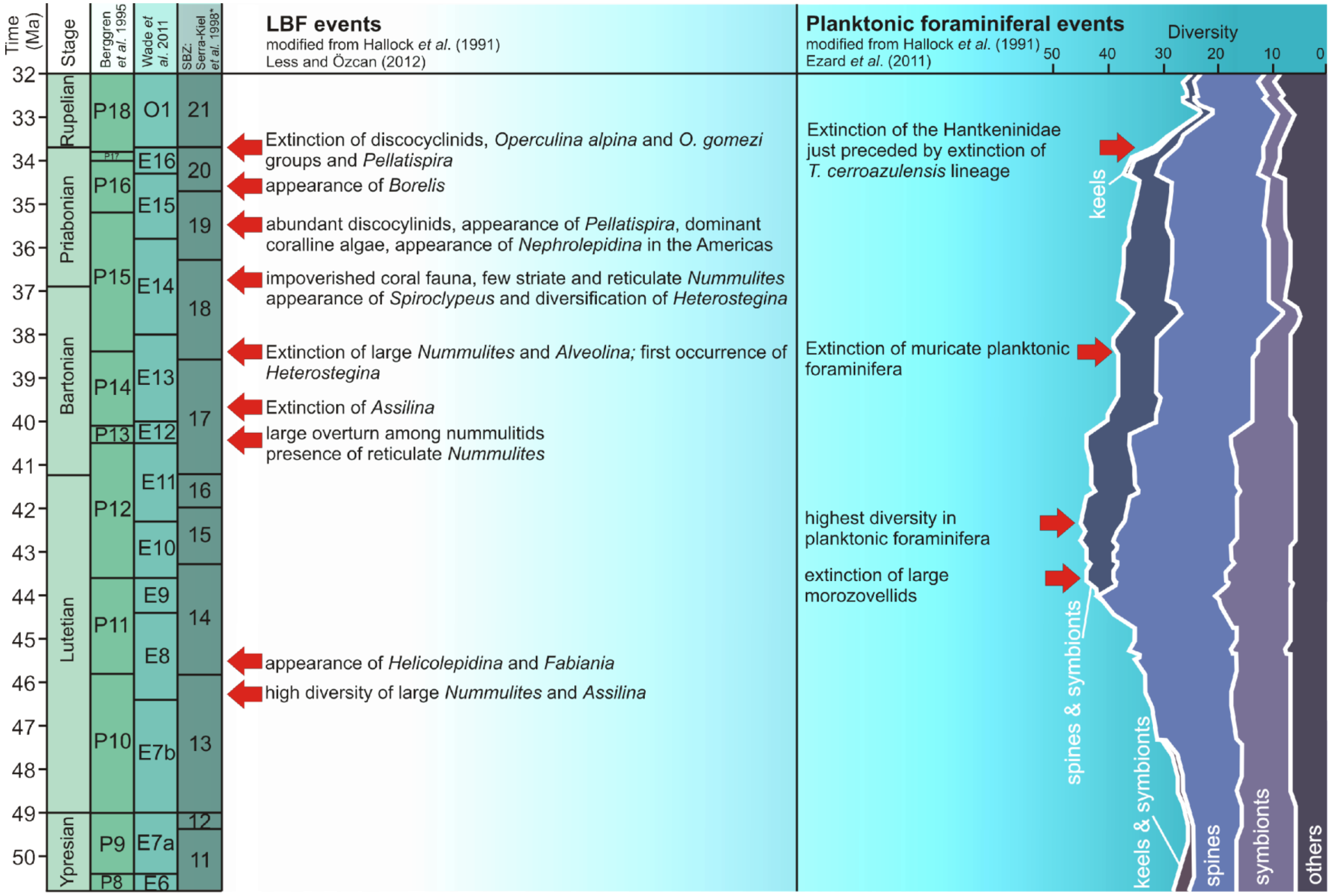


Figure 1.2. Diagram comparing large events in LBF history with planktonic events and diversity over time (Hallock et al., 1991; Ezard et al., 2011), against the timescales of Berggren et al., (1995), Wade et al., (2011) and Serra –Kiel et al., (1998; *modified version from Less and Özcan, 2012)

1.3 A note on LBF provinces

During the Paleocene and Eocene the Tethyan Ocean still existed and the Mediterranean was connected to the Indo-Pacific via a low latitude sea passageway. The LBF assemblages of the Mediterranean and Indo-Pacific therefore share many common features during the Eocene (Renema, 2007). During the Early Miocene this pathway closed leading to a divergence of LBF, however there remain similarities (Renema, 2007). The evolution of Paleogene LBF in the American province, however, shows considerable differences when compared with the Indo-Pacific and Tethyan regions. The recovery period following the K/T extinction in the American province was much longer than elsewhere (Boudagher-Fadel, 2008). Whilst the Tethys and Indo-Pacific are dominated by *Nummulites* during the Eocene, in the Americas they make up only a small proportion of LBF assemblages, their taxonomic status also remain uncertain. *Assilina* which is, again, abundant in the Eocene of the Tethys and also found in the Indo-Pacific, is absent in the American province (BouDagher-Fadel, 2008). The lepidocyclinids first occur in the American province in the Lutetian, but are not found in the Tethys and Indo-Pacific until the late Early Oligocene. *Discocylina* in the American province became extinct during the late Bartonian extinctions, rather than during the EOT as seen elsewhere (BouDagher-Fadel and Price, 2010). For these reasons and due to the geographic location of Tanzania, this thesis largely focusses on the LBF of the Indo-Pacific region and comparisons with the Tethys.

1.4 Tanzanian Geology and the Tanzania Drilling Project.

Cenozoic sediments are known to occur in the southern coastal region of Tanzania from the Kilwa Peninsula south to the Mozambique border (Kent et al., 1971, Nicholas et al., 2006; 2007). The geology of this region has remained little studied and poorly understood since the oil company work of the 1960s and 1970s. However, recent work by the Tanzania Drilling Project (TDP) has helped resolve some of the Mesozoic and Cenozoic depositional history of the region (Pearson et al., 2004; Nicholas et al., 2006; Pearson et al., 2006; Nicholas et al., 2007; Bown et al., 2008; Lear et al., 2008; Pearson et al., 2008). The TDP is a collaborative onshore drilling program between a number of universities and the Tanzanian Petroleum Development Corporation (TPDC), whose main aim is to recover records for palaeoclimatic analysis from the Paleogene, but also improve the geological understanding of this region of Tanzania.

Since 1998, a series of field surveys and shallow drilling has been carried out around the areas of Kilwa and Lindi, which has provided a large amount on new data. Reconnaissance work, sampling and mapping were carried out during 1998 and 2000. During this work over 500 sites were sampled and biostratigraphic ages were found for many of them (Nicholas et al., 2006). Many of the Paleogene clays were found to contain exceptionally well preserved micro- and nannofossils, making them ideal for palaeoclimatic analysis. A program of drilling then began in 2002 and to date 40 TDP Sites have been drilled and sedimentary successions recovered from the Upper Cretaceous to the Miocene (see Pearson et al., 2004; Nicholas et al., 2006; Pearson et al., 2006, 2008; Berrocoso et al., 2012), including three Sites which appear to have a continuous succession through the EOT.

LBF were recognised in many of the TDP successions from the Eocene and Oligocene, occurring as secondary limestone beds or loose specimens within clays. LBF, particularly large *Nummulites*, were also found in outcrop during the reconnaissance fieldwork. The occurrence of LBF in this region of Tanzania is reported by Kent et al., (1971) and Blow and Banner (1962), but the latter work is largely focussed on the planktonic foraminifera. Though the occurrences of LBF found during TDP work are mentioned by Nicholas et al (2006, 2007) little detailed work was carried out on them, with the exception of those found in the EOT drill Sites. A preliminary study was carried out on these LBF and found that the LBF EOT extinction was visible within the TDP succession (Pearson et al., 2008). Younger (Oligo-Miocene) carbonates containing lepidocyclinids are reported from further south (Kent et al., 1971; unpublished TDP data), however as the TDP is primarily concerned with recovering Paleogene clay records this more southerly area remained little studied.

This thesis is closely linked to the work of the TDP and extensively uses TDP samples to examine the LBF of Tanzania. Additionally, fieldwork was carried out in collaboration with Chris Nicholas, Niamh O’Sullivan and Wellington Hudson with one of the main aims being to work on mapping and increasing understanding of the younger, more southerly region.

1.5 LBF basics: ecology, morphology and identification

LBF are an informal group of foraminifera recognised by their complex internal structures and large test size. Tests generally exceed 3 mm^3 in volume (Ross, 1974) and may be up to ~150 mm in diameter (*Nummulites millecaput*; Beavington-Penney and

Racey, 2004). LBF generally inhabit shallow tropical carbonate platforms, within the photic zone, as most extant species harbour photosymbionts and their presence is inferred from morphology in extinct species (Cowen, 1983). LBF are important carbonate producers in both modern and ancient times. Studies of *Marginopora kudakajimensis* have shown that it accounts for 10% of the inorganic carbon production in protected lagoon communities (Fujita and Fujimura, 2008). Additionally, Langer (2008) estimates LBF are responsible for the production of almost 5% of the annual $CaCO_3$ in reef and shelf areas and ~2.5% of the $CaCO_3$ of all oceans.

LBF have an environmentally sensitive depth distribution, reproductive strategy and morphology (e.g. Hallock and Glenn, 1986; Hohenegger, 1995; Beavington-Penney and Racey 2004; Renema, 2005, 2006). Light levels (strongly related to depth) and energy are generally considered to be two of the main factors influencing test shape and distribution over the platform. LBF living deeper water tend to have a more flattened test shape to allow more light to enter the test, whilst those in the shallower water tend to have more robust test shapes and thicker test walls. This strong relationship between morphology (species) and environment is exceptionally useful for interpreting paleoenvironment or carrying out facies analysis of carbonate deposits. Studies of modern LBF have shown this and have been used to interpret LBF limestone deposits and create generalised facies models (e.g. Hallock and Glenn, 1986). This has been used within this thesis to interpret the environments and depositional setting of many of the Tanzanian outcrops.

Although the external morphology gives indications of environment, it is the internal structure of the test which is used for identification. The morphology of LBF varies considerably between genera, but there are some common features. The description here is based on Cenozoic genera of LBF as the Eocene and Oligocene are the main focus of this thesis. The initial chambers consist of a spherical proloculus and kidney shaped deuteroconch which together form the embryon. Often (e.g. in nummulitids) these are approximately central to the test, however in some LBF such as miogypsinids the embryon is offset towards one side. The LBF then grows from this point commonly with either spiral (e.g. in *Nummulites* or *Operculina*) or annular growth (e.g. as seen in *Discocyclina*) and may be involute or evolute. The chambers within the LBF may be simple or further divided into chamberlets, which are thought to be related to the harbouring of symbionts and strengthening of the test (Haynes, 1965; Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004; Hottinger, 2006a). Many LBF have additional morphological features such as pillars, pustules, ribs etc which vary between families and genera (Hottinger, 2006b). A basic overview of how to identify the main groups of LBF found within Tanzania is shown in Figure 1.3.

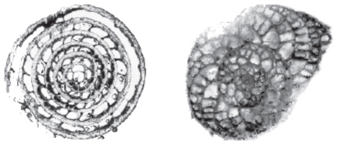
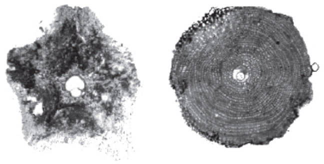
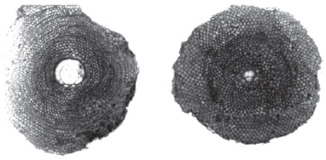
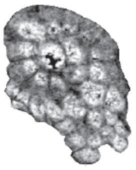
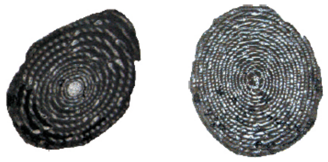
Example image	**LBF group**	**Characters for ID**
	Nummulitids	Planispiral test, generally lenticular shape. Involute or evolute, with spiral growth (annular growth is seen in some advanced forms). Chambers may be simple or with secondary septa forming chamberlets. Marginal chord present.
	Orthophragmines	Lenticular test, often flattened, may be "saddle shaped", involute. Generally subspherical protoconch enclosed by a larger deuteroconch (in A forms). Annular growth with small rectangular chamblets. May have ribs or rays, can be star shaped (e.g. *Asterocyclina*).
	Lepidocyclinids	Lenticular, involute test, often flattened (particularly in B forms). Generally subspherical protoconch enclosed by a larger deuteroconch - amount of enclosure is variable. Annular growth with small rounded chambers producing a "fish scale" pattern in equatorial or sub equatorial section.
	Miogysinids	Flattened to biconvex test. B form has trochospiral or planispiral initial growth, A form has bilocular embryon followed by a fan of median chamberlets
	Alveolinids	Test enrolled along elongate axis, planispiral to fusiform or globular - often "pill" or "rugby ball" shaped. Whorls may be irregular. Chambers are divided into chamberlets. Porcellaneous calcite test appears dark in thin section.

Figure 1.3. Table giving a basic overview of identifying the main groups of LBF found in the Eocene to Miocene of Tanzania.

Additional complications arise in LBF identification due to their reproductive strategy. LBF exhibit sexual dimorphism with an asexual generation which has a large proloculus and small overall test size referred to as the A or megalospheric form and a sexual generation with a small proloculus and large test size known as the microspheric or B form. B forms reproduce by multiple fission whilst A forms release gametes. There is also a third generation which is documented in some living foraminifera (Dettmering et al., 1998) where a B form produces a megalospheric schizont rather than an A form (Figure 1.4). Most species descriptions of LBF in the literature and morphometric studies are based on A forms, as often in B forms it may not be possible to measure certain parameters. However, major works on the genus *Nummulites* taxonomy mainly used B forms (e.g. Schaub, 1981). The majority of LBF found and studied in Tanzania, with the exception of the lepidocyclinids and some large middle Eocene *Nummulites*, were A forms.

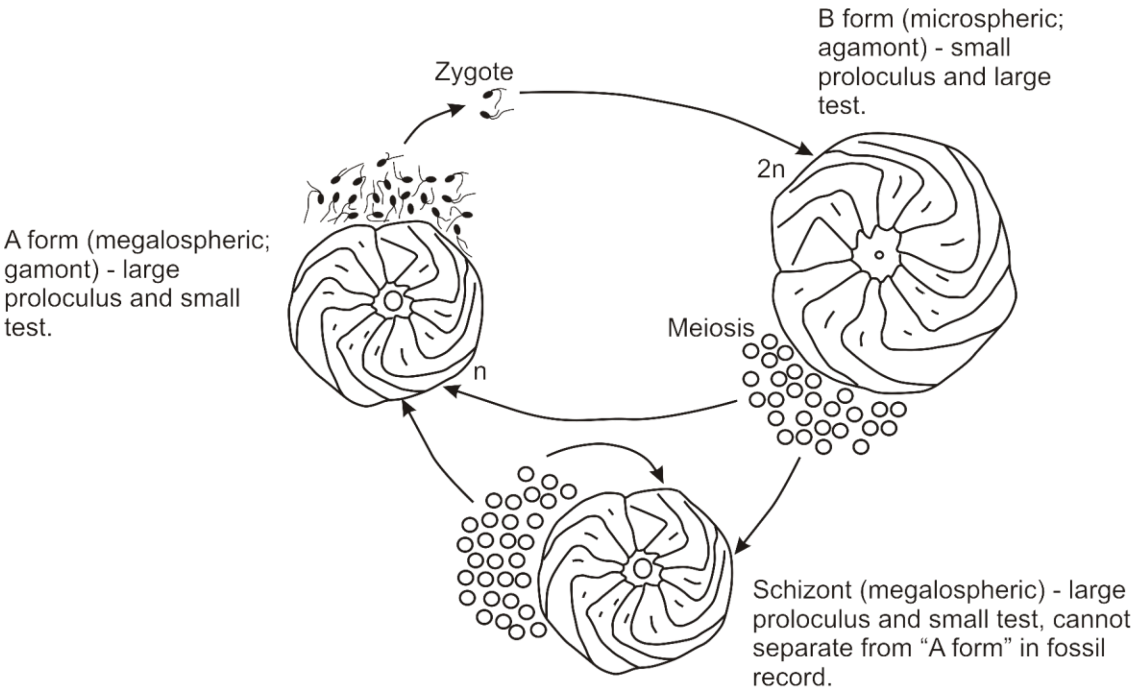


Figure 1.4. Diagram showing the life cycle of *Amphistegina gibbosa* with A forms and B forms (modified from Dettmering et al., 1998; Beavington-Penney and Racey, 2004). 2n: diploid; n: haploid.

1.6 Biostratigraphy of LBF

The biostratigraphy of LBF is has limitations largely due to the environments they inhabit. Unlike planktonic foraminifera and nannofossils which occur throughout the surface waters of the oceans LBF are restricted to carbonate platforms within the tropics. The discrete nature of carbonate platforms mean that endemic species to a region often occur. Additionally there are differences in ranges of species or genera between localities due to migration events. This has led to the formation of regional zonal schemes. Within the Indo-Pacific the East Indian Letter Classification is used (see reviews by Adams, 1970; Renema 2007), whilst in the Tethyan region the Shallow Benthic Zones (SBZ) are used (Cahuzac and Poignant, 1997; Serra-Kiel et al., 1998).

These are discussed in detail in section 4.2. The common lack of planktonic foraminifera within LBF environments, and LBF often occurring within thick carbonate successions make independent dating problematic. Therefore whilst LBF turnover events are well known, their timing with respect to climatic events and extinctions within other fossil groups is often vague.

1.7 Thesis aims and outline

The aims of this thesis are:

- Study the LBF across the EOT at high stratigraphic resolution using TDP records.
- Determine how the EOT correlates to the climatic record and implications for extinction mechanisms.
- To give an overview of the LBF distribution, facies and biostratigraphy of Tanzania using TDP technology and extensive additional fieldwork
- To compare both the longer range and the EOT Tanzanian records with the better known Tethyan and Indo-Pacific records
- Improve LBF stratigraphic correlation.

The scientific results from this work are presented within Chapters 3 to 5. Chapter 3 gives an overview of LBF from the Eocene to Miocene of Tanzania using both outcrop and TDP samples. Chapter 4 then focusses on the EOT and uses high resolution records from TDP Sites to determine exact timing of the LBF extinction and then discusses the implications this has for mechanisms. Chapter 5 contains three smaller scale studies of other LBF rich sections for comparison with the work on Tanzania; the EOT succession from the Melinau Limestone, Sarawak, the Fuente Caldera EOT succession from Southern Spain and the Cortes Zarabanda, Upper Oligocene section also from Southern Spain.

1.8 Fieldwork

1.8.1 Tanzania

Fieldwork was carried out in Tanzania between 17/08/09 and 28/09/09. During the first week of this work limestone core samples from TDP 11, 12, 17, 20, 2, 13, 4, 18 and 6 were collected from the TPDC core store in Dar es Salaam. These are the samples used for the study in Chapter 3. 3. Following this I joined a team consisting of

Christopher Nicholas, Niamh O’Sullivan and Wellington Hudson from Trinity College, Dublin to carry out fieldwork. My role was to collect samples of the Cenozoic LBF for biostratigraphy and palaeoenvironmental analysis. A large area was covered during the fieldwork from Kilwa Masoko in the north to the Mozambique border in the south and inland as far as Tendaguru, the famous dinosaur site. Chapter 3 gives a detailed description of the areas covered, samples collected and results of this work.

1.8.2 Malta

Following the work in Tanzania a week of opportunistic fieldwork was carried out from the 17/10/09 to 23/10/09 on Malta and Gozo. Though not reported directly in this thesis this work was very useful for understanding the LBF facies distribution on a well-studied Miocene carbonate ramp. Sections were visited on the south western side of the Marfa ridge, which was the deeper part of the carbonate ramp during the Miocene. A sample was also taken near Il Mara on the southern end of the island, which was the shallower part of the Miocene ramp. Heterosteginid rich limestones on Gozo were also observed. In Malta the transition from large flattened lepidocyclinids in the deeper part of the shelf to more robust forms in the shallower part is very clear and was very useful for the study of the Tanzanian lepidocyclinid rich sediments.

1.8.3 Spain

Fieldwork was carried out between 28/12/2010 and 1/1/2011 at Fuente Caldera and Cortez Zarabanda near Granada in Spain, with Eustoquio Molina and Alba Legarda from the University of Zaragoza and Helen Coxall from the University of Cardiff. The aim of this work was to sample the LBF rich limestones across the EOT at Fuente Caldera to determine ranges of orthophragmines and through the section at Cortes Zarabanda to assist in determining biostratigraphy. Previous work by Eustoquio Molina and other researchers at the University of Zaragoza had resulted in a detailed log of both sections. Therefore fieldwork primarily consisted of sampling the LBF rich limestones and recording these on the existing logs, along with observations. Details of the sampling and results are given in section 5.3 for Fuente Caldera and section 5.4 for Cortes Zarabanda.

Chapter 2:

General Methods

The methods described within this chapter are those which have been used throughout this thesis. Where a method is specific to only one chapter or section it has been described within that respective section.

2.1 Oriented thin section

The identification and classification of larger benthic foraminifer (LBF) is largely based on their internal structures. For this reason they are studied in thin section. Oriented thin sections are used to enable accurate comparison of measurements of the internal structure between specimens. Sections are generally made of the equatorial plane (horizontal) and the axial plane (vertical; see Figure 2.1).

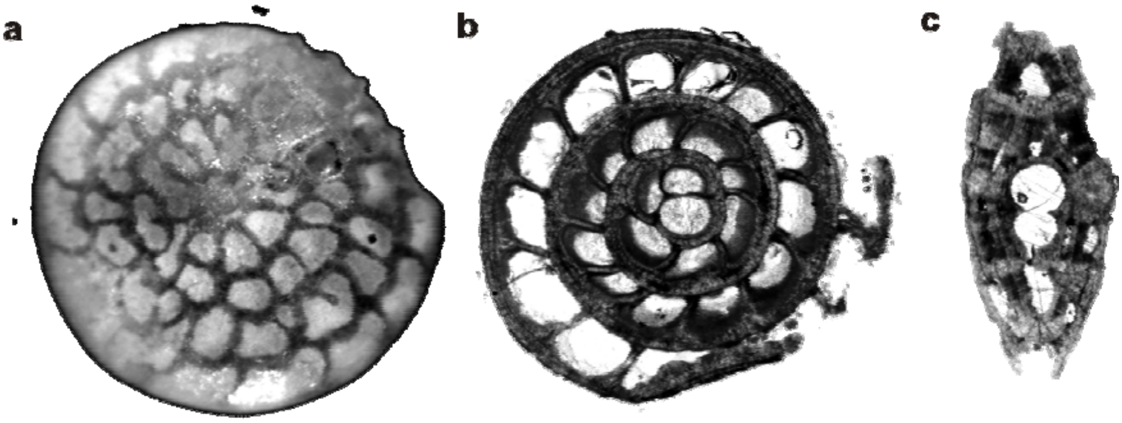


Figure 2.1. External view (a), equatorial view (b) and axial view (c) of a reticulate *Nummulites*.

2.1.1 Equatorial sections

Specimens free from matrix or with very little matrix are used. These are usually washed out of clays or can be removed from limestones. As the technique is destructive an image is taken of the external view of the test before the thin section is made. External ornamentation can be useful for identification particularly within orthophragmines or *Nummulites*. The following method is not commonly fully described in papers and so was demonstrated to the author by Prof. Ercan Özcan at Istanbul Technical University.

To make the section a frosted slide is placed upon a hot plate and once warm a small piece (depending on the size of the LBF) of Lakeside 70 cement is placed upon the slide. The cement should melt but not bubble. The LBF is then placed onto the cement and the slide removed from the hot plate. Before the cement cools the LBF is manipulated under the microscope using a mounted needle or a drawing pin until it is horizontal. The slide is then allowed to cool and the cement sets. The LBF can then be ground on fine, wet, silicon carbide paper (800 to 1200 grade). The slide should be washed and progress checked frequently under the microscope to see how close the proloculus is. Once near the proloculus or when the proloculus/equatorial layer has been reached the slide is washed and dried and returned to the hot plate. When the cement has fully melted the LBF can be flipped using the pin or needle so that the flat side is "safe" against the slide and can be ground no further. Under the microscope the LBF is then gently pushed down into the cement using the pin to make sure it remains flat against the slide whilst the cement cools. It is important to avoid bubbles under the LBF, particularly around the proloculus as these may affect measurements. The grinding process can then be repeated on the new side until only a thin section through the equatorial layer remains.

If the original side was not close enough to the equatorial plane the cement can be melted and the LBF flipped again and ground on the original side, and this process can be repeated until the equatorial layer is reached. The LBF position and orientation can also be adjusted during the process by re-melting the cement (e.g. if the LBF was not completely horizontal initially). The slide is then labelled and is complete.

2.1.2 Axial sections

This follows the method of the equatorial section, but with the LBF oriented the opposite way, on its edge. This often requires more cement to support the specimen in this position whilst being ground. The cement is melted on a frosted slide, the LBF is then manipulated using the pin or needle to stand on its edge in a vertical position. The LBF is then ground until the proloculus is reached, with frequent washing and checking of progress under the microscope. The slide is then replaced on the hot plate and when the cement has melted is flipped so the flat side is against the slide. It is then pushed gently down with the pin or needle and when cool ground on the opposite side, until a thin section through the proloculus remains. The slide is then labelled. Like the equatorial section adjustments to the LBF position can be made by remelting the cement at any point during the process.

2.1.3 Measurement of specimens

Thin sections are imaged using a digital camera microscope attachment and Leica image manager software. Images are calibrated and measurements taken using this program. For most LBF measurements of proteroconch and deuteroconch were taken to aid in identification. In some species of *Nummulites* which were common in samples whorl measurements were taken to allow more accurate comparison between specimens and with previous studies (see Chapter 4). Figure 2.2 shows the method of measurement in some of the major LBF groups found in Tanzania.

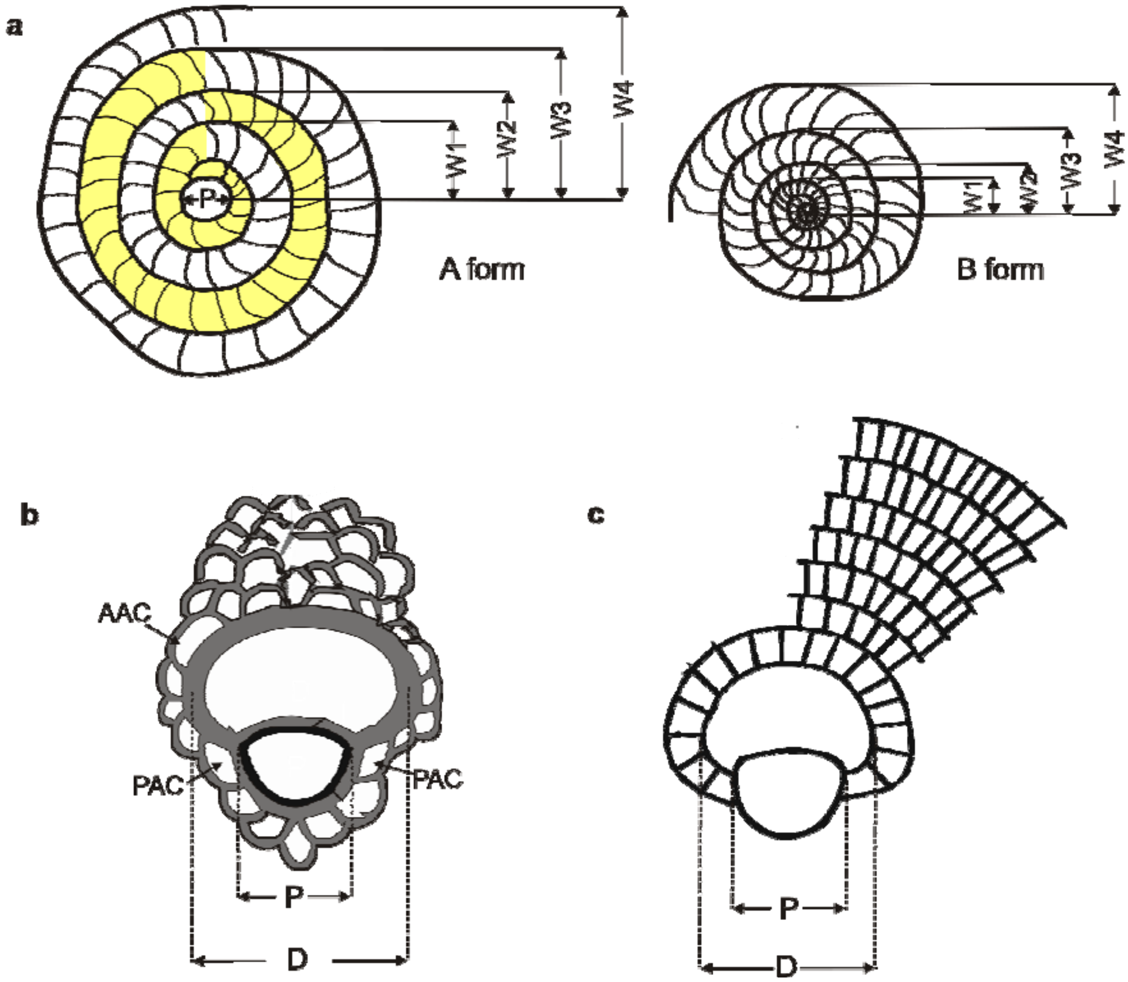


Figure 2.2. a) Diagram of equatorial sections of *Nummulites* (A and B forms) showing method of measurement for proloculus diameter (P) and whorl radii (W1-5), modified from Renema (2002); b) measurement of proloculus (P) and deuteroconch (D) in lepidocyclinids also showing primary auxiliary chamberlets (PAC) and accessory auxiliary chamberlets (AAC), modified from Özcan et al., (2010a); c) measurement of proloculus (P) and deuteroconch (D) in orthophragmines, modified from Özcan et al., (2007).

2.2 Acetate Peels

Acetate peels are the imprint of an etched surface of the rock on a transparent plastic film. They are easy and quick to produce and virtually non-destructive to the specimen and are effective on well cemented carbonates. The following method is based on Dickson (1965, 1966).

To create a peel the sample is cut and polished with a final polish of 800 grade carborundum powder or finer. The polished surface of the sample is then etched in 1.5% hydrochloric acid for 10 to 15 seconds and then rinsed in deionised water. The surface is initially stained using a mix of potassium ferricyanide and Alzarin red-S for 30 to 45 seconds and rinsed with deionised water. It is then stained a second time using Alzarin red-S for 10 to 15 seconds and is rinsed in deionised water. Stains are used in the concentrations shown in table 2.1. The sample is then allowed to dry. Once dry, plasticine can be used to support the specimen so that the polished surface is horizontal. A suitable sized piece of acetate is cut. The surface of the sample is flooded with acetone and the acetate carefully placed on top. Care should be taken to avoid bubbles. The acetate and sample should be left to dry. The acetate is then removed, if possible, with one smooth continuous motion. Excess acetate should be trimmed from the edge to avoid crinkling and the peel should be stored flat. It can be studied under the microscope as it is, or between two glass slides to keep it flat.

Stain	Concentration
Alzarin red-S and potassium ferricyanide mix	0.2 g A.R.S/100 ml 1.5 % HCl 2.0 g P.F/100 ml 1.5 % HCl Mixed in ratio A.R.S:P.F =3:2
Alzarin red-S	0.2 gm A.R.S/ 100 ml 1.5 % HCl

Table 2.1. Concentrations of stains used for acetate peels.

Chapter 3:

An overview of the LBF biostratigraphy and biofacies of southern coastal Tanzania

The work on the nine TDP sites within this chapter has been published (Cotton, L.J. and Pearson, P.N., 2012. Larger benthic foraminifera from the Middle Eocene to Oligocene of Tanzania, Austrian Journal of Earth Sciences 105, 189-199). LJC is responsible for the scientific content, PNP contributed in discussions and paper revisions. This paper has been incorporated within this chapter with a modified introduction and conclusion. The field work and discussions leading to the remainder of this chapter were carried out in collaboration with a team from Trinity College Dublin, in particular Niamh O’Sullivan, who also assisted in the preparation of maps. This chapter focusses on the biostratigraphy and palaeoenvironment of LBF bearing localities. For more structural and tectonic analysis and interpretation, including localities without LBF, see O’Sullivan 2012. Planktonic foraminiferal identifications and age determination were carried out by Paul Pearson.

3.1. Introduction

The coastal basins of southern Tanzania contain a thick succession of Paleogene and Neogene marine sediments. The Paleogene, in particular, has been the focus of much recent research on the palaeontological and palaeoclimatic history of the area (Pearson et al., 2004, 2006; Nicholas et al., 2006, 2007; Pearson et al., 2008; Wade and Pearson, 2008; Lear et al., 2008; Dunkley Jones et al., 2008, 2009; Pearson et al., 2009). Rich assemblages of larger benthic foraminifera (LBF) occur throughout both periods but have received relatively little attention. Blow and Banner (1962) gave a brief overview of LBF species found in much of the succession, but largely concentrated on the planktonic foraminifera. Kent et al. (1971) also mention some LBF found in outcrop used to assign ages to the stratigraphy, but not in detail. The region is of active interest for oil exploration; however it remains poorly mapped with the facies and ages of many areas uncertain.

The aim of this chapter is to give a comprehensive overview of occurrences, ages and palaeoenvironments of LBF bearing strata and the LBF genera present in Tanzania, using firstly the Tanzania Drilling Project (TDP) drill core record and secondly field outcrop samples collected by myself and Niamh O'Sullivan in 2009, thereby improving the overall geological understanding of this region.

The Kilwa and Lindi Districts of Tanzania contain a thick succession of clay sediment from Santonian to Oligocene age (Nicholas et al., 2006, 2007). These sediments are formally defined as the Kilwa group and are split into four formations: the Nangurukuru (Santonian to Paleocene), Kivinje (Paleocene to lower Lutetian), Masoko (lower Lutetian to mid Bartonian) and Pande formations (mid Bartonian to the Rupelian; Nicholas et al., 2006). A large proportion of this succession has been recovered in a series of shallow drill cores by the TDP (see Nicholas et al., 2006 for review). The sediments of the Kilwa group are broadly homogeneous and consist of a succession of dark greenish grey clays and claystones to marls with limestones and calcareous sandstones deposited as sediment gravity flows. LBF are abundant in the limestone beds and they also occur in clay horizons in the succession. Specimens from the clays are generally better preserved than those from the limestone but are smaller and more dispersed. Calcareous micro- and nannofossils are often exceptionally well-preserved (e.g. Pearson et al., 2008; Bown et al., 2008) and planktonic foraminiferal and nannofossil studies have been used to determine the stratigraphy of the succession (Pearson et al., 2004, 2006; Nicholas et al., 2006; Wade and Pearson, 2008, Dunkley Jones et al., 2008, 2009). Stable isotope analysis has been carried out on three sites which span the Eocene - Oligocene transition (EOT) enabling these sites to be correlated with the global isotope stratigraphy (Pearson et al., 2008).

Nine of the TDP sites are stratigraphically placed between the Upper Ypresian and Late Rupelian (Pearson et al., 2004, 2006; Nicholas et al., 2006). During this interval LBF are known to have undergone several global turnover events (Hallock et al., 1991). Towards the late Middle Eocene there is a large turnover in nummulitids, followed by the extinction of *Assilina* and then the extinctions of *Alveolina* and large species of *Nummulites*. A further global extinction of LBF is then seen at the EOT, with the extinction of the orthophragmines, the pellatispirids and several species of *Nummulites* (Adams et al., 1986). All of these are long ranging and widespread groups of LBF.

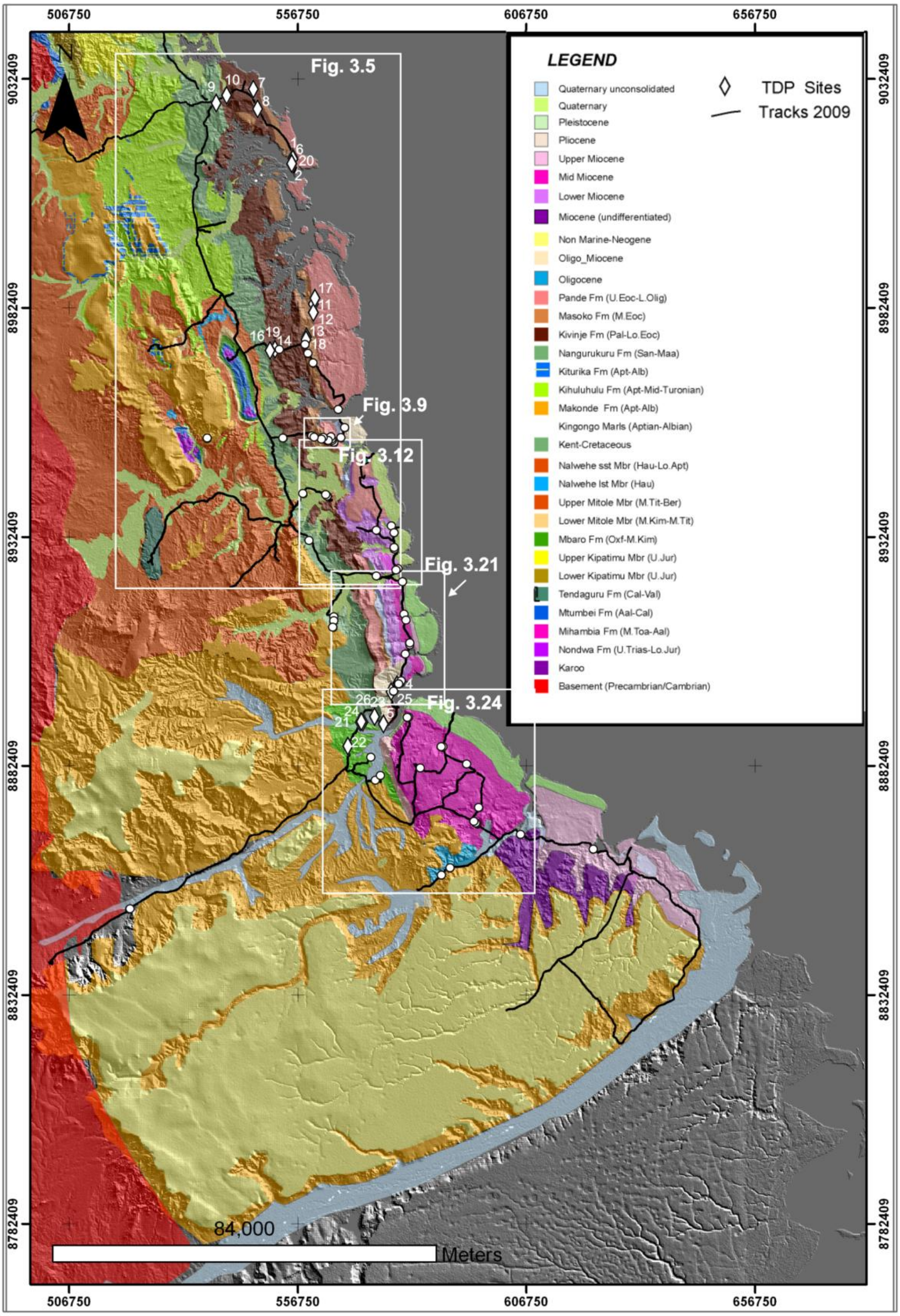


Figure 3.1. Location map showing the total field area, with field tracks, TDP sites and sample positions (white dots) marked. Sampling areas shown in more detail later figures in this chapter are outlined in white. Key applies to all maps in this chapter.

Although the TDP ages of LBF occurrences are well constrained, the area they sample is limited and LBF only occur in these records as transported grains. Therefore field sampling was carried out over a much wider area, ranging across approximately 200 km along the coast from Kilwa Masoko to the Mozambique border (Figure 3.1) to gain a more complete overview of LBF present, identify potential new drill sites and further investigate the Oligo-Miocene LBF which are not found in the TDP record cores but are known to occur in this region (Blow and Banner, 1962, Kent, 1971, Nicholas et al., 2007).

Limestones rich in LBF from a variety of depositional environments are abundant in the field area. In the north of the area, from Kilwa to the Kiswere peninsula, outcrops are Paleocene in age. Several sites known to contain LBF within this region had previously been described by Nicholas et al. (2006, 2007) and were revisited during the 2009 fieldwork to examine the LBF in more detail. Additional Paleogene localities were also identified. South of the Kiswere peninsula the majority of sediments are of a younger, Neogene age. This region is very rich is shallow water carbonate successions and lepidocyclinid beds are particularly common. The LBF and other fossils can be used study platform evolution and sea-level fluctuation. Where possible, dating of the outcrops has been carried out using planktonic foraminifera from clay sediments from within successions or nearby. Where there are no clay sediments the age has been determined using the LBF genera with the most robust global ranges (Adams 1970; Cahuzac and Poignant, 1997; Serra-Kiel et al., 1998, Boudaher-Fadel and Banner, 1999; Renema, 2007).

The combined study of both TDP sites and more widespread surface sampling presented within this chapter provides a solid overview of the occurrences of LBF in Tanzania through the Paleogene and Neogene and also allows potential links between LBF extinctions and global climatic events to be explored. Additionally, this study has identified a number of new localities and at least one of these shows significant potential as a possible future drilling site.

3.2. Materials and methods

Section 3.3 and 3.4 utilise nine TDP sites from the top of the Kivinje formation to the top of the Pande formation to examine LBF occurrences across the Middle Eocene to Oligocene interval. The locations (see Figure 3.1), assigned planktonic foraminiferal zones and ages of these cores are summarised in Table 3.1. The second part uses samples collected by myself and Niamh O'Sullivan during extensive fieldwork carried out in 2009 (see Tables 3.2 and 3.3). The main field areas described are outlined in Figure 3.1, more detailed maps showing sample locations are given with the respective descriptions of localities.

Clay samples were washed through a 63 μm sieve and residues dried. Oriented sections of loose individual LBF were made for identification according to the method described in Chapter 2. The majority of samples were studied in randomly oriented thin sections prepared and acetate peels (prepared according to Dickson, 1965, 1966; as described in Chapter 2).

Site	**Location**	**UTM**	**Planktonic foraminiferal Zone**	**Age**
TDP 2	SW Kilwa prison (80m from TDP 20)	37L 555371 9013813	E7-E9	L. Ypresian to Mid Lutetian
TDP 20	SW Kilwa prison	37L 555457 9013846	E7-E9	L. Ypresian to Mid Lutetian
TDP 13	Roadside N of Mkazambo	37L; 558673 8975981	E9-E11	Middle to Upper Lutetian
TDP 18	Roadside N of Mkazambo	37L; 558640 8975370	E12 (lower part)	Bartonian
TDP 4	Ras Tipuli	37L; 578530 8900033	E12-E13	mid Bartonian
TDP 11	Close to the village of Stakishari	37L; 560250 8983211	E16-O1	Upper Priabonian to Lower Rupelian
TDP 12	Close to the village of Stakishari	37L; 560222 8981309	E16-O1	Upper Priabonian to Lower Rupelian
TDP 17	Close to the village of Stakishari	37L; 560539 8984483	E15-O1	Upper Priabonian to Lower Rupelian
TDP 6	W of Kilwa Masoko airstrip	37L; 555752 9014922	O2-O4	Lowe Oligocene

Table 3.1. Location and age data for the TDP sites used in this study.

Sample no.	X	Y	Location
K04	08 55' 29.8" S	039 30'19.1" E	Kilwa Creek
K05	08 55'29.8"	039 30'17.9"	Kilwa Creek
K06	08 55'27.1"	39 55'27.9"	Kilwa Creek
K07	08 55'27.1"	39 30'18.1"	Kilwa Creek
K08	08 35'26.9"	39 30'18.1"	Kilwa Creek
K09	08 55'27.7"	39 30'15.0"	Kilwa Creek
K10	08 55'28.0"	39 30'14.4"	Kilwa Creek
K11	0552530	897358	Pande quarry
K12	0552530	897358	Pande quarry
K13	0552530	897358	Pande quarry
K14	0552530	897358	Pande quarry
K15	-	-	Nr TDP sites 13 and 18
K16	0558573	8976122	Nr TDP sites 13 and 18
K17	560034	8981434	EOB site
K18	560034	8981434	U. Eocene at E/O site
K19	560073	8981374	Oligocene at E/O site
33	559644	8954469	Kiswere
34	560320	8954186	Kiswere
35	563053	8953908	Kiswere
44	581123	8909169	Mitonga river quarry
61	580940	8892982	Kitunda
62	580915	8892978	Kitunda
63	580899	8892977	Kitunda
79	580261	8914225	Base Likonga river
83	578105	8925029	Mchinga school
84	578105	8925029	Mchinga school
88	855562	8929994	Past Mchinga school
92	588185	8858446	Mikindani area
98	585096	8870310	Mikindani area
100	573996	8923800	Mbuyuni
101	573996	8923800	Mbuyuni
107	573956	8923858	Mbuyuni log
109	564575	8913779	Moka
111	558009	8941703	Near lake Mkoe
113	563211	8941314	Near lake Mkoe
119	577757	8933141	North Mchinga
120	577243	8934781	North Mchinga
122	574037	8933657	North Mchinga
131	593583	8882771	Pangaboi (S. Kitunda)
135	590942	8883840	Navanja
137	583557	8881821	Naminda
138	583557	8881821	Naminda
143	566130	8953943	Kiswere
145	536971	8953844	Kiswere

Sample no.	X	Y	Location
148	564291	8953149	Kiswere
149	564126	8953679	Kiswere
150	563960	8954208	Kiswere
151	562298	8954028	Kiswere
152	561835	8953923	Kiswere
165	573957	8923748	Mbuyuni

Table 3.2. Location data for the limestone (LBF) field samples used in this study; co-ordinates are given in UTM 37L (Arc 1950) except K04-K10 which are given and lat. and long. (WGS'84).

Sample no.	X	Y	Area
36	566999	8956081	Kiswere
43	581123	8909169	Mitonga river quarry
45	580001	8915412	Likonga
64	580621	8892914	Kitunda
65	573654	8879177	Kitunda
69	579120	8900348	Nr Ras Tipuli
77	577503	8598875	Ras Bura
78	577503	8598875	Ras Bura
80	579659	8922502	Nr Mchinga turning
81	579659	8922502	Nr Mchinga turning
85	578105	8925029	Mchinga school
86	-	-	Past Mchinga school
89	321240	8864420	Mikindani area
104	573956	8923858	Mbuyuni
112	562823	8941623	Nr Lake Mkoe
134	590942	8883840	Navanja
144	539971	8953844	Kiswere
162	573957	8923748	Mbuyuni

Table 3.3. Location data for the clay (planktonic foraminifera) field samples used in this study; co-ordinates are given in UTM 37L (Arc 1950).

3.3 TDP Succession

3.3.1 TDP results

The Eocene limestone beds are bioclastic pack-grainstones. LBF are the dominant bioclastic component, but also present are echinoid fragments, red algae, smaller foraminifera and serpulid worm tubes. The LBF occur in a matrix of finer carbonate fragments including smaller-sized foraminifera and quartz grains. Most LBF have suffered at least some abrasion to the outer test whorls, comparable with category 2 to 3 on the scale of Beavington-Penney (2004). Intraclasts are present in some samples, but are rare. Several large-sized LBF show evidence of boring and/or overgrowth by red algae. The Oligocene beds are calcareous sandstones with a high fine grained quartz content. Bioclasts including LBF are present but less abundant than in the Eocene beds. The samples from TDP Site 6 are distinctly different from the rest of the succession. These contain a large number of reworked carbonate clasts including LBF in a finer quartz-rich matrix.

The stratigraphic occurrences of the LBF genera are shown in Figure 3.2 with the levels of the TDP sites. The assemblage throughout the Lutetian (TDP Sites 2, 20 and 13) remains fairly constant and is generally dominated by *Nummulites* and *Alveolina* with orthophragmines and *Linderina* (Figures 3.3 and 3.4). Also present but less frequent are *Lockhartia*, *Assilina*, *Glomalveolina* and *Orbitolites* (Figures 3.3 and 3.4), although the latter two genera only occur in the lower half of the Lutetian. *Assilina* are rare in the core samples, but are abundant in outcrops on the edge of Kilwa Creek, close to the drill sites of TDP 2 and TDP 20 and thought to be of similar age. Towards the top of TDP Site 13 the last *Alveolina* specimen is found, which has had an almost continuous presence in the TDP samples to this point. In the Bartonian (TDP Site 18) there is a high diversity of LBF genera and there appears to have been a change in the LBF assemblage between the uppermost samples of TDP Site 13 and the lowermost samples of TDP Site 18. In TDP Site 18 there are the first occurrences of reticulate *Nummulites*, *Operculina*, *Sphaerogypsina* and *Heterostegina* (Figure 3.3f), although a possible *Heterostegina* occurs towards the top of TDP 13. There is also the last occurrence of *Lockhartia*, and the last definite occurrence of *Linderina*. TDP Site 4 is still within the Bartonian but stratigraphically slightly higher than TDP Site 18. In these samples *Nummulites* are most common and occur with *Discocyclina*, *Operculina* and possible *Linderina*. There is then a gap in the TDP record and the next sites are Upper Priabonian to Lower Rupelian (TDP Sites 11, 12 and 17) and continuously span the EOT (Pearson et al., 2008). These samples also show a relatively high diversity of LBF. At these sites the majority of the genera present go extinct at the Eocene / Oligocene boundary (EOB), coincident with the extinction of the Hantkeninidae (see the more detailed study in Chapter 4 and Cotton and Pearson, 2011). Only *Sphaerogypsina* and some species of *Nummulites* pass through the boundary apparently unaffected. Several of the genera which do go extinct at the boundary, including *Fabiania*, *Pellatispira* and *Palaeonummulites*, (Renema, 2002) are only present in these samples. In the Upper Rupelian (TDP Site 6) limestone beds there are a large number of intraclasts and the only LBF in them that do not appear to have been reworked are small *Nummulites*.

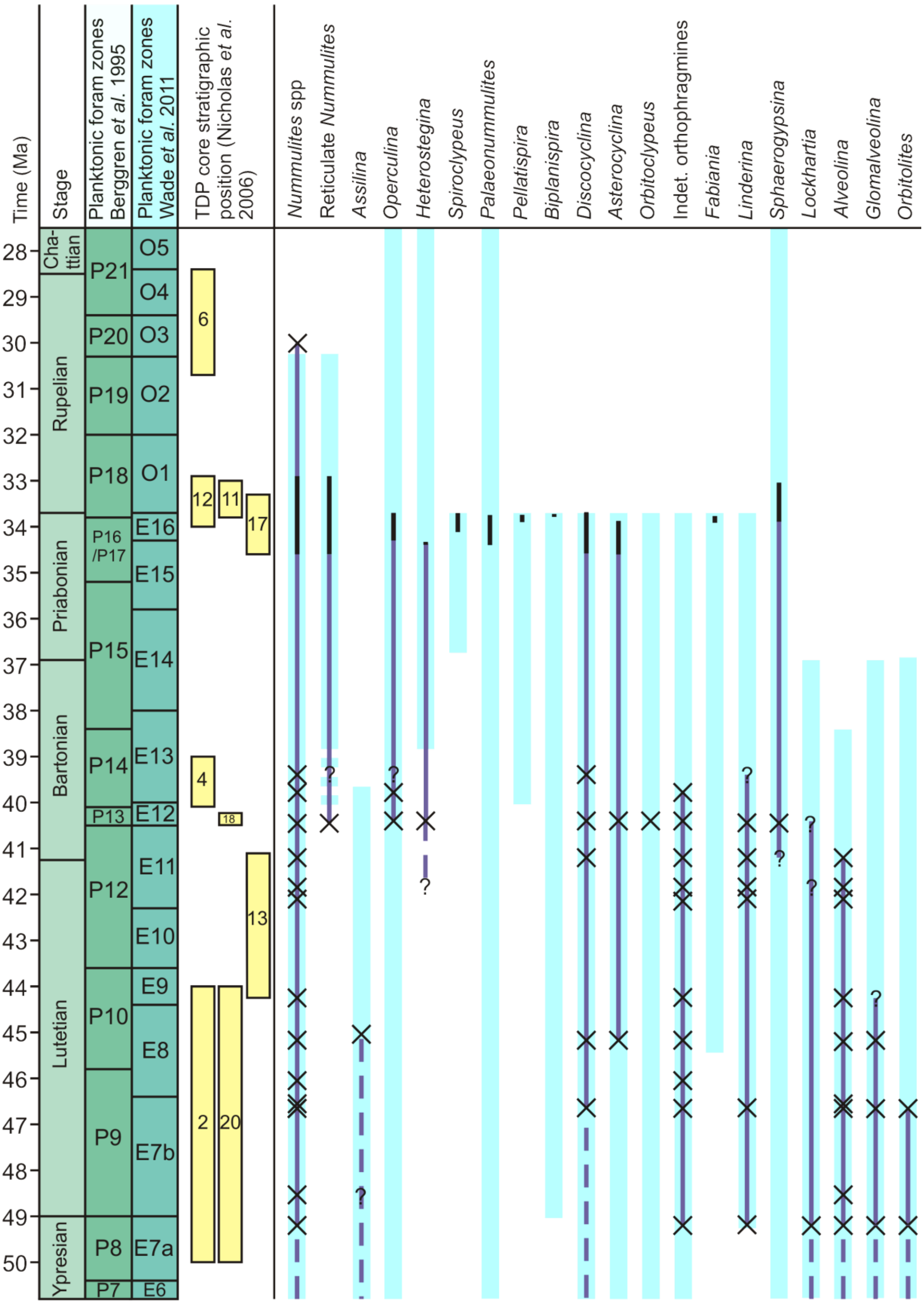


Figure 3.2. Range chart showing the stratigraphic occurrence of LBF genera in the TDP succession. Stratigraphic levels of the TDP sites are shown in the left hand column. Crosses indicate the occurrence of a genus; black lines are used to indicate the occurrences of genera in TDP 11, 12 and 17 as a high resolution study has been carried out. Pale blue bars in the background show known global ranges of genera (Hallock et al., 1991; Renema, 2002; BouDagher-Fadel, 2008).

3.3.2 TDP discussion

As LBF are known to inhabit the shallow carbonate environment (Beavington-Penney and Racey, 2004) all specimens occurring in the hemipelagic clay succession of the Kilwa group have been transported. Despite this, they can still be used to give ranges of LBF as the majority appear to have been deposited penecontemporaneously with the clay sediments. There are occasional examples of large-sized LBF which have been bored ; the borings are infilled by the surrounding matrix indicating they were still uncemented when re-deposited. LBF in clay layers are commonly not recrystallised. Intraclasts are rare in the sediment and the foraminifera appear to have been deposited as uncemented grains, evidenced by the tests within limestone beds having been highly abraded during transport. The high levels of abrasion suggest high energy transport and rapid deposition (Beavington-Penney, 2004). The exception to this penecontemporaneous sedimentation are the limestone beds from site TDP Site 6 which contains numerous intraclasts often with biostratigraphically older LBF. The only LBF that do not appear to be reworked are small *Nummulites*.

The ranges of the LBF genera found in the TDP sites from Tanzania all fall within global ranges (Adams, 1970, Adams et al., 1986, Hallock et al., 1991, Serra-Kiel et al., 1998, Renema, 2002, Renema, 2007). One of the largest changes in the Tanzanian LBF assemblage takes place between the last sample of TDP Site 13 and the first sample of TDP Site 18. These two sites were drilled less than 1 km from each other, making it unlikely that the assemblage change is due to geographic location or varying sediment source. The succession in TDP Site 18 has been assigned to the lower part of planktonic foraminiferal Zone E12 (Nicholas et al., 2006) and is therefore close to a global climatic warming event known as the Mid Eocene Climatic Optimum (MECO). The MECO was a global interval of rapid warming from ~40 Ma to ~40.8 Ma which interrupted the overall cooling trend of the Eocene (Boharty et al., 2009; Edgar et al., 2010). The MECO is relatively little studied with regards to both planktonic foraminifera and LBF response. Some overturning within the planktonic acaraninids and morozovellids is associated with this period and there is the occurrence of a short ranging 'excursion taxon', *Orbulinoides beckmanni*, which spans the MECO (Edgar et al., 2010). In LBF, overturning within *Nummulites* and the first occurrences of reticulate *Nummulites* have been noted to occur around this level (Hallock et al., 1991) although have not been previously directly associated with the MECO event.

Studies of planktonic biostratigraphy from TDP Site 18 show that the *Orbulinoides beckmanni* present are apparently early forms (Nicholas et al., 2006), suggesting that the succession is from the very early stages of, or even slightly precedes, the MECO. Therefore the faunal change in Tanzania occurred before the peak of the MECO. Additionally TDP Site 18 samples contain reticulate *Nummulites* from the *N. fabianii* group and therefore their evolution pre-dates the main phase of the MECO. Preceding the MECO is an interval of cooling from ~40.6-41.6 Ma which has also been recognised in $\delta^{18}O$ records (Boharty et al., 2009). A cooling trend followed by the onset of rapid warming may have been responsible for at least local changes in the LBF assemblage.

The global extinction of *Alveolina* and large species of *Nummulites* are known to occur in the late Middle Eocene, slightly preceded by the extinction of *Assilina* (Hallock et al., 1991). Although attempts have been made by the TDP to locate and drill this stratigraphy, thus far these have proved unsuccessful. *Assilina* is rare in the TDP samples, and little light is shed on its extinction level. No examples of *Assilina* were seen above the Lutetian, however their abundance in outcrop suggests that this may be due to the small area sampled by the TDP cores and the fact that LBF assemblages vary across the shelf. Further outcrop samples may therefore be able to help with this issue. The disappearance of large sized species of *Nummulites* requires a more detailed species-level study. However, *Nummulites* specimens > 10 mm diameter are present in the clays of TDP Site 18 and *Nummulites* > 25 mm belonging to the *N. perforatus* group were found in outcrop close to the drill site. These large *Nummulites* are not found at TDP Sites 11, 12 and 17. This suggests that they became extinct within the un-sampled interval. *Alveolina* has a lower last occurrence at the top of TDP Site 13 and is found in almost all TDP samples until this point. This indicates that the mechanism causing the assemblage changes between the successions in TDP Sites 13 and 18 may have also caused a local “early” extinction of *Alveolina*.

The EOT shows a rapid extinction of a number of genera shown to have long ranges in the Tanzanian record. The Priabonian samples are the most diverse, but this could be in part due to the higher-resolution study carried out on them. The Tanzanian sites have allowed accurate correlation between the LBF extinctions and plankton extinctions in the EOT (see Chapter 4; Cotton and Pearson, 2011).

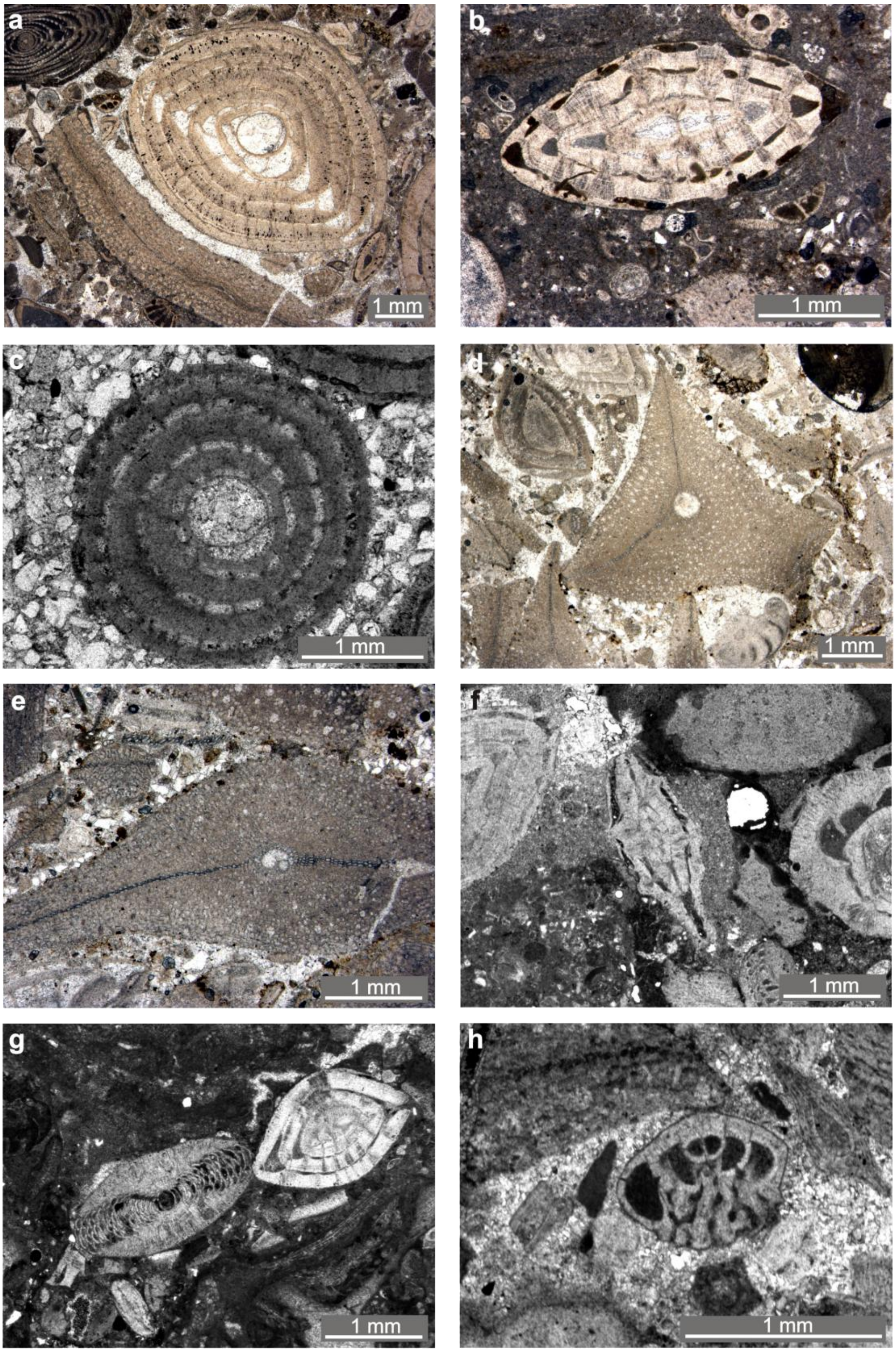


Figure 3.3. LBF in petrological thin sections from limestones. a) *Nummulites* sp. (TDP 20); b) *Nummulites* sp. (TDP 18); c) *Nummulites* sp. (TDP 4); d) *Asterocyclina* sp. (TDP 20); e) *Discocyclina* sp. (TDP 13); f) *Heterostegina* sp. (TDP 18); g) *Linderina* sp. (TDP 18); h) *Lockhartia* sp. (TDP 20)

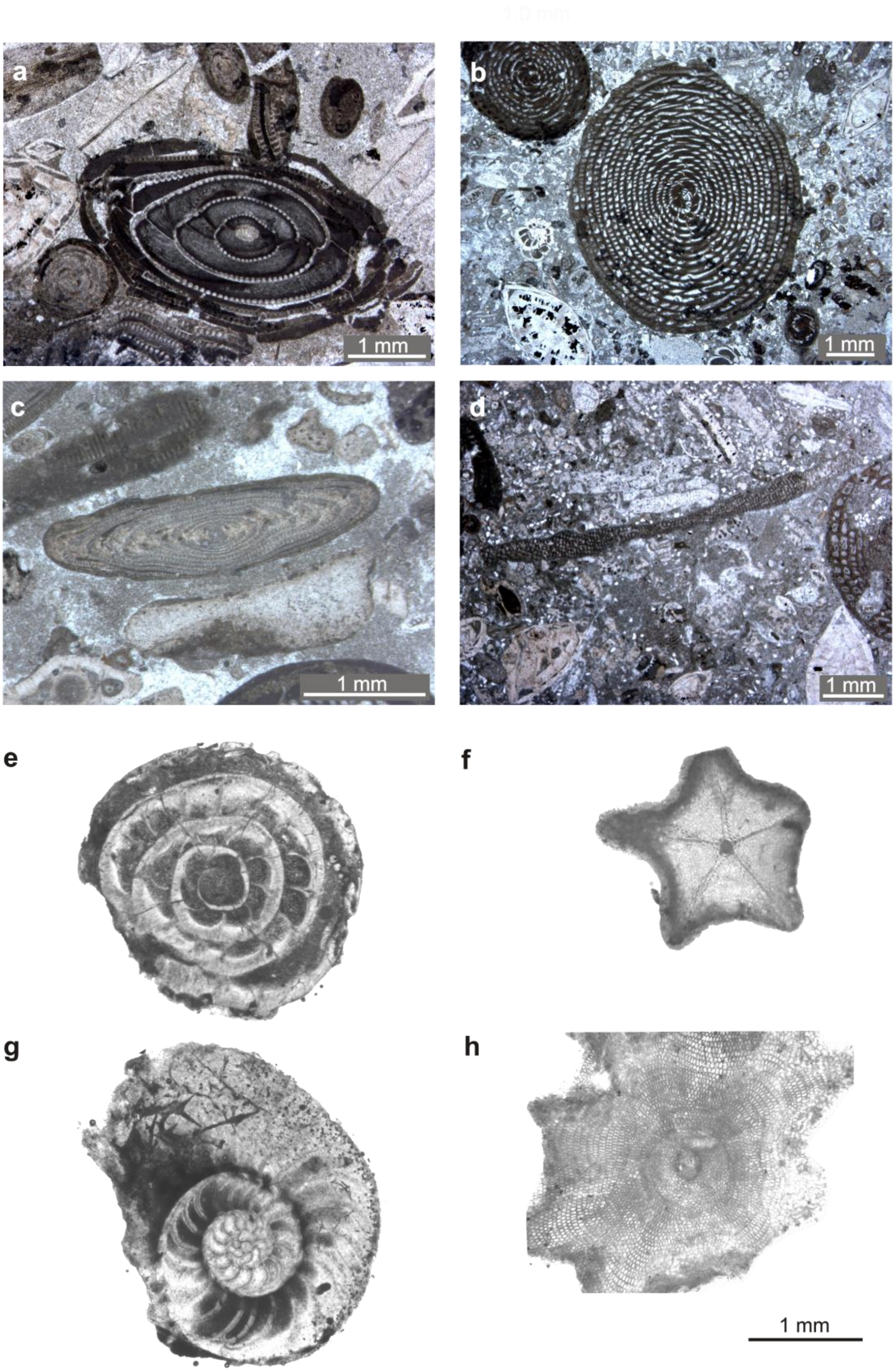


Figure 3.4. a-d) LBF in petrological thin sections from limestones; e-h) Oriented 384 individual LBF thin sections of specimens from clays. a) *Alveolina* sp. (TDP 2); b) *Alveolina* sp. (TDP 2); c) *Glomalveolina* sp. (TDP 2); d) *Orbitolites* sp. (TDP 2); e) Reticulate *Nummulites* of the *N. fabianii* group (TDP 18); f) *Asterocyclina* sp. (TDP 18); g) *Operculina gomezi* (TDP 18); h) *Orbitoclypeus* sp. (TDP 18).

3.4 Field samples

The results from analysis of field samples are broadly divided into the Eocene to Early Oligocene localities and the Upper Oligocene to Miocene localities, within this they are then ordered geographically, roughly north to south.

3.4.1 Field sample results: Eocene to Early Oligocene

Several Eocene localities were known to contain LBF from previous studies (Nicholas et al., 2006, 2007; P. Pearson pers. comm.). These sites were re-visited to sample and study the LBF in more detail. Additionally, several new sites were also found during the fieldwork.

3.4.1.1 Kilwa Creek

Middle Eocene limestones of a similar age and facies type to those found at recovered in TDP sites 2 and 20 and found at Kilwa Prison are known to outcrop along the northern bank of Kilwa Creek, but had not been studied in detail (Nicholas et al. 2006, 2007; P. Pearson pers. comm.). Samples were collected along the mangrove edge along Kilwa Creek at Kilwa Masoko (Figure 3.5). Large fallen blocks are common where supporting sediment (i.e. clays) have been washed out from underneath (Figure 3.6d). Some in situ beds were visible where the surface sediments and vegetation had been removed and a short log was made (Figure 3.6a-c). The limestone beds are approximately 20 cm to 50 cm thick within a clay sequence. The limestones are bioclastic pack-grainstones, largely comprised of LBF. *Nummulites* spp. dominate the assemblage, but large numbers of *Assilina* are present in particular beds (Figure 3.6c) and *Discocyclina* is also frequently found. Large rounded *Nummulites* of the *Nummulites perforatus* group along with large *Assilina* can be found eroded out on the soil surface. The LBF show damage to their tests, particularly the outer whorls and broken fragments are common, indicating extensive transportation has taken place (Beavington-Penney, 2004).

The sedimentation is similar to that found in TDP sites 2 and 20, however the LBF assemblage differs slightly in that it has very few *Alveolina* which is common in the core samples. Additionally, *Assilina* spp. is abundant in outcrops on Kilwa Creek whilst they are extremely rare in TDP 2 and 20. This is likely to be related to varying source area for the two deposits, as LBF tend to be strongly zoned with different genera inhabiting different depth habitats (Beavington-Penney and Racey, 2004; see section 1.5 for discussion) or may possibly be due to slight differences in age.

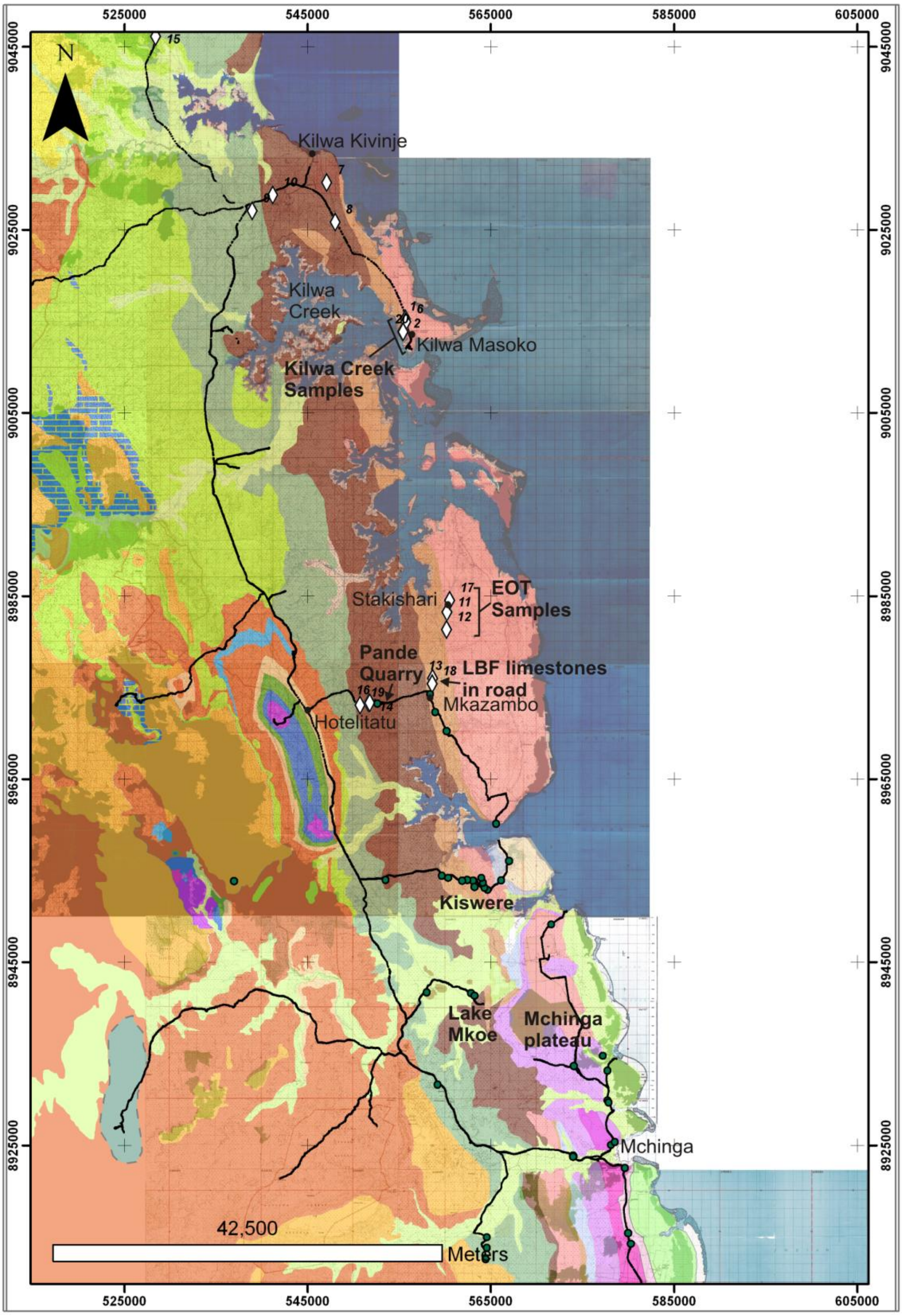


Figure 3.5. Location map showing the Kilwa Creek, Pande, Kiswere and Mkoe localities and samples collected, for more detailed maps of the Kiswere and Lake Mkoe areas see Figures 3.9 and 3.12 respectively.

Figure 3.6. a) Short log of exposed *in situ* beds of *Nummulites* and *Assilina* rich limestone; b) Photograph of beds logged, hat for scale; c) Close up of *Assilina* rich layer; d) One of many large blocks found on the banks of the creek, person for scale; e) Surface of LBF rich limestone; f) Thin section of Kilwa Creek limestone, showing *Nummulites* spp., orthophragmine fragments and complex miliolids (sample K08).

3.4.1.2 Pande Quarry

Pande quarry is a white limestone quarry found on the road between Hotelitatu and Mkazambo (see Figure 3.5), at the edge of the lower Eocene sediments mapped by Nicholas et al. (2006). The quarry contains two lithologies; an *Alveolina* rich grainstone and a softer, marly, *Nummulites* rich carbonate. Within the quarry wall the softer sediment can be seen overlying the blocky grainstone (Figure 3.7a). The grainstone is also found in large blocks on the quarry floor (Figure 3.7b). It is extremely rich in *Alveolina*, with varying amounts of *Nummulites* (Figure 3.7d-f). Occasional bryozoan and gastropod fragments are also present. Dasyclads are very common and thalli of thyrsoporellids (*Thyrsoporella* and *Belzungia*) and *Ovulites* (probably *Ovulites maillolensis*) are visible (Figure 3.7e-f) and indicate a Lower to Middle Eocene age, consistent with the age given by Nicholas et al (2006) which is based on planktonic foraminifera. These coupled with the abundance of *Alveolina*, the undamaged nature of the LBF and low diversity assemblage indicate the limestone was formed in the inner part of the carbonate platform. The softer, marly sediment can be seen on the quarry floor to the north eastern end of the quarry. Loose *Nummulites* up to ~1 cm diameter are abundant (Figure 3.7c) and complete tests of irregular echinoids are common in this sediment. Planktonic foraminifera were also found during in previous studies (P. Pearson, per. comm). These softer sediments represent a deeper environment than that of the grainstones.

The occurrence of this outcrop in the middle of a hemipelagic succession of clays is puzzling. It has been suggested that the quarry represents a gully infill (P. Pearson pers. comm.). The *Alveolina* rich limestone was cemented on the shelf and redeposited as blocks within a gully in the platform, possibly due to tectonic movement. Less cemented sediment, mixed in with pelagic clays and planktonic foraminifera was then deposited on top. This accounts for the blocky nature of the grainstones, variation in lithology and presence of planktonic foraminifera in the upper beds. However, the LBF and echinoids are unlikely to have survived long distance transportation within soft sediment and remained intact. Alternatively, the quarry may represent a patch reef with very shallow facies. The overlying more marly *Nummulites* rich beds may represent deeper water, with increasing clay content as the platform begins to drown and finally clays are draped over the top. The blocky nature of the grainstone could be due to differential cementation. Eocene patch reefs have been found in other parts of the field

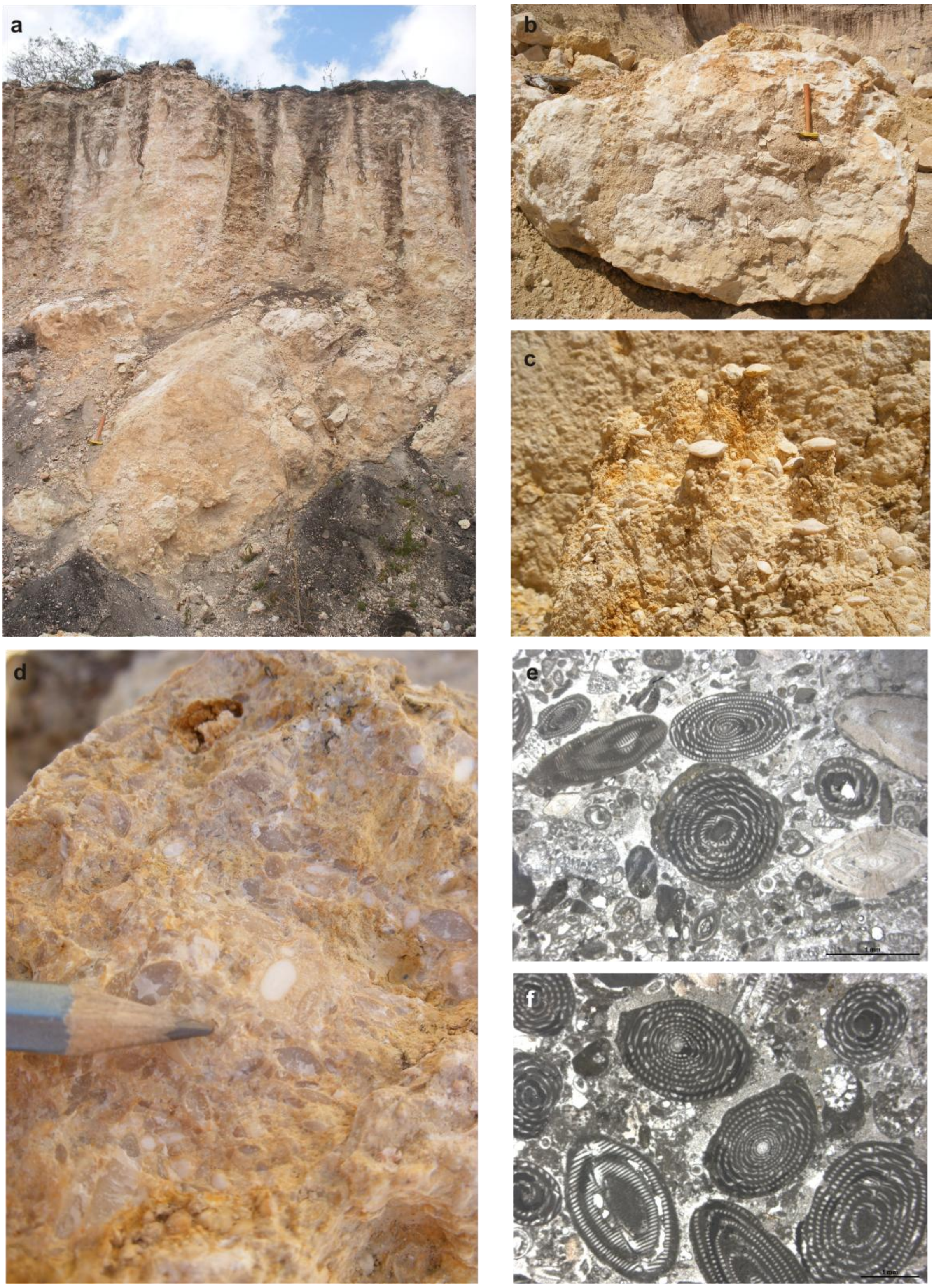


Figure 3.7. Images from Pande quarry outcrop: a) Photograph of quarry face showing blocky sparry limestone beneath softer, marly sediment, hammer for scale, b) Large block of Alveolina rich grainstone on quarry floor, hammer for scale, c) *Nummulites* on "pillars" weathered out of soft marly sediment, d) Fresh surface of *Alveolina* rich grainstone, showing *Nummulites* and *Alveolina*, e and f) Thin sections of the *Alveolina* rich grainstone, showing abundant *Alveolina* with *Nummulites* and dasyclads, scale bars 1 mm (sample K14).

area and so this interpretation is not unreasonable. However, a further more detailed study of the quarry and surrounding lithology would be needed to ascertain its true mechanism of formation.

3.4.1.3 Mkazambo-Stakishari road

Just after the road turns north, close to Mkazambo, limestones are found exposed in and to the side of the road close to the sites of TDP 18 and 13 as reported in Nicholas et al. (2006). These are similar in appearance to the limestones found in Kilwa Creek, with an orange weathered surface and occur as debris flow beds within the clay. Samples from this site contain large *Nummulites* spp., including some from the *N. perforatus* group, *Assilina* and *Discocyclina* indicating a lower to middle Eocene age.

Further north, close to Stakishari, the EOT is found partially exposed on the hillside close to the site of TDP 12 (Nicholas et al., 2006). Unfortunately, the hillside was more overgrown than when visited by Nicholas et al. (2006), but it was still possible to find the transition from Eocene to Oligocene sediments. The limestones occur as sediment gravity flow beds, within a hemipelagic clay sequence. Within the Eocene the limestones are bioclastic packstones, rich in LBF. *Pellatispira* cf. *madarazi* is very common in the last Eocene bed collected from this site and indicates Priabonian age (Hottinger et al., 2001). Also present are reticulate *Nummulites*, *Discocyclina*, other orthophragmines and *Spiroclypeus*. Samples from this site and from the TDP sites 11, 12 and 17 are discussed in detail and a comprehensive list of LBF present given in Chapter 4.

3.4.1.4 Ras Mtama

Middle Eocene limestones are also known to crop out on the foreshore at Ras Mtama (Nicholas et al 2006) and were revisited during the 2009 fieldwork. Ras Mtama is further south, close to the town of Lindi and can be seen on Figure 3.8. Nicholas et al. (2006) place these limestones in the Lutetian, within the upper part of zone E9. This corresponds to the middle of the succession recovered by TDP 13. The limestones dip landwards and are unconformably overlain by Pleistocene reef sediments, which are exposed in a cliff face (Figure 3.8). The middle Eocene limestones occur in beds up to ~50 cm thick within a clay succession and are packstones dominated by LBF, many of which show breakages and abrasion to the outer whorls. There is a diverse LBF assemblage within these limestones, dominated by *Nummulites* spp. and *Alveolina* spp., also present but less abundant are *Assilina*, *Sphaerogypsina*, *Linderina*, *Neorotalia*, *Planolinderina*, *Asterigerina*, *Gyroidinella*, *Asterocyclina*, *Glomalveolina*, indeterminate orthophragmines and a single fragment of *Somalina* was identified by L Hottinger (in pers. comm. to P. Pearson). This is one of only two sites where *Somalina* was identified. The beds occur between clay layers and are composed of shallow carbonate debris and therefore probably formed as sediment gravity flows of material from the carbonate platform.

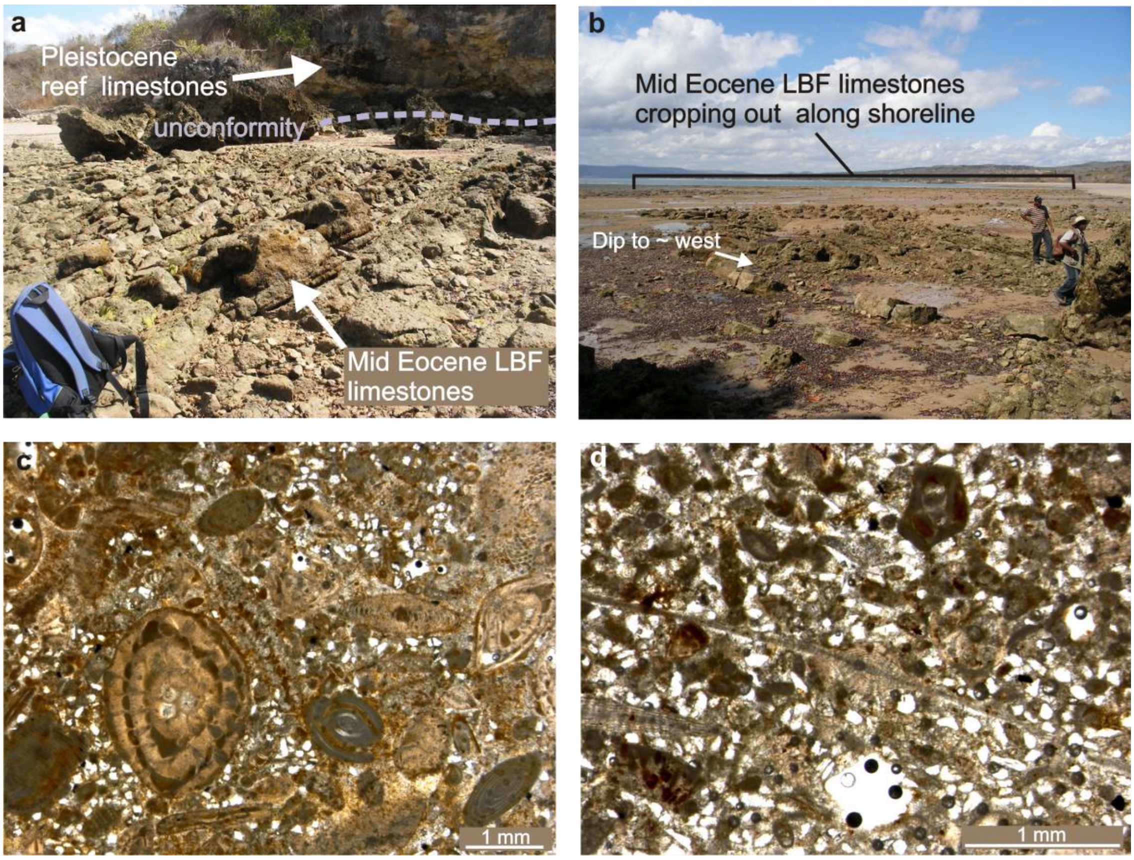


Figure 3.8. Images from Ras Mtama: a) Middle Eocene LBF limestones overlain by Pleistocene limestones, b) Middle Eocene LBF limestones cropping out along the foreshore, c) thin section showing *Nummulites*, *Alveolina*, *Linderina* and miliolids in a quartz rich matrix, d) thin section showing small orthophragminids, also with high quartz content (RAS99-24 and RAS99-51).

3.4.1.5 Kiswere

Kiswere is a small peninsula south of Pande peninsula bounded by Kiswere Haven and Msungu Bay (see Figure 3.5). A series of samples were take along the road which goes east to Rushungi and were found to be a succession from the Middle Eocene to Upper Oligocene (Figure 3.9). The succession begins with Samples 33 and 34. These are pack-grainstones containing mostly LBF, but also coral fragments, miliolids and dasyclads (Figure 3.10a-b). The LBF appear to be undamaged and uncompacted and matrix is present, this along with the presence of dasyclads, suggests the sediment formed on the carbonate platform. *Somalina* up to 2 cm in diameter are common (Figure 3.10a) and are the largest bioclasts, occurring with *Nummulites*, *Alveolina* and *Discocyclina*. This is the only site where complete *Somalina* were found during the fieldwork. *Somalina* has a Lutetian age (Loeblich and Tappan, 1987; BouDagher-Fadel, 2008) and is listed as a Middle Eocene Tanzanian genus by Blow and Banner (1962). The following sample (152) is a pack-grainstone with a largely micro-sparite cement. The bioclasts consist mostly of LBF typical of the Eocene (see Figure 3.10c), there is some abrasion to the outer whorls of *Nummulites* tests and LBF fragments are visible in the matrix. Large *Nummulites* are present with extensive borings which have been infilled. Occasional small intraclasts are present. Poorly preserved dasyclads were also observed in some sections. The sediment type and assemblage closely matches those found in TDP 18 and so it is likely to be a similar Bartonian age. Sample 151 is a very clean grainstone largely composed of miliolids and red algae with intact orthophragmines (?*Discocylina*) (Figure 3.10e) and occasional other LBF, including *Halkyardia* (Figure 3.10d). Sample 35 is very similar with the addition of bryozoan encrusted mollusc shells. Both samples indicate the limestone was formed on the carbonate platform. The assemblage gives an Eocene age as *Discocyclina* and other orthophragmines apparently became globally extinct at the end of the Eocene, see Chapters 4 and 5. The lower limit is constrained by the previous sample and so it is Bartonian or younger in age.

Samples 148, 149 and 150 are taken in a series up the slope on the northern side of the road. Sample 148 bears some similarity to the previous two samples. It is a pack-grainstone largely composed of miliolids and red algae, but contains few LBF – only *Sphaerogypsina* was identifed in thin section. The matrix differs from the previous samples in being largely micritic with some patches of sparite cement. Sample 149 contains more abundant LBF; mainly *Nummulites* spp. including both radiate and reticulate forms, with *Sphaerogypsina*, ?*Operculina*, *Amphistegina* and ?*Linderina*. Miliolids are common, with fragments of red algae and coral and occasional dasyclads. Some *Nummulites* tests are broken but most appear complete; there is a large amount of matrix and little compaction of the LBF. The presence of reticulate *Nummulites* indicates an Eocene age younger than middle Bartonian. Sample 150 is a pack-grainstone with a microsparite cement. The bioclasts consist of small fragments of red algae and miliolids with LBF and occasional coarse grains of quartz. The LBF assemblage is much more diverse than the previous two samples, containing common *Pellatispira* cf. *madaraszi* (Figure 3.10g), *Nummulites* (cf. *fabianii*; Figure 3.10f), *Orbitolites*, *Spiroclypeus* (or possibly *Heterostegina*), *Discocyclina*, ?*Biplanispira*, *Linderina*, smaller rotaliids and *Sphaerogypsina*. *Pellatispira* is a largely Priabonian genus (Hottinger et al., 2001) and in Tanzania *Pellatispira* cf. *madarazi* has been found in the limestone beds just prior to the EOB in the TDP succession (see Chapter 4) and in the uppermost Eocene sediments cropping out on the hillside close to the TDP 12 site. This therefore indicates a probable Priabonian age for this sample, likely close to the EOB.

Samples 143, 144 and 145 are taken close together further east along the road, on the downward slope of the scarp. Samples 143 and 145 are both pack-grainstones; 143 contains large *Nummulites* in a matrix of carbonate (including LBF) fragments and smaller foraminifera and 145 contains *Nummulites*, *Planostegina* (Figure 3.10h) and poorly preserved dasyclads, again with a large number of LBF fragments. Between the two samples is a clay level (sample 144) containing planktonic foraminifera which indicated an upper Lower Oligocene age (probably O3). The large number of fragments and presence of the clay layer suggests that there is redeposition of the carbonate material in the Upper Oligocene. A final clay sample was taken after the road turned north towards Rushingi. Planktonic foraminifera were sparse in this sample and preservation was poor, only a Paleogene age could be determined. lepidocyclinids were found weathered out on the surface of the clay, but their source was uncertain. This does, however, suggest Upper Oligocene to Miocene limestones are present on the most easterly part of the peninsula.

The Kiswere peninsula therefore appears to be a near continuous in situ carbonate succession through the Lutetian to Priabonian, which then continues into the Oligocene and possible Miocene but perhaps as redeposited sediments in deeper water, as indicated by clay horizons. The importance of this section is discussed further in section 3.4.

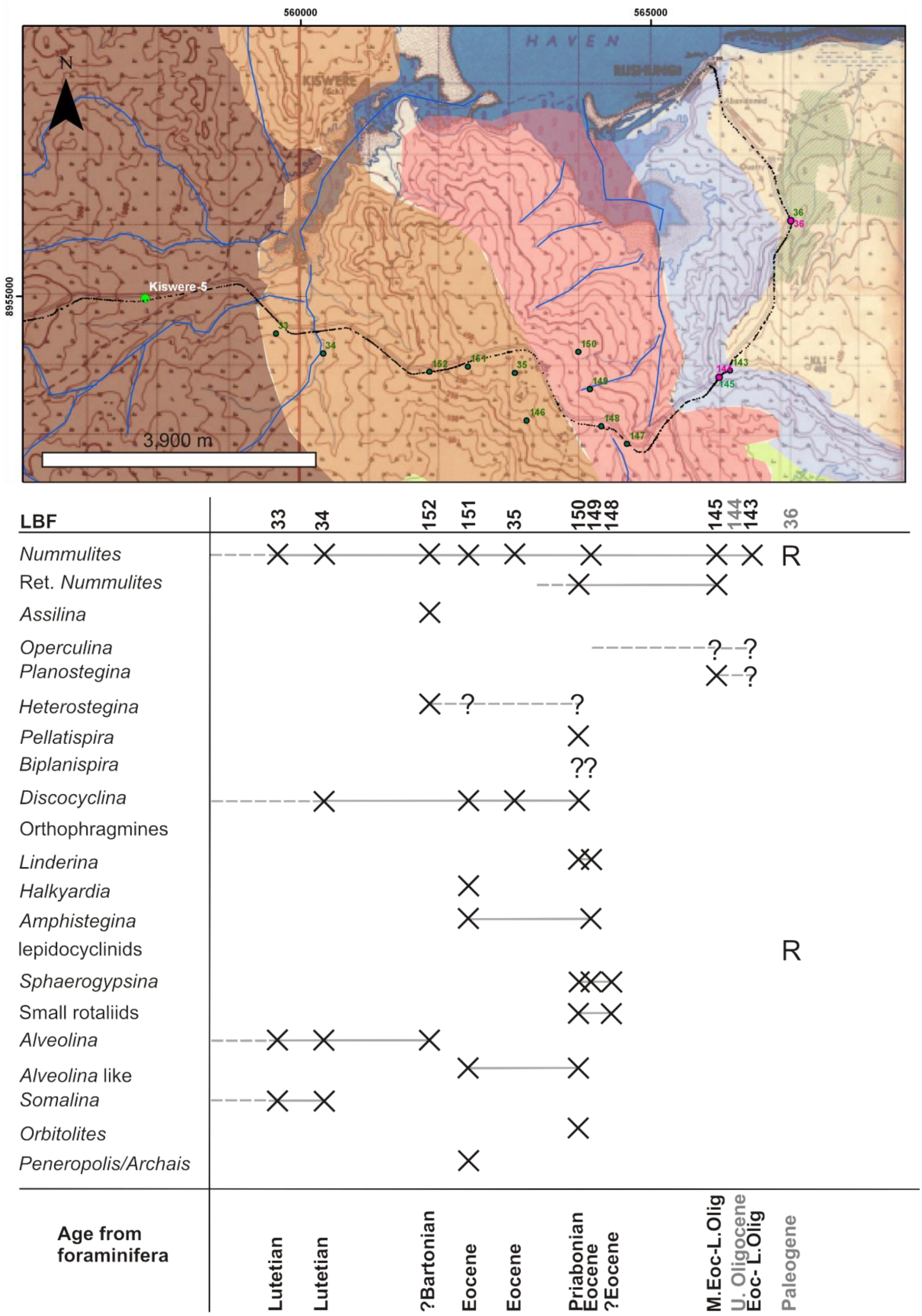


Figure 3.9. Diagram showing location, occurrence of LBF and ages of samples from the Kiswere peninsula. LBF occurrences are marked with crosses, solid lines joining them indicate observed range and dashed lines indicate inferred range. Clay samples and ages are in grey; R indicates reworked specimens.

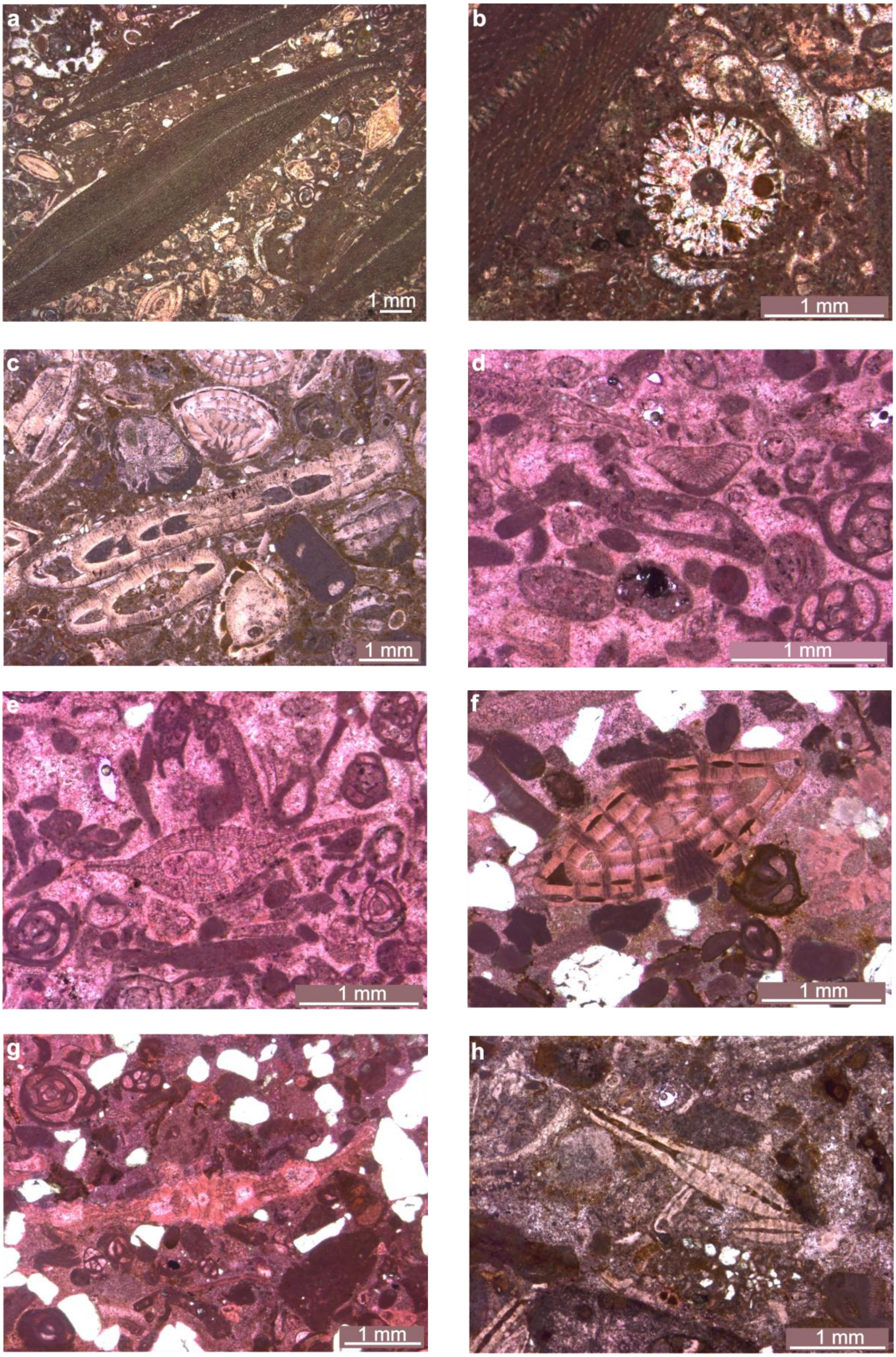


Figure 3.10. LBF from Kiswere peninsula samples: a) *Somalina* sp. (sample 33) b) Dasyclad with *Somalina* (sample 33) c) *Assilina* sp (sample 152) d) *Halkyardia* sp. (sample 151) e) orthophragmine - *?Discocyclina* (sample 151). f) *Nummulites* cf *fabianii* (sample 150) g) *Pellatispira* cf *madarazi* (sample 150) h) *Planostegina* sp. (sample 145).

3.4.1.6 Lake Mkoe

The lake Mkoe area is southwest of the Kiswere peninsula (see Figure 3.5). The topography in this area is very flat with occasional prominent small limestone hillocks (Figure 3.11). Sample 111 was taken from a hillock approximately 50 m wide and 8 m high, to the East of Mkuru village. This was a pack-grainstone containing *?Orbitoclypeus*, *Nummulites* and *?Alveolina* with red algae (including *Distichoplax*), which indicates an Paleocene to Eocene age. A further sample (113) was taken from a small outcrop past Lake Mkoe. This contained *Nummulites* with echinoderm fragments, in a matrix of smaller red algae fragments and sparite cement. The *Nummulites* indicate an Eocene to Lower Oligocene age.

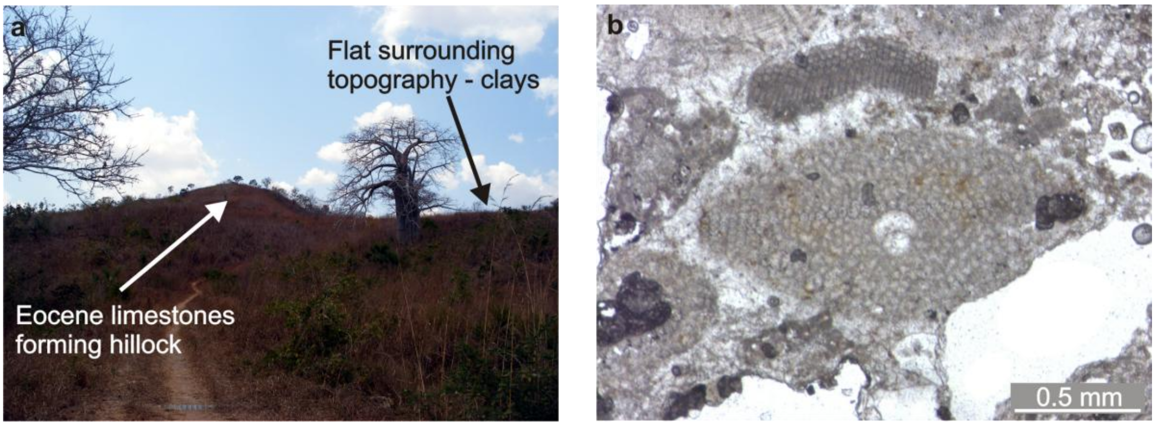


Figure 3.11. Images from Lake Mkoe: a) Small limestone hillock, b) *?Orbitoclypeus* in pack-grainstone collected from hillock shown in “a” (sample 111).

3.4.2 Results: Oligocene to Miocene

3.4.2.1 North Mchinga and Mchinga Bay

The Miocene outcrops have been divided into geographic areas from north to south, beginning with those in the North Mchinga and Mchinga Bay. Figure 3.12 shows a map of the regions described and locations of samples.

3.4.2.1.1 Mchinga school

The Mchinga school locality is just north of the village of Mchinga, close to Mchinga bay (Figure 3.12). The school sits above a ~ 5 m high outcrop of limestone with clay forming the ground level (Figure 3.13a). Sample 83 and 84 are from the limestone outcrop and contain small rounded lepidocyclinids (probably

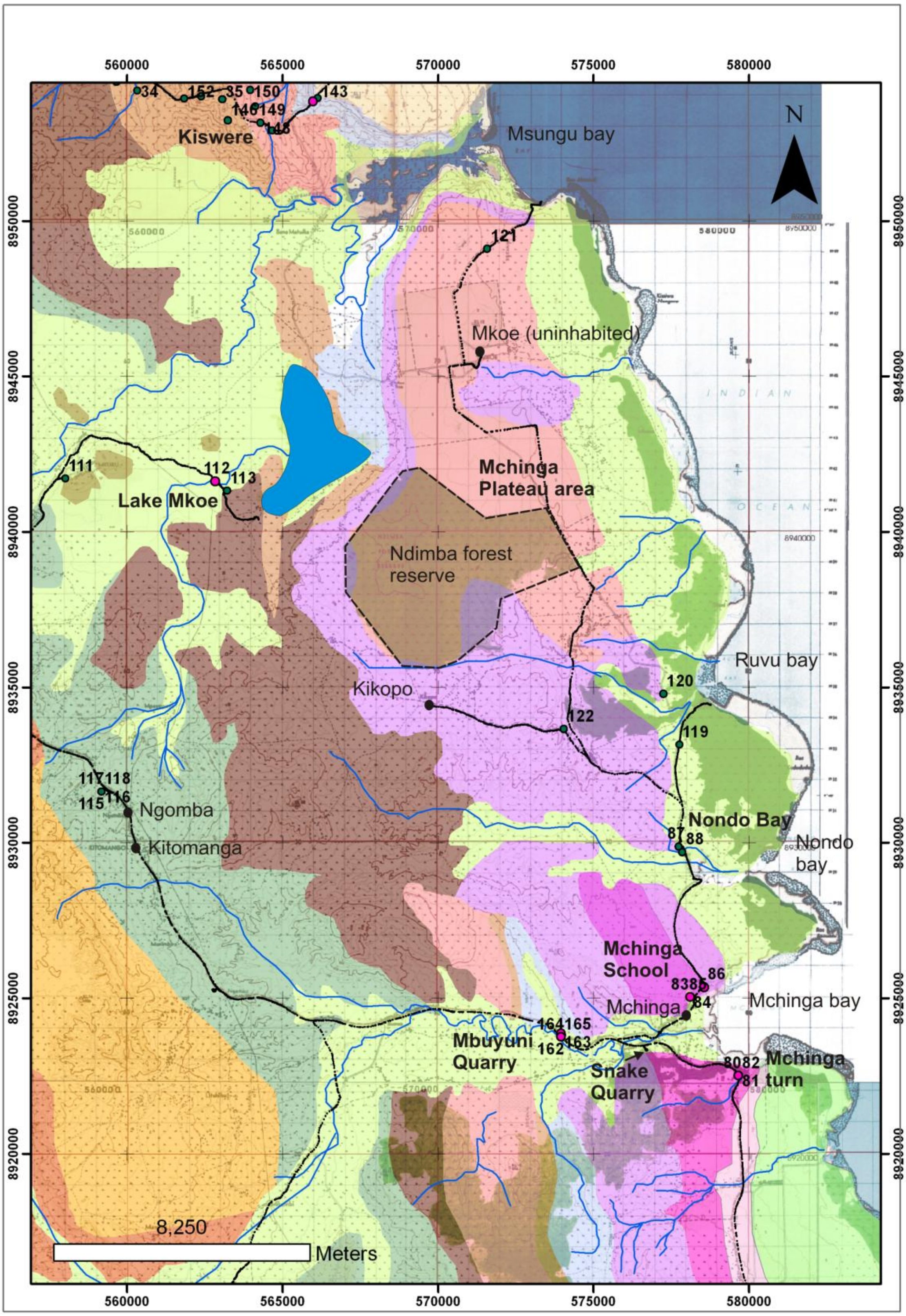


Figure 3.12 Map of North Mchinga and Mchinga bay areas showing sampling localities.

Nephrolepidina), *Miogypsina* and *Sphaerogypsina* in a sparry cement with red algae and smaller foraminifera (Figure 3.13b). The assemblage of LBF indicates a Miocene age which is confirmed by planktonic foraminifera from the clay underlying the limestone outcrop (sample 85) which indicates an Early / Middle Miocene boundary age (*Praeorbulina glomerosa* zone). Sample 86 was taken in a roadside gully from a clay which appears to stratigraphically overlie the limestones. Planktonic foraminifera from this sample also yielded an Early / Middle Miocene boundary age (*P. glomerosa* subzone).

3.4.2.1.2 Nondo bay

Nondo bay is to the North of Mchinga Bay. Here a bioclastic limestone which passes up into a more marly sandy carbonate and crops out from 7.5 m to 18.8 m along the road towards Ruvu. There is a gap in the exposure, suggesting a possible eroded clay layer, followed by a 50 cm thick bioclastic packstone at 21.6 m with visible LBF. A further 5 m gap in exposure is then followed by a coralline limestone. A sample was taken from the limestone at 21.6 m which is a bioclast rich packstone containing lepidocyclinids, *Miogypsinoides, Borelis ?pygmeaus* and *Amphistegina* and indicates a Miocene age (~Aquitanian; Figure 3.13c-e). The limestone also contains red algae, coral fragments, echinoid fragments and planktonic foraminifera. The planktonic foraminifera are largely globular forms (Figure 3.13f), and a single specimen was identified as *?Globorotalia praescitula* by P. Pearson. The presence of planktonic foraminifera suggests a position on the transition from the photic zone to basin on an open ramp with a pelagic infux or possible transportation of the shallow water material and mixing with pelagic sediments. Both explanations are consistent with the position of the bed between two potential clay layers, occurring either due to fluctuating sea level or transport into deeper water.

3.4.2.1.3 Mchinga plateau

Mchinga plateau forms a distinct topographic feature. The plateau extends for ~ 25 km in the north-south direction (see Figure 3.12) and the Mchinga school and Nondo bay localities are on the edges of this platform. A number of samples were taken along the roads crossing the top of the plateau, however exposure is limited by the Ndimba Forest Reserve. The surface is composed of a sandy coralline limestone (Figure 3.14) and beneath this is a LBF rich limestone visible in river cuttings.

The limestone forming the plateau is a packstone with *Miogypsina* (particularly abundant in sample 122), lepidocyclinids, *Sphaeorogypsina*, *Borelis*, *Amphistegina* and *?Operculina* and therefore is Miocene or uppermost Oligocene age.

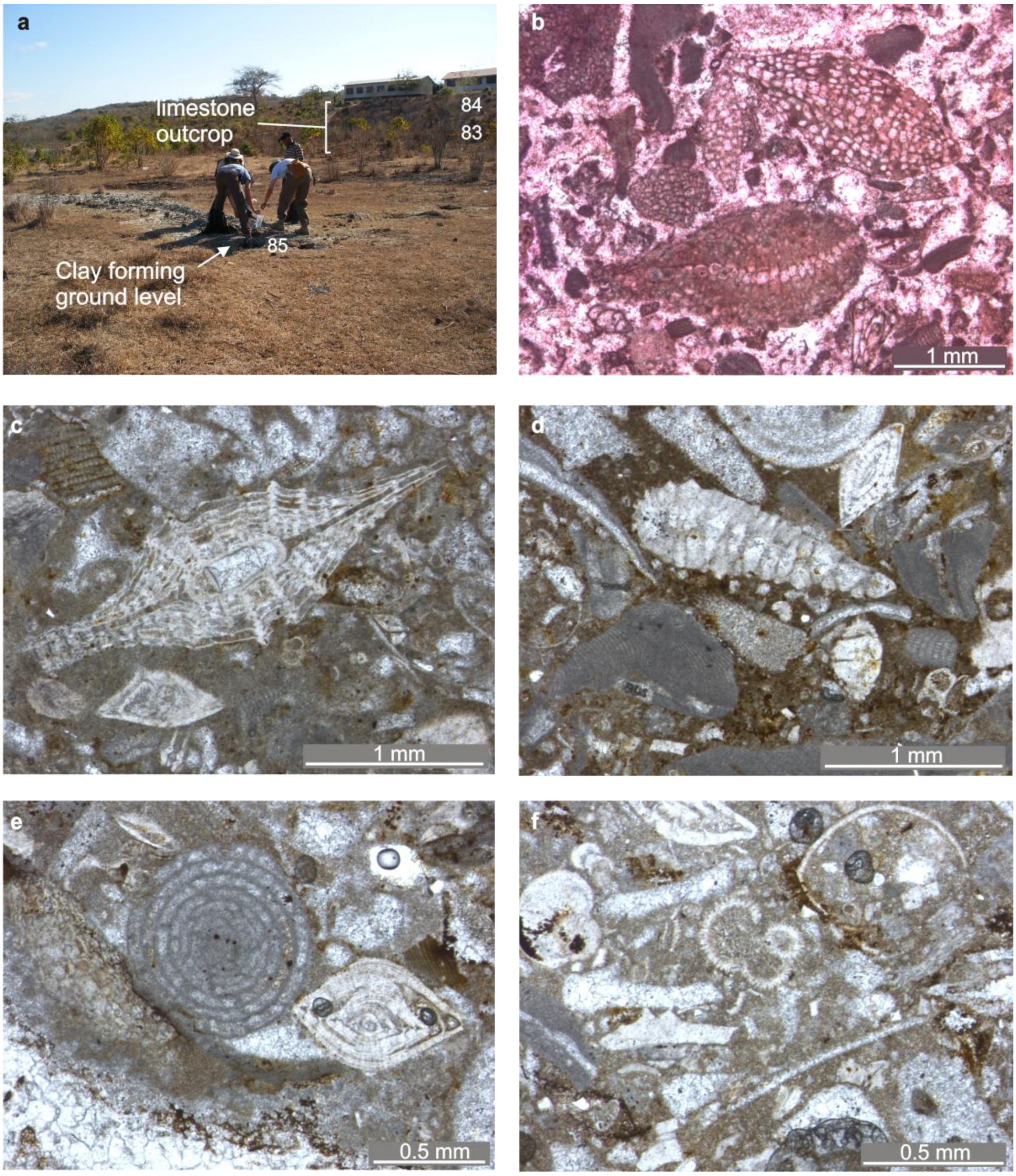


Figure 3.13. Mchinga school images: a) Photograph of Mchinga school locality showing clay from the ground level being sampled (85) and outcrop of limestones beneath school in background (samples 84 and 83) b) *Miogypina* in petrological thin section from sample 84; Nondo bay images: c) Lepidocyclinid axial section d) *Miogypsinoides* e) *Borelis ?pygmeaus* with *Amphistegina* f) globular planktonic foraminifera, all from sample 88.

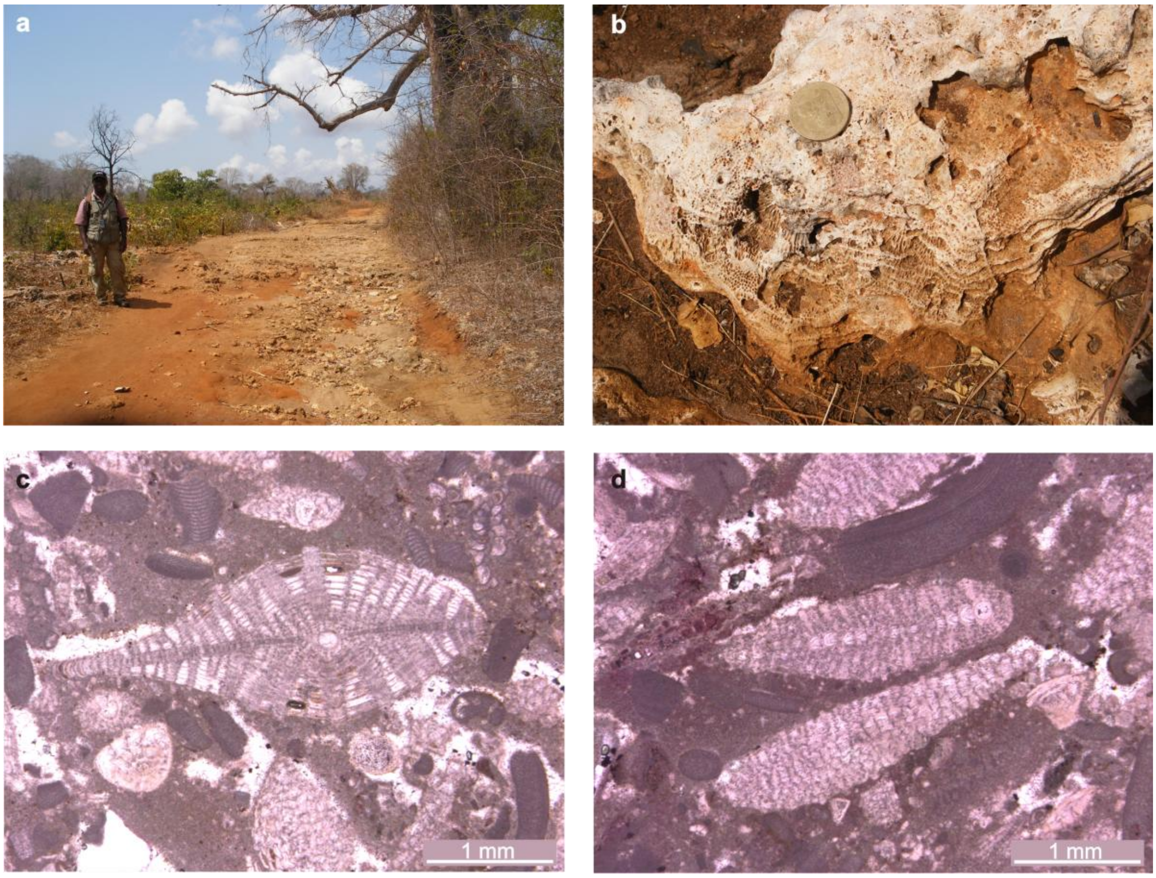
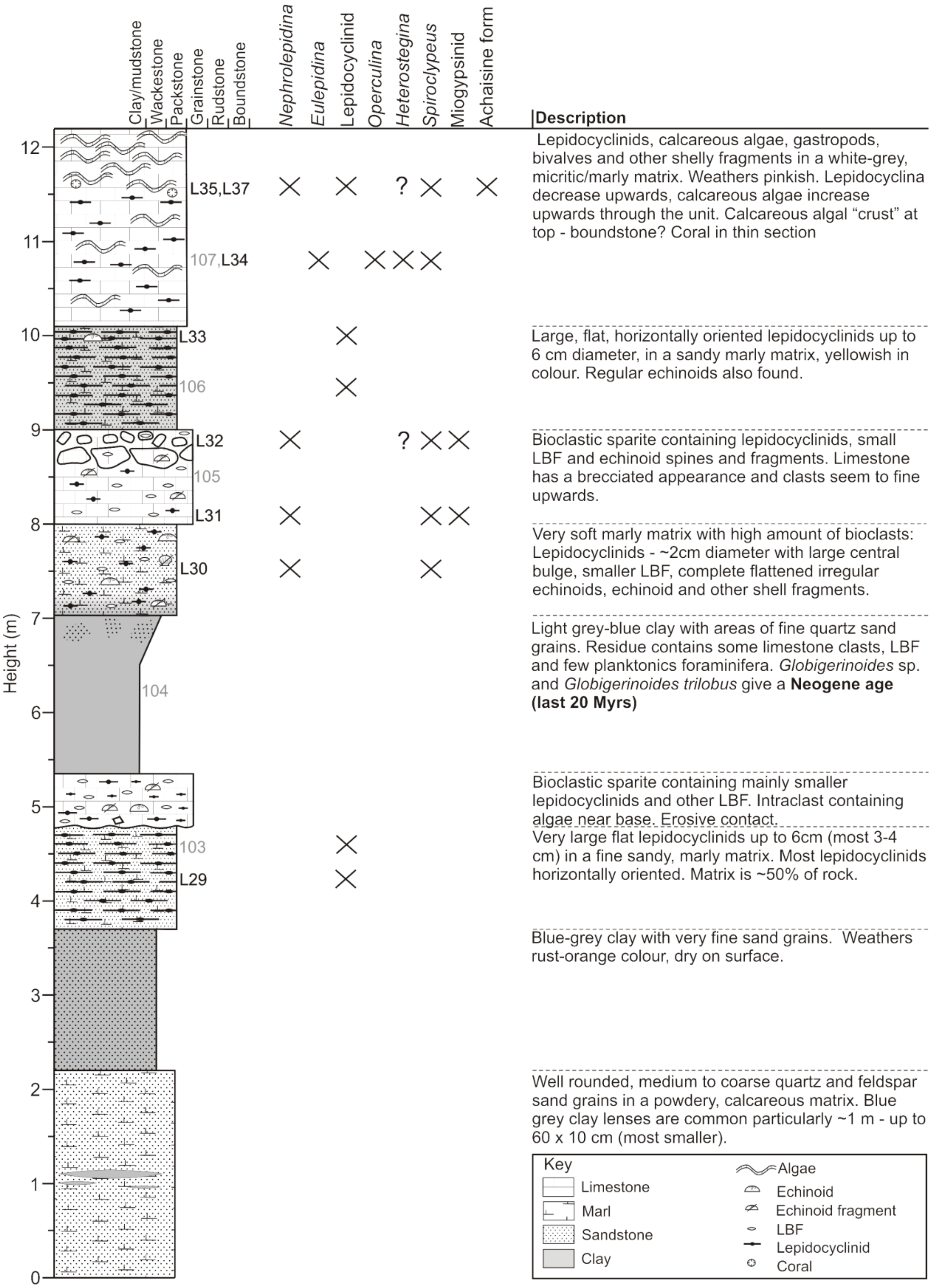


Figure 3.14. Images from Mchinga platform: a) road surface outcrop on the plateau, b) detail of outcrop showing fossilised coral, coin for scale, c) lepidocyclinid in packstone with red alge (sample 122) d) *Miogypsina* (sample 122).

3.4.2.1.4 Mbuyuni quarry

Mbuyuni quarry is west of Mchinga Bay and contains three logged sections: the Mbuyuni main quarry, Mbuyuni east (a shorted section exposed in the eastern side of the quarry) and Mbuyuni roadside (exposed on the roadside next to the quarry). The main quarry section consists of approximately 12 m of well bedded stratigraphy, consisting of clays, sandy clayey limestones with very large (up to 6 cm) lepidocyclinids and harder more well cemented limestones with smaller bioclasts, which become more algal towards the top (Figure 3.15). Both the Mbuyuni east and roadside sections show similar sediments (Figure 3.16) and can be correlated to the main quarry section, as shown in Figure 3.17. The assemblage consists of large lepidocyclinids, *Nephrolepidina*, *Operculina*, *Heterostegina*, *Spiroclypeus*, miogypsinids (Figure 3.18) and a small achaisine form and indicates a Miocene age. One clay sample contained few planktonic foraminifera but could only constrain the age to the Neogene. The sediments are carbonate platform deposits. Large flattened and unbroken lepidocyclinids along with complete large echinoid tests suggest that there was probably no significant transport of tests.



Description

Lepidocyclinids, calcareous algae, gastropods, bivalves and other shelly fragments in a white-grey, micritic/marly matrix. Weathers pinkish. Lepidocyclina decrease upwards, calcareous algae increase upwards through the unit. Calcareous algal "crust" at top - boundstone? Coral in thin section

Large, flat, horizontally oriented lepidocyclinids up to 6 cm diameter, in a sandy marly matrix, yellowish in colour. Regular echinoids also found.

Bioclastic sparite containing lepidocyclinids, small LBF and echinoid spines and fragments. Limestone has a brecciated appearance and clasts seem to fine upwards.

Very soft marly matrix with high amount of bioclasts: Lepidocyclinids - ~2cm diameter with large central bulge, smaller LBF, complete flattened irregular echinoids, echinoid and other shell fragments.

Light grey-blue clay with areas of fine quartz sand grains. Residue contains some limestone clasts, LBF and few planktonics foraminifera. *Globigerinoides* sp. and *Globigerinoides trilobus* give a **Neogene age (last 20 Myrs)**

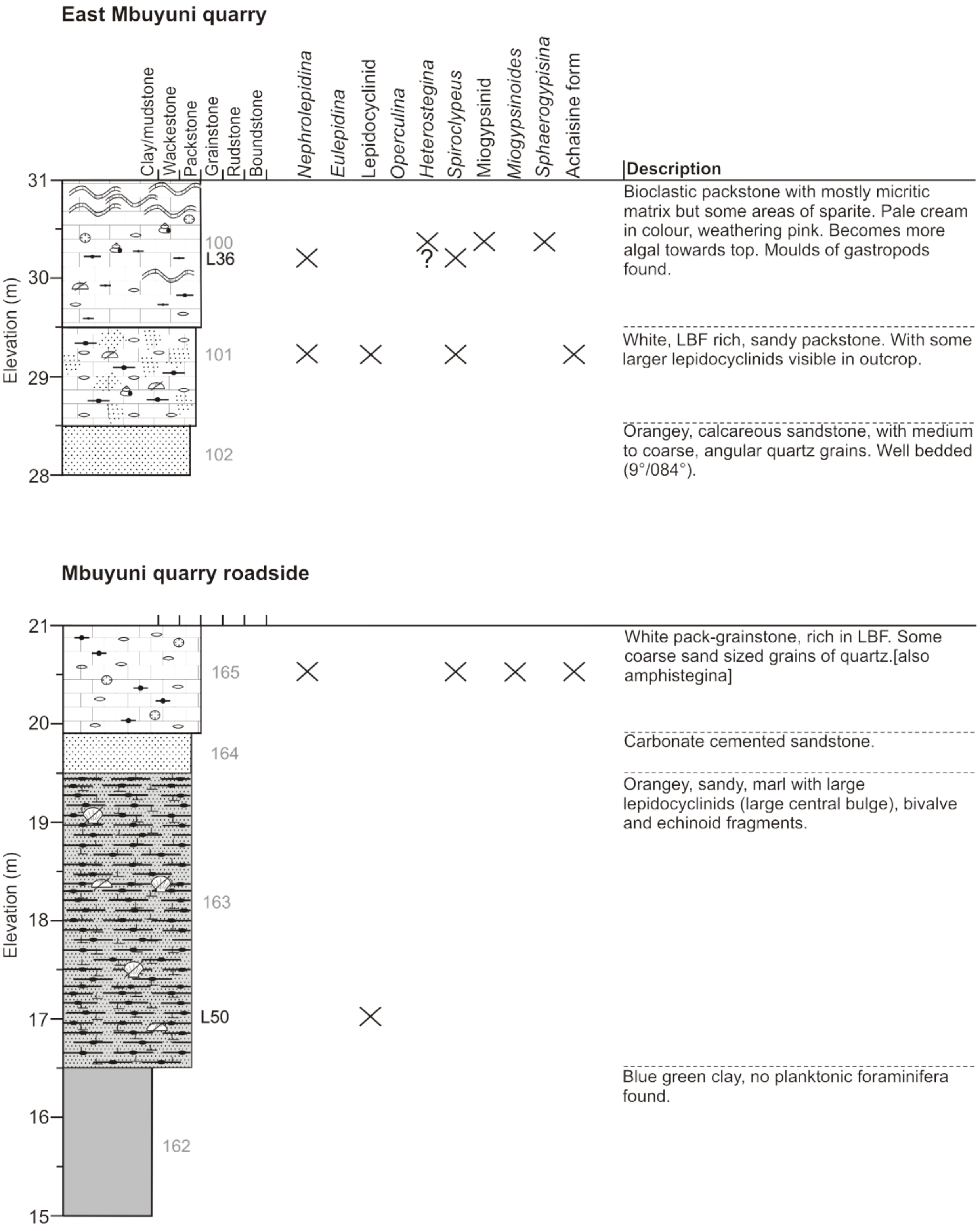
Bioclastic sparite containing mainly smaller lepidocyclinids and other LBF. Intraclast containing algae near base. Erosive contact.

Very large flat lepidocyclinids up to 6cm (most 3-4 cm) in a fine sandy, marly matrix. Most lepidocyclinids horizontally oriented. Matrix is ~50% of rock.

Blue-grey clay with very fine sand grains. Weathers rust-orange colour, dry on surface.

Well rounded, medium to coarse quartz and feldspar sand grains in a powdery, calcareous matrix. Blue grey clay lenses are common particularly ~1 m - up to 60 x 10 cm (most smaller).

Figure 3.15. Main Mbuyuni quarry log, showing occurrences of LBF genera.



Description

Bioclastic packstone with mostly micritic matrix but some areas of sparite. Pale cream in colour, weathering pink. Becomes more algal towards top. Moulds of gastropods found.

White, LBF rich, sandy packstone. With some larger lepidocyclinids visible in outcrop.

Orangey, calcareous sandstone, with medium to coarse, angular quartz grains. Well bedded (9°/084°).

White pack-grainstone, rich in LBF. Some coarse sand sized grains of quartz.[also amphistegina]

Carbonate cemented sandstone.

Orangey, sandy, marl with large lepidocyclinids (large central bulge), bivalve and echinoid fragments.

Blue green clay, no planktonic foraminifera found.

Figure 3.16 East and roadside quarry logs, both give occurrences of LBF marked by crosses. For key please see main Mbuyuni quarry log.

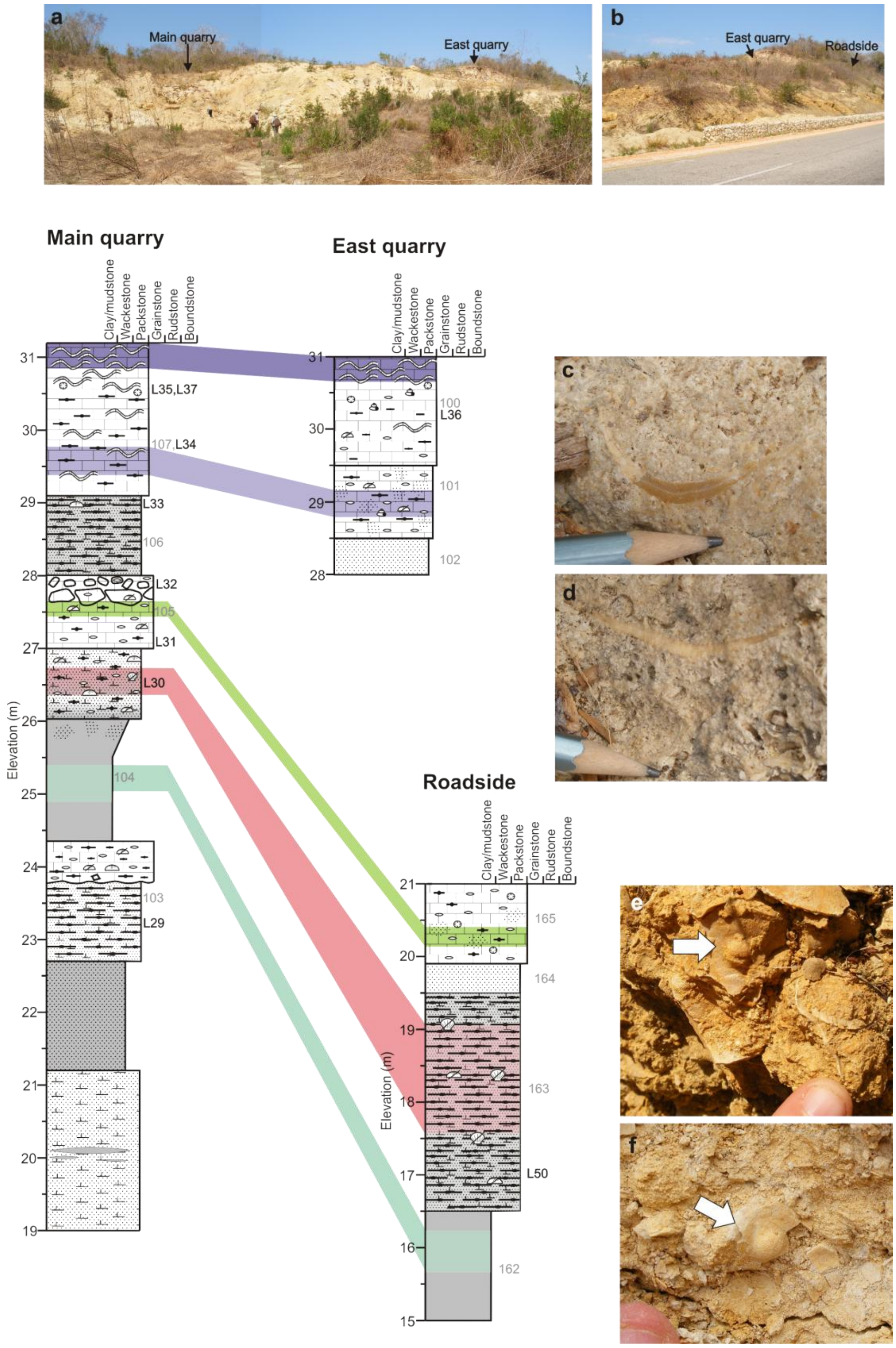


Figure 3.17 Diagram showing correlation between the three sections a) view showing main quarry and east quarry outcrops b) view showing roadside and east quarry outcrops. c and d) lepidocyclinids from uppermost bed of main log and middle bed of east quarry respectively, showing very similar lithology and LBF in outcrop, e and f) very similar lepidocyclinids from the roadside (~18 m) and main log (~26.5 m).

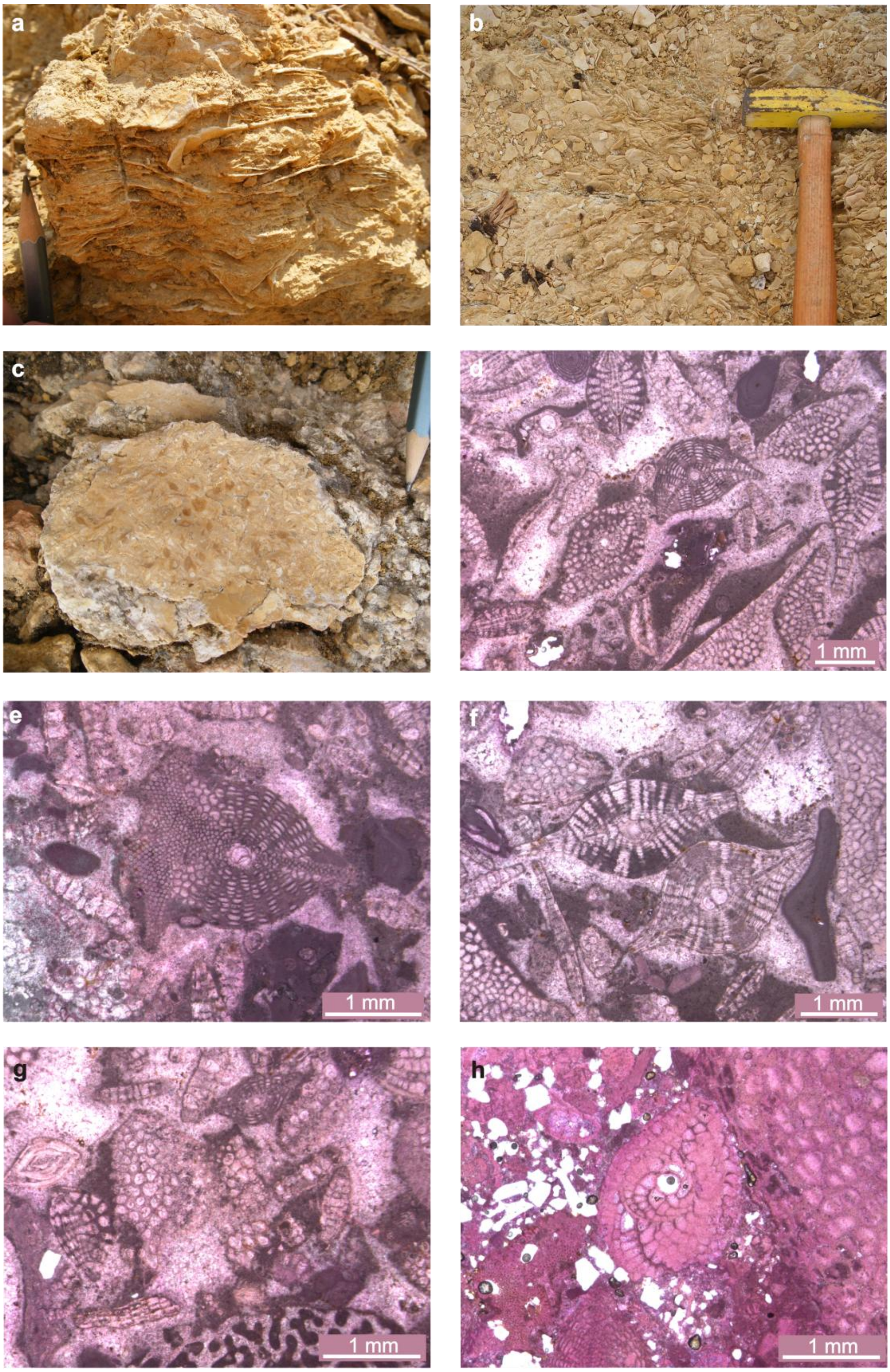


Figure. 3.18. Mbuyuni quarry log images: a) Highly flattened large lepidocyclinid bed at 3.7 m b) lepidocyclinid bed at 9 m c) small lepidocyclinids and other LBF in sparry limestone from bed at ~ 11 m d) *Nephrolepidina*, *Spiroclypeus* and *Borelis* also showing geopetal micritic cement e) *Nephrolepidina* f) *Spiroclypeus* g) *Miogypsina*, *Nephrolepidina* and *Amphistegina* all from sample 162 h) *Spiroclypeus* from sample 101

Additionally, the top bed contains coral-algal layers. The clays represent the deepest facies away from the platform. Large flattened lepidocyclinids inhabit the outer part of the platform with some clay deposition to form a clayey carbonate matrix and more diverse LBF assemblages which are generally smaller in size occur on the middle to inner platform. The succession therefore shows a fluctuating relative sea level during this period, but with an overall shallowing as the smaller LBF limestones become more common upwards through the sequence. It seems likely that at least the smaller fluctuations are related to tectonics as a large number of Miocene faults are recognised from this region (O'Sullivan, 2012).

3.4.2.1.5 Snake quarry

Snake quarry is close to Mbuyuni (see Figure 3.12) and has a similar lithology. Here there is an 8 m high outcrop of poorly consolidated bioclastic limestone overlain by a harder sparry limestone (Figure 3.19). Both contain LBF, the lower unit is particularly rich in LBF up to ~ 5 mm in size and also contains echinoid fragments and sand grains. The contact between the two beds appears unconformable and small faults are visible in the quarry. Snake quarry and Mbuyuni quarry form prominent westerly facing ridges and are probably part of the same depositional sequence, but offset ~3 km from each other by a dextral west-east fault (O'Sullivan, 2012).

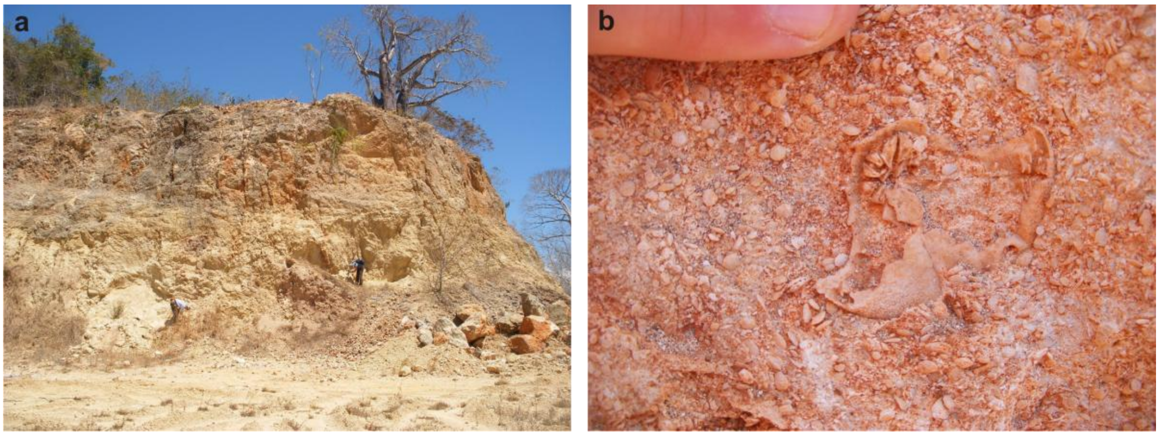


Figure 3.19 a) Outcrop at snake quarry with visible small faults b) detail of boulder at base of outcrop showing LBF and echinoid.

3.4.2.1.6 Mchinga turn

Where the road turns south, south of Mchinga Bay (see Figure 3.12) there is a 16 m exposure of sediments as a road cutting (Figure 3.20). Some material has slumped due to the recent nature of the cutting, but it is still possible to distinguish the stratigraphy. At the base of the section was a green-grey clay containing planktonic foraminifera which yielded an Early – Middle Miocene boundary age (*Praeorbulina glomerosa* zone; sample 80). This is followed by an LBF rich sandy bioclastic marl containing lepidocyclinids. Above this is a green clay which gave a base middle Miocene age from planktonic foraminifera and the sequence is capped by boulders of harder reefal limestones. The lithology here is very similar and the same age as that at Mchinga school and similar to some of the Mbuyuni section, consisting of shallow carbonate LBF rich limestones and clay beds.

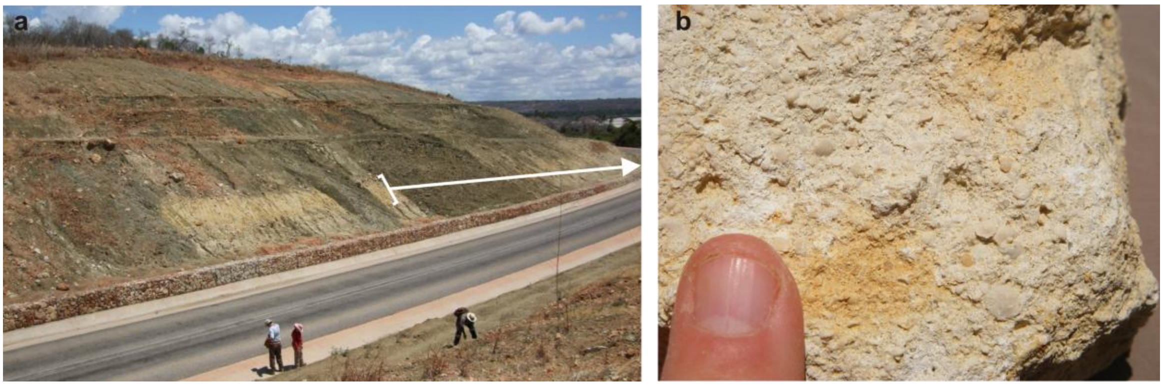


Figure 3.20 a. Photo taken of the Mchinga turn road cutting b) LBF rich limestone bed.

3.4.2.2 Lindi area

The Lindi area is considered here as the region south of Mchinga Bay to the Lindi Creek (Figure 3.21).

3.4.2.2.1 Likonga river

A series of outcrops occur along the roadside at Likonga (Figure 3.21). North of the village reef limestones displaying karstic weathering with clints and grikes crops out at the roadside and forms the top of a plateau. A greenish clay is found in roadside gullies further along the road (sample 45), this contains planktonic foraminifera which give an Upper Miocene to Lower Pliocene age. This is followed by a marly limestone at the roadside before the riverbed. On the south bank of the river is a 5 m high limestone outcrop. The upper part of this consists of a LBF rich pack-grainstone (sample 79) with a high medium to fine quartz grain content. LBF consist of *Miogypsina*, small (< 5mm) *Nephrolepidina* and ?*Operculina* along with common red algae fragments (Figure 3.22a). The LBF assemblage indicates a Miocene age and is therefore consistent with the clay date. The lower part of the outcrop is a rubbly limestone rich in coral fragments.

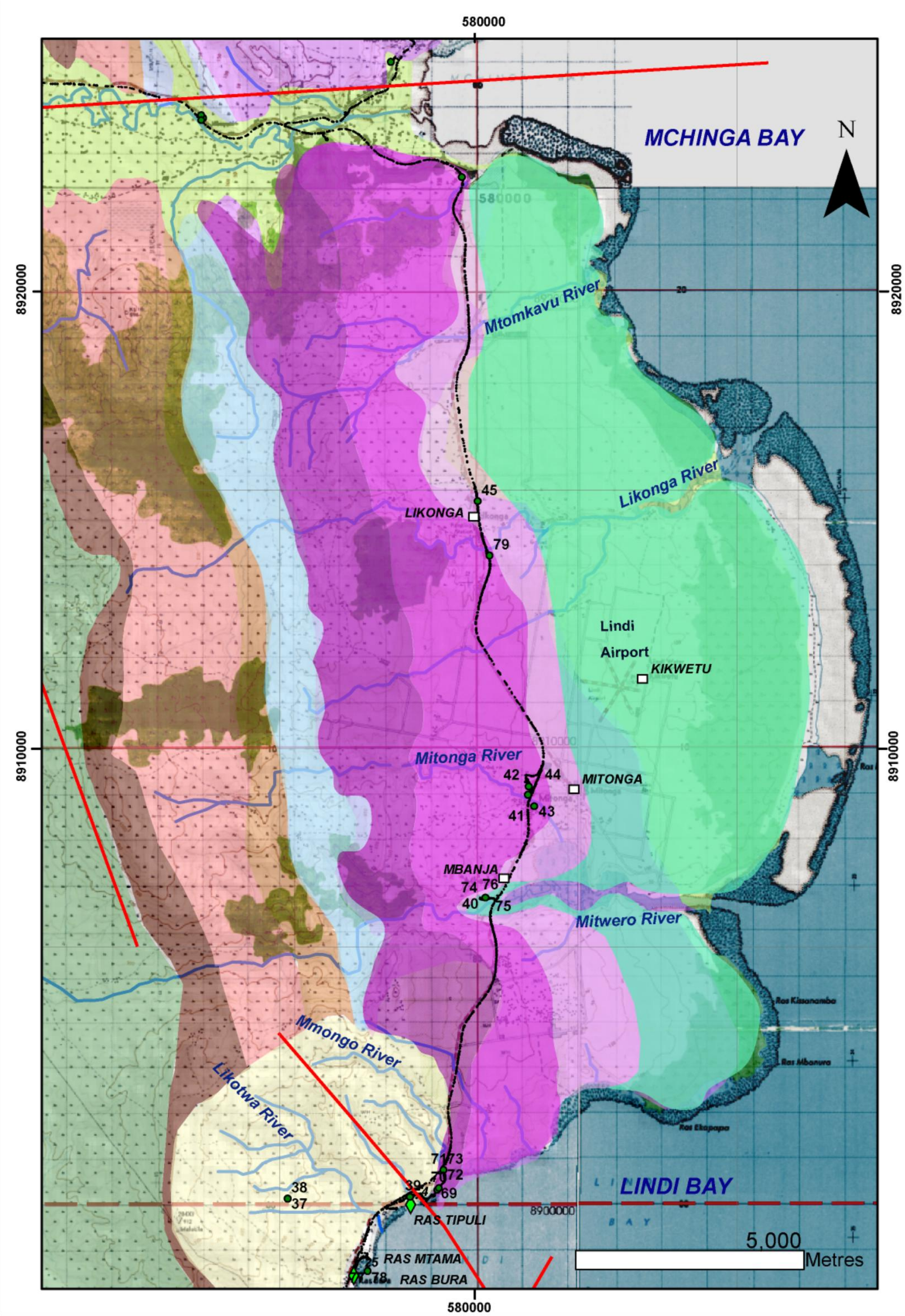


Figure 3.21. Map of the Lindi area showing localities and field samples.

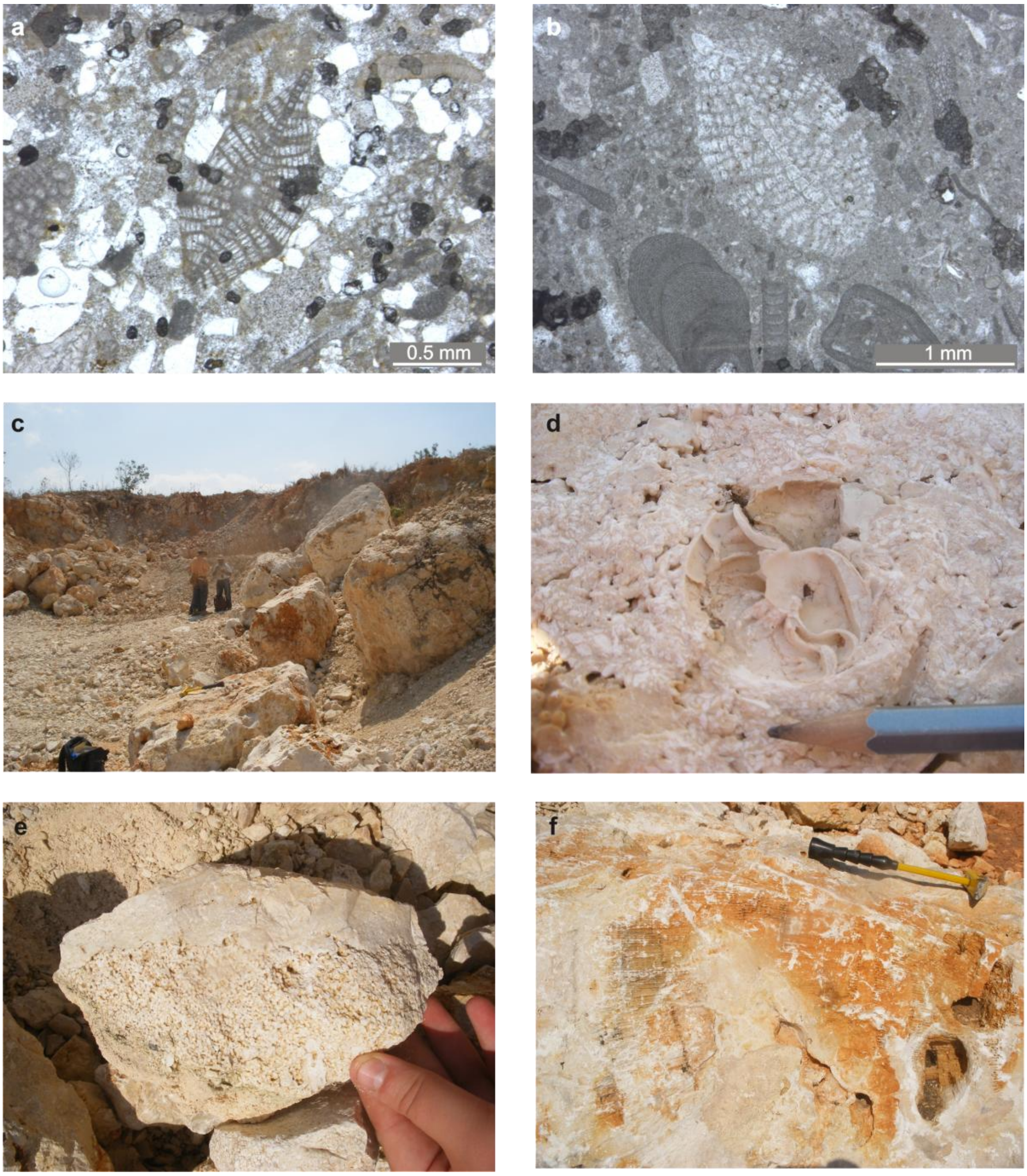


Figure 3.22. a) *Nephrolepidina* from Likonga (sample 79); b) *Miogypsina* from Mitonga (sample 44); c) Coralline limestone quarry at Mitonga; d) *Nautilus* in LBF limestone in Mitonga quarry; e) LBF limestone with meniscus cement in Mitonga quarry; f) large fossil coral in Mitonga quarry.

3.4.2.2.2 Mitonga river

A similar series of roadside outcrops occur near the village and river of Mitonga, as the road continues downhill (Figure 3.21). Between 73 m and 53 m coral and LBF rich limestone is found as boulders and in outcrop, and forms the surface of the road between here and Likonga (sample 44). This is a bioclastic packstone with *Miogypsina* and *?Nephrolepidina* with common red algae and miliolids, indicating a Miocene age (Figure 3.22b). Between 52 m and 42 m green clays crop out in roadside gullies; planktonic foraminifera from these indicate a base Mid Miocene age. Further along the road at 34 m asl is a white limestone quarry. The quarry outcrop is approximately 3.5 m high and consists of reef limestone (Figure 3.22c-f). Large blocks composed of fossilised coral are common. Between the corals there is a very well sorted LBF grainstone, containing *Miogypsina* and lepidocyclinids. In some areas the LBF have a meniscus cement and there are numerous vugs in the limestone. A single *Nautilus* fossil was found within the LBF limestone.

From stratigraphy and the planktonic foraminiferal age the sections at Mitonga lie below those at Likonga and the top reefal limestone therefore appears likely to correspond to the basal bed at Likonga. The complete sequence therefore shows a variation in facies between pelagic clays with planktonic foraminifera, inner platform sediments rich in red algae and LBF and coral and LBF dominated reef limestones, indicating variation in relative sea level.

3.4.2.2.3 Ras Tipuli

Ras Tipuli is one of a series of small headlands found north of Lindi at the edge of Lindi Bay (Figure 3.21). Ras Tipuli is described as being a “geobreccia” in an unpublished report by Martin (1954) reported in Kent *et al.* (1971). More recently Nicholas et al. (2006, 2007) have studied the Ras Tipuli “geobreccia”. Large blocks, up to 10 m across, of yellowish, sandy carbonate, rich in LBF occur on or within clays. They are randomly oriented with a variety of dips. This unusual formation is thought to have formed through slumping or faulting causing large blocks of older already cemented material to be redeposited onto the clay sediment (Nicholas et al, 2006; 2007, O’Sullivan, 2012). Several clay samples from this locality were analysed by Stewart et al. (2004), an Early Miocene age (M1) was assigned to clay beside the bridge the headland is entered over, Base Mid Miocene (M6; 14.3-15.7 Ma.) and base Upper Miocene (M11-M12; 10.46-11.63) ages were assigned to the clays north of the boulders, close to the location of sample 69 in this study. Gastropods at this locality have also been studied by Harzhauser (2009) and yielded an Aquitanian age. The

Figure 3.23. Images from Ras Tipuli: a) Large “geobreccia” blocks, b) *Planostegina*, c) Lepidocyclinids d) Pectin with *Planostegina* e) ?Echinoid spine with smaller lepidocyclinids and other LBF, f) mould of coral.

gastropods studied were from a 2.5 m thick section of grain- and rudstones in a coastal cliff and not within the geobreccia blocks (Harzhauser, 2009).

The lithology of the blocks is very similar to Miocene deposits seen elsewhere. They are bioclastic, sandy packstones extremely rich in LBF, though the dominant LBF genus varies between blocks. *Planostegina* and both microspheric and megalopheric lepidocyclinids are abundant (Figure 3.23). Complete Pecten valves and articulated specimens, echinoids and other invertebrate fossils are also common. The complete nature and assemblage of shallow water fossils indicates the sediment was cemented on the platform and then later formed the blocks of the “geobreccia”. The varying LBF content of the blocks may relate to varying facies within the platform sediment, the large flattened lepidocyclinid beds represent the outer part of the platform, whilst smaller lepidocyclinids are likely to have been shallower.

North around the headland the boulders are no longer present. Greenish clays are overlain by planar calcareous sandstones. The clay here (69) is dated as Mid Miocene (M6 14.3-15.7 Ma). Continuing towards Ras Mongo a 1 m exposure is seen in the cliff consisting of a yellowish, soft, friable, sandy marl containing LBF overlain by a white LBF-rich grainstone with an abutting more recent clay with caliche.

3.4.2.3 South Lindi and Sudi Bay

The south Lindi and Sudi Bay area is the most southerly region sampled and spans from the southern shore of Lindi Creek and the Kitunda Plateau to Mikindani bay. South of here no further LBF rich outcrops were found.

3.4.2.3.1 Kitunda

Kitunda plateau is south of Lindi Creek (Figure 3.24). The base of the cliff near the landing jetty is composed of Pande formation clays (Nicholas et al., 2006). Further up the cliff a there are younger carbonates; a continuous 55 m section was logged along a footpath from the top of the plateau (village) to a water well where the topography flattens out (Figure 3.25). Clays from the base of the section were sandy and contained planktonic foraminifera, but generally poorly preserved. The planktonic assemblage gives an Upper Oligocene to Lower Miocene age, constraining the lower age on the section. The clay is followed by a 36 m thick section of sandy, powdery white marls with occasional harder sandier beds with burrowed tops. The upper part of the section is a series of LBF rich limestones with varying LBF and other shallow water fossil content. Lepidocyclinids and *Spiroclypeus* dominate the assemblages, with *Miogypsina*, *Planorbulinella* and an archaiasine form (Figure 3.26a-c). The lepidocyclinids are larger towards the bottom of the LBF rich limestones and are smaller rounded forms near the top – including *Nephrolepidina* cf. *sumatrensis* (Fig 3.26a). Large complete clypeid echinoids are also common with the larger lepidocyclinids. Towards the top of the section there is an increase in algal material with oncoids and layers visible in both outcrop and thin section. The uppermost samples also show dedolomitisation.

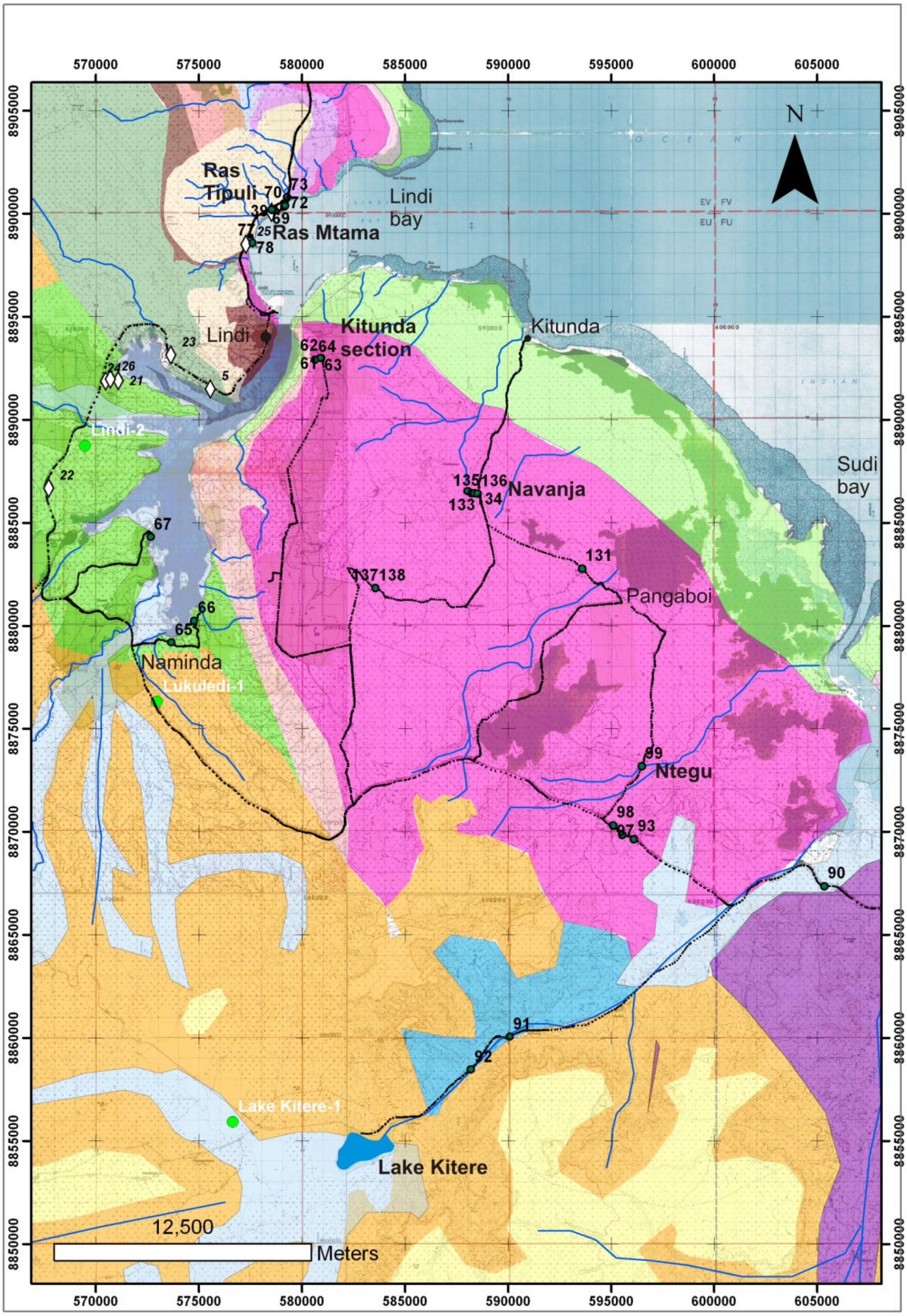
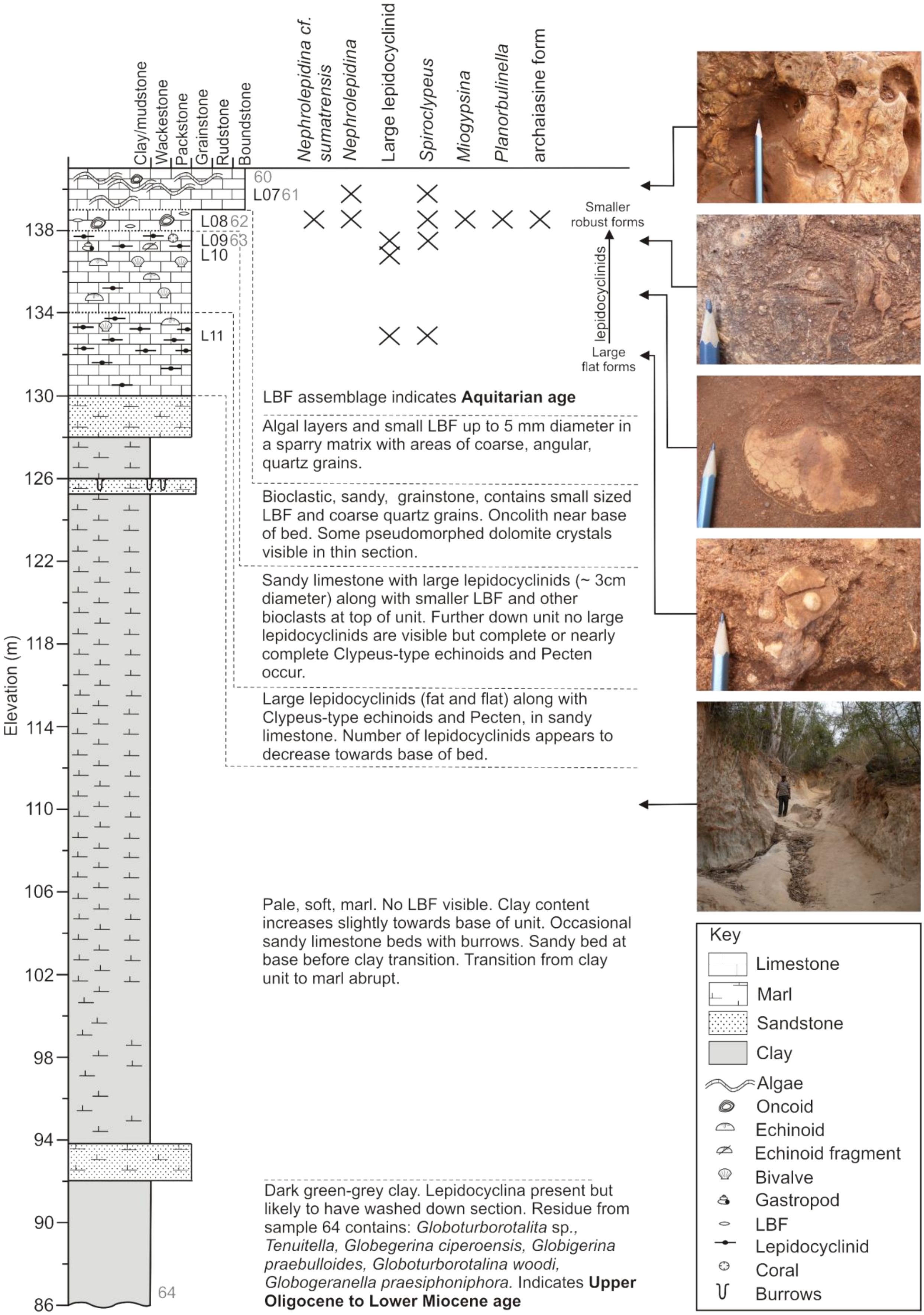


Figure 3.24. Map of the south Lindi and Sudi Bay areas, showing sample localities.



LBF assemblage indicates **Aquitarian age**

Algal layers and small LBF up to 5 mm diameter in a sparry matrix with areas of coarse, angular, quartz grains.

Bioclastic, sandy, grainstone, contains small sized LBF and coarse quartz grains. Oncolith near base of bed. Some pseudomorphed dolomite crystals visible in thin section.

Sandy limestone with large lepidocyclinids (~ 3cm diameter) along with smaller LBF and other bioclasts at top of unit. Further down unit no large lepidocyclinids are visible but complete or nearly complete Clypeus-type echinoids and Pecten occur.

Large lepidocyclinids (fat and flat) along with Clypeus-type echinoids and Pecten, in sandy limestone. Number of lepidocyclinids appears to decrease towards base of bed.

Pale, soft, marl. No LBF visible. Clay content increases slightly towards base of unit. Occasional sandy limestone beds with burrows. Sandy bed at base before clay transition. Transition from clay unit to marl abrupt.

Dark green-grey clay. Lepidocyclina present but likely to have washed down section. Residue from sample 64 contains: *Globoturborotalita* sp., *Tenuitella, Globegerina ciperoensis, Globigerina praebulloides, Globoturborotalina woodi, Globogeranella praesiphoniphora.* Indicates **Upper Oligocene to Lower Miocene age**

Figure 3.25. Log of Kitunda section showing occurrences of LBF and images of beds.

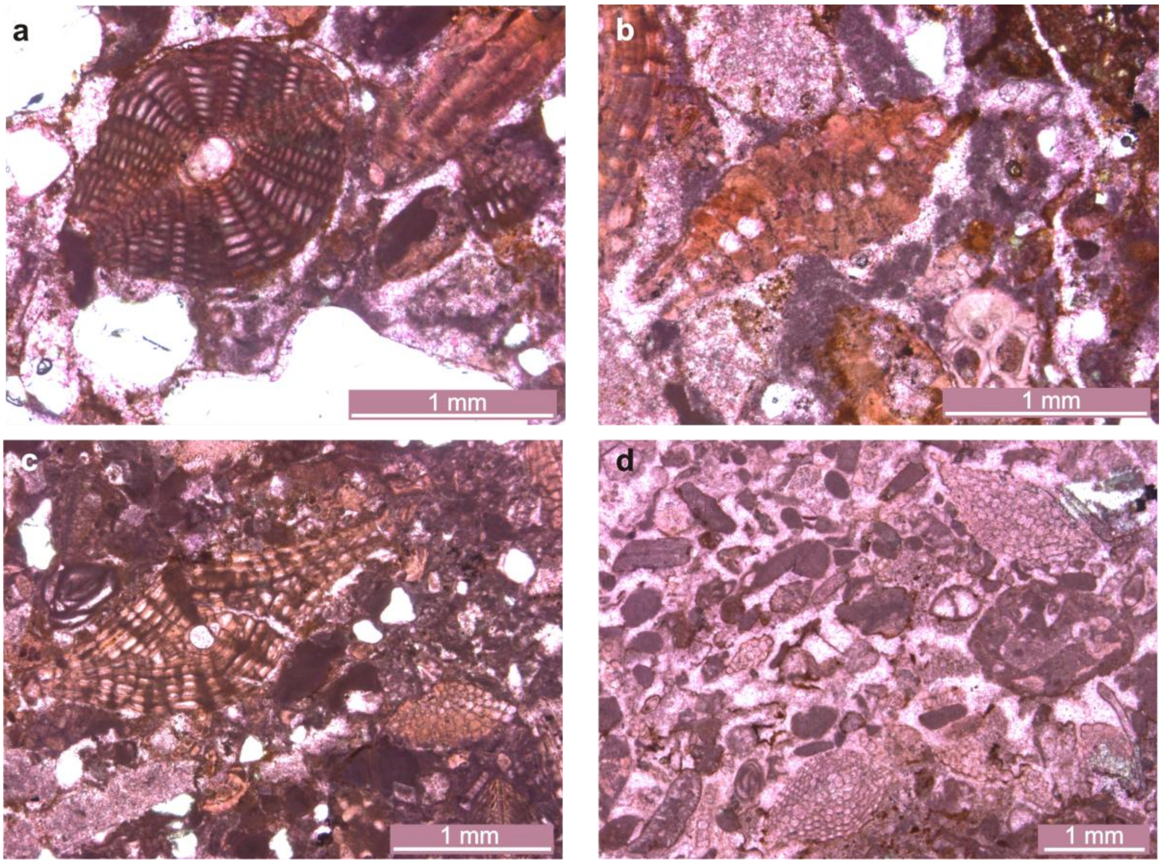


Figure 3.26. a-c) thin section images from Kitunda limestones, sample 62: a) *Nephrolepidina* cf *sumatrensis* b) *Planorbulina* c) *Spiroclypeus*; d) Pack-grainstone with *Miogypsina* from outcrop near Naminda (sample 137).

The log suggests shallowing upwards through the section, from a deeper environment where clay is deposited, to shallower with carbonate deposition but few fossils and then photic zone carbonates with a large number of LBF fossils. A trend can also be seen upwards through the LBF limestones at the top of the section from large flatter lepidocyclinids to small, rounded robust *Nephrolepidina* towards the top suggesting further shallowing from outer to middle platform.

A similar section is seen to the south east at Navanja, also within the Kitunda Plateau. Here 64 m of section consisted of silty clays barren of foraminifera (sample 73), calcareous sandstones and LBF packstones with coarse quartz and large lepidocyclinids similar in morphology to those in the Kitunda section. Further inland, near Naminda LBF rich pack- grainstones are seen near the road (sample 137 and 138) which contain *Miogypsina*, lepidocyclinids, A*mphistegina* and ?*Borelis* along with algae, large coral fragments, miliolids, mollusc and echinoid shell fragments and also indicate a Miocene age (Figure 3.26d).

These outcrops and sections indicate it is likely that the whole of the Kitunda Plateau consists of Miocene limestones extending to the Mambu river to the south and inland as far as Lake Kitere.

3.4.2.3.2 Lake Kitere

Further south and inland near Lake Kitere (see Figure 3.24) there was a 20 m long roadcut of lepidocyclinid limestone, composed of mostly large flattened B form lepidocyclinids in a sandy packstone (Figure 3.27). They are similar to those found at Ras Tipuli and Mbuyuni and so probably of similar age.

3.4.2.3.4 Ntegu

Ntegu is inland from Sudi Bay on the Kitunda Plateau (see Figure 3.24) A running log was constructed along the roadside near Ntegu from 74m to 118 m asl. Approximately 3 m of powdery white marl outcropped in the roadside at Ntegu which contained small (< 5 mm) hydrobiid or rissoid gastropods (Figure 3.27). These gastropods are known to inhabit brackish to freshwater environments. Overlying this at 102 m is a sandy carbonate which contained a very large gastropod (20 cm), worm tubes and bivalve shells, above this was a coarse sandy limestone which contained visible LBF. Further along the road at 118 m a cream calcareous sandstone cropped out, with no visible LBF. At 124 m there is a grey, powdery, sandy limestone containing poorly sorted angular quartz grains. Sample 98 from this outcrop contains miogypsinids, lepidocyclinds and a large soritid giving a probable Miocene age. Capping the section is a cream coralline limestone which seems to form the surface of the plateau. Very similar outcrops were also found close to Pangaboi, which is located approximately half way between the Ntegu road section and Navanja.

This series of outcrops represents a transgressive sequence from freshwater-brackish conditions through very sandy nearshore carbonates and LBF rich inner platform/lagoonal pack-grainstones to finally a reefal limestone.

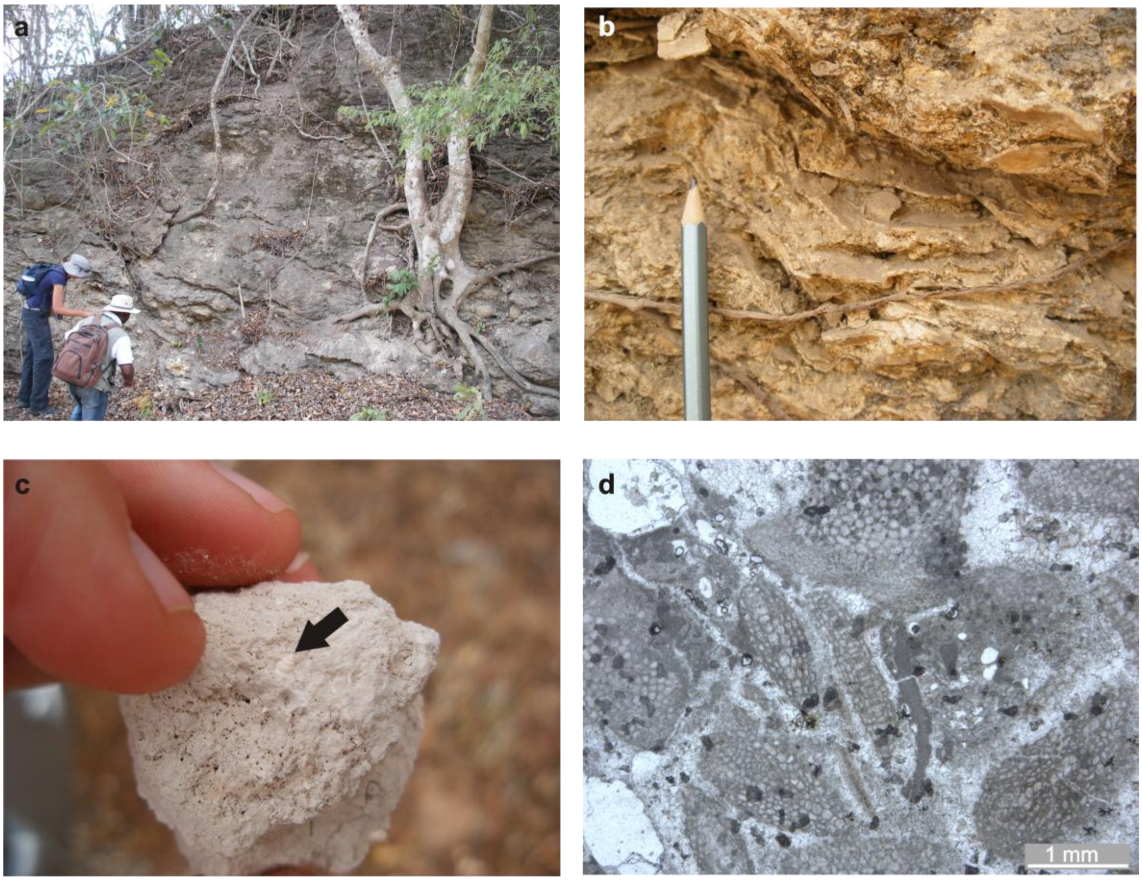


Fig. 3.27. a) Outcrop at Lake Kitere; b) close up showing large lepidocyclinids, pencil for scale; Ntegu images: c) gastropod in ?tufa; d) image of thin section of sample 98 showing

3.4.3 Field samples discussion

An overview of LBF genera present and ages of all localities described is shown in Figure 3.28. The Eocene LBF rich sediments are deposited in a variety of settings: debris flows within hemi-pelagic clays, in-situ carbonate platform and patch reef/reef knoll deposits (Figure 3.29). The depositional environment of Pande quarry remains uncertain but either gully infill or isolated platform are likely. This variety of sedimentation provides a good overview of the LBF present in different environments on the carbonate platform, and the sedimentary processes taking place. The debris flow deposits and reef knolls indicate the platform is nearby to the west. However, in-situ platform deposits (including those of the inner platform) are found on the Kiswere peninsula. The Kiswere peninsula appears to be a faulted block moved eastwards, with the two bays bounding it marking the position of two faults. This also explains why in-situ Eocene platform deposits are not found elsewhere.

The section at Kiswere is a new and important discovery. The section spans the Lutetian to Upper Oligocene. The Lutetian to Priabonian appears to be a continuous or

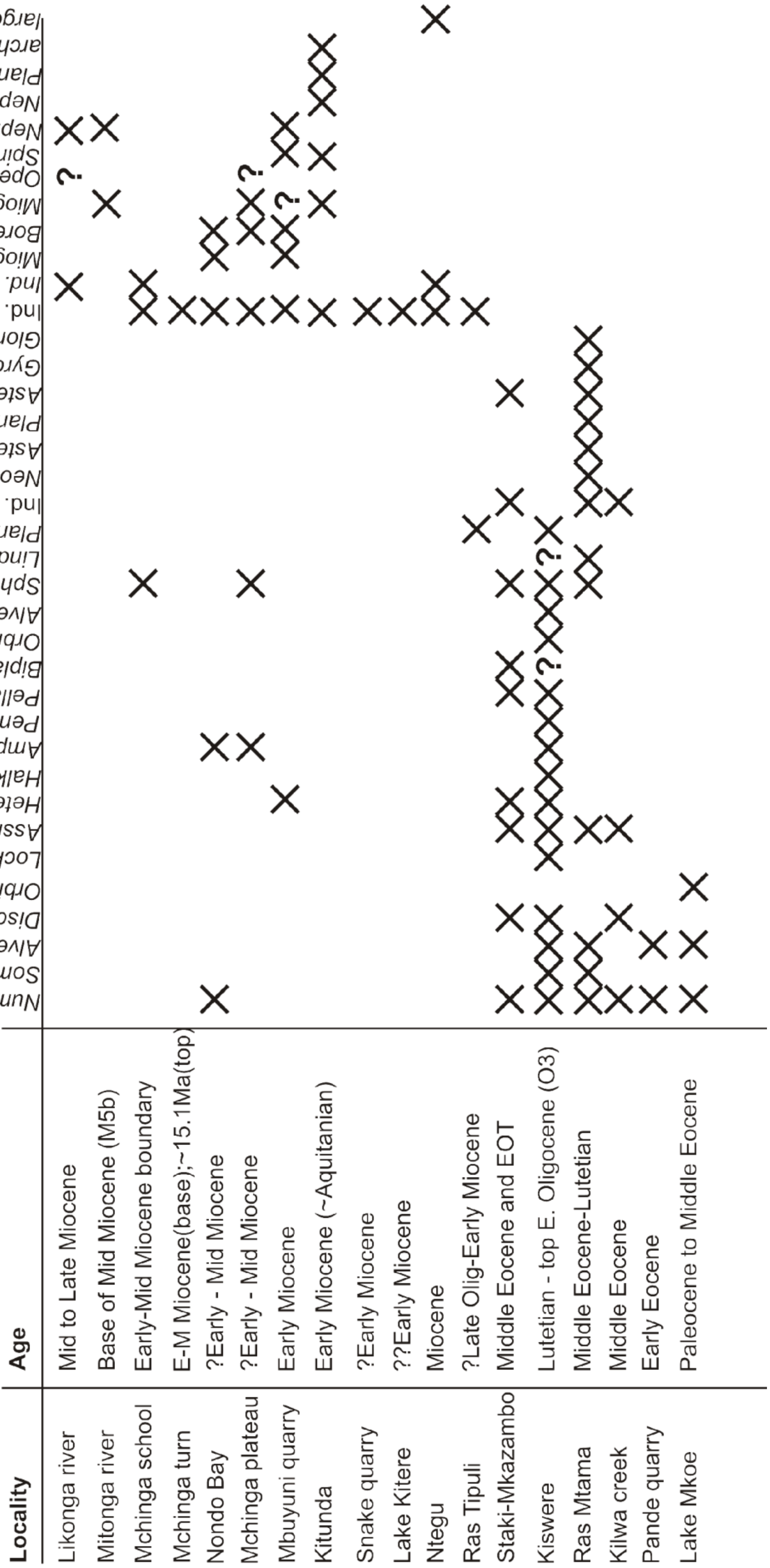


Figure 3.28. Summary diagram showing occurrences of LBF genera and ages determined at all localities.

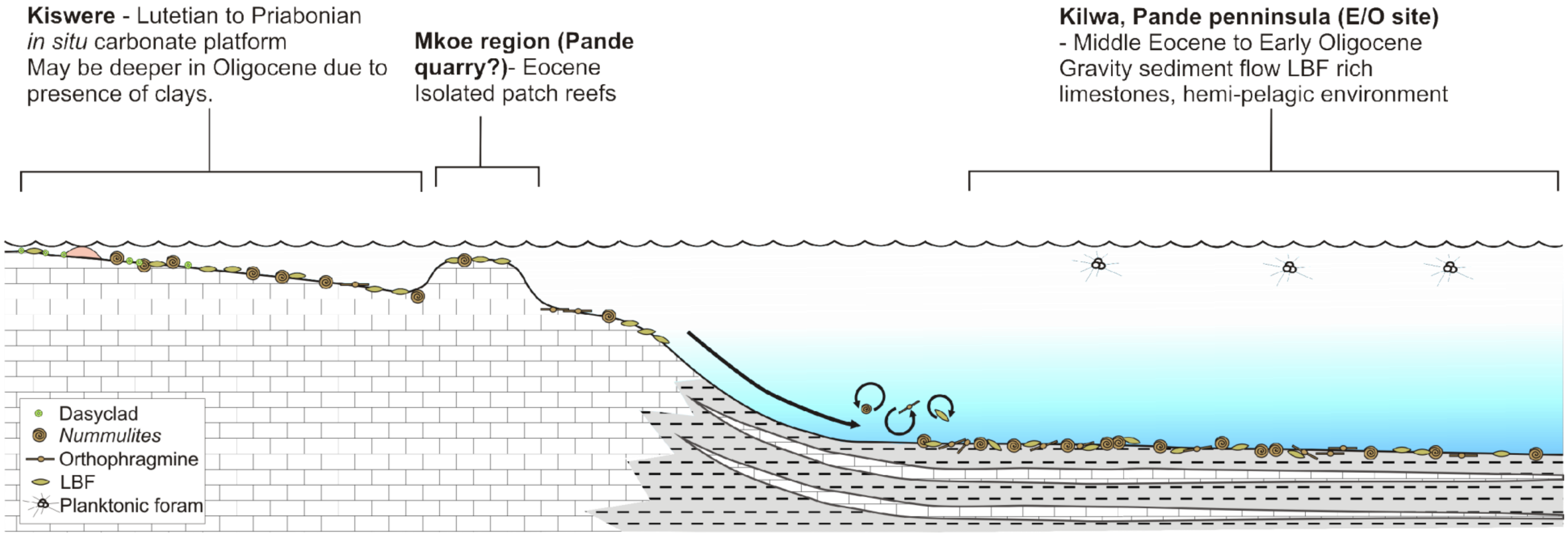


Fig.ure 3.29. Schematic diagram showing the Eocene depositional environments.

near continuous limestone succession. It should therefore include the end middle Eocene extinction event of LBF, which is missing from the TDP succession. The section also includes a boundary between the Priabonian and Oligocene although it is not known if it is conformable or not. This site has high potential for future investigation and also as a potential drilling site.

The Oligo-Miocene outcrops consist of a large number of small sections and rubbly outcrops over a wide geographic area. The majority of the limestones appear to have been formed on the carbonate platform. The laterally discontinuous nature of LBF biofacies and extensive faulting known to occur in the region (Nicholas et al., 2006; 2007, O'Sullivan, 2012) make it difficult to correlate between sections. However, some general observations can be made.

The samples from the Mchinga Plateau all indicate ages from the Early/Middle Miocene boundary to the Middle Miocene. Though the individual outcrops are difficult to correlate between, they indicate this interval is composed of a series of clays, large flattened lepidocyclinid packstones and smaller sized LBF packstones or pack-grainstones which contain mostly lepidocyclinids (*Nephrolepidina*) and miogypsinids, all capped by a reefal limestone also containing lepidocyclinids and miogypisinids which forms the surface of the plateau. The Mbuyuni quarry outcrop is considered to be older than the other Mchinga Plateau localities due to its location, eastward dip of the beds and presence of *Spiroclypeus*, it is of probable Early Miocene age. Further south in the region north of Lindi at Mitonga and Likonga a similar sequence of LBF and coralline limestones and clays is seen, but here it continues into the Upper Miocene. The limestones at these localities generally appear to have been formed on the plateau and not been transported. The variation between large lepidocyclinid limestones, clays and smaller LBF/coralline limestones is therefore explained by relative sea-level changes due to fault movement, which is known to have occurred during the Miocene in this region (O'Sullivan, 2012).

To the south of Lindi the Kitunda shore section is Early Miocene, with the basal clay potentially being Upper Oligocene to Early Miocene. The sedimentation here is less variable than seen at Mchinga, Likonga and Mitonga. The Kitunda plateau appears to have undergone a consistent gradual shallowing during the Early Miocene.

The Kitunda shore section is therefore either older than the faulting, but of a similar age to Mbuyuni quarry which shows the repeated changes in facies, or it did not occur in the

Kitunda plateau region at this time. This may be related to the large Lukeledi fault which passes through Lindi bay separating these two regions.

At a generic level the Eocene Tanzanian LBF assemblage is similar to that of both the Tethys and Indo-Pacific, with *Alveolina*, *Nummulites* (particularly reticulate *Nummulites* in the mid to late Eocene) and orthophragminids dominating the assemblage. The Tethys and Indo-Pacific at this time only have a limited difference in LBF (Renema 2007) and so similarity to both regions would be expected. The Tanzanian assemblage additionally includes an abundance of *Somalina* in the inner platform environment. *Somalina* is only known from the Middle East (including Oman, Iran, Iraq, Turkey), East Africa (including Egypt, Somalia, Tanzania) and has more recently been found in Greece (Loeblich and Tappan, 1987; White, 1997; BouDagher-Fadel, 2008; Di Carlo et al., 2010), suggesting Tanzania is part of an intermediate or West Pacific-type fauna. *Pellatispira* appears to only occur in the Priabonian, possibly only in the upper part (close to the stratigraphic EOB) and not in the middle Eocene as seen elsewhere (Romero et al., 1999). *Pellatispira* cf. *madaraszi* shows more similarity to the *P. madaraszi* form common in Europe, than the more globular pellatispirids of Indo-Malaysia (Hottinger et al., 2001). The uppermost Eocene LBF are discussed and compared in more detail within Chapter 4.

The Miocene assemblage is typical of that period, with abundant lepidocyclinids and miogypsinids (Renema, 2007). The Tanzanian lepidocyclinids consist of mostly *Nephrolepidina* and large B forms which cannot be attributed to a genus. *Eulepidina* is present but far less frequently observed than *Nephrolepidina*. B form lepidocyclinids appear to be more common in the Early Miocene (or Late Oligocene to Early Miocene in the case of Ras Tipuli), forming large beds where they are the dominant component. Lepidocyclinids first occurred in the Americas during the Eocene and migrated to the Tethys, with a first occurrence in the late Rupelian, followed by the Indo-Pacific, with a first occurrence in the Early Miocene (Renema, 2007; Boudagher-Fadel and Price, 2010). The Tanzanian lepidocyclinids definitely occur in the Early Miocene which corresponds to the first occurrences seen in the Indonesia/Malaysia (Renema, 2007; Boudagher-Fadel and Price, 2010). It is possible that the blocks at Ras Tipuli may be Upper Oligocene, which would mean an earlier first occurrence of lepidocyclinids more similar to the Tethys, but this is uncertain. *Nephrolepidina* is abundant in the Early to Middle Miocene of the Indo-Pacific region (Renema, 2007). *Nephrolepidina sumatrensis* is a rounded robust form, abundant in the Indo-Pacific and listed as a diagnostic form to recognise stages Te_5 and Tf (Early and Middle Miocene) of Indonesia (Adams, 1970; Adams, 1965). A very similar rounded *Nephrolepidina*, with no pillars and stacks of lateral chamberlets which is typical for *N. sumatrensis* (W. Renema pers. comm.), is seen in the Kitunda section, suggesting at least some affinity with the Indo-Pacific species. Lepidocyclinids have a last occurrence in the Tethys within the Middle Miocene. In the Indo-Pacific the *Tribliolepidina* lineage continues to occur until the end of the late Miocene (Renema, 2007; Boudagher-Fadel and Price, 2010). The only definite upper Miocene sequence occurs at Likonga, in which *Nephrolepidina* was found. The sequence here does not appear to be reworked, indicating that *Nephrolepidina* continue into the Upper Miocene in East Africa, as they do in Indonesia. However, more specimens are needed to confirm this.

Miogypsina is found in both Early and Middle Miocene outcrops, but appears to be more common within the Middle Miocene. The reefal limestone at Mitonga contains a particular abundance. *Miogypsina* are also present within the Upper Miocene of Likonga. Within the Indo-Pacific, Miogypsina is known from the beginning of the Early Miocene to the very earliest Upper Miocene (Renema, 2007). Tanzanian occurrences are within this range. *Miogypsinoides* is far less common, with only a single definite occurrence within the Middle Miocene, which is within the global range for this genus (Cahuzac and Poignant, 1997; Renema, 2007).

Spiroclypeus is abundant within the Early Miocene sediments at Mbuyuni and Kitunda, but has not been seen in any younger deposits. Within the Indo-Pacific *Spiroclypeus* occurs until the end of Te5 (Early Miocene) (Adams, 1970, Boudagher-Fadel and Banner, 1999; Renema, 2007). Whilst in the Tethys it occurs until the Oligocene/Miocene boundary (Cahuzac and Poignant, 1997). The Tanzanian occurrence of *Spiroclypeus* therefore appears similar to that in Indo-Pacific.

Planostegina is found within several thin sections in the Paleogene of Kiswere, however is only seen in abundance at Ras Tipuli. The age of this locality is uncertain, but thought to be late Oligocene to Early Miocene. *Planostegina* has a range from Paleocene to Holocene (BouDagher-Fadel, 2008). It is common within the Tethys, but also known from the Indo-Pacific where it is typical of Tc-Td (Lower Oligocene) assemblages of Java and Borneo (Banner and Hodgekinson, 1991; Renema, 2007).

Notably *Cycloclypeus* has not been found in the assemblage. *Cycloclypeus* is common in upper Oligocene and Miocene assemblages in both the Tethyan and Indo-Pacific regions (Renema, 2007). However, no specimens of this genus have been found in the Tanzanian samples to date, indicating that they may not be present or are extremely rare in this region. They are not confirmed from any other localities in East Africa (Renema pers. comm.). It has been suggested that Tethyan and Indo-West Pacific *Cycloclypeus* may have evolved as separate lineages (MacGillavry, 1962, O'Herne, 1972, Renema, 2007). If neither lineage then migrated far from its origin this could perhaps account for their apparent absence in Tanzania.

3.5 Conclusion

This study gives an insight into the range and distribution of LBF genera present in a previously little-studied region. The penecontemporaneous redeposition of the LBF into the hemipelagic environment during the Eocene and Oligocene enables LBF ranges to be tied to global nannofossil and planktonic foraminiferal biostratigraphy. The TDP succession shows a similar overall Eocene assemblage to that found in field samples. However, the wider distribution of field samples enabled local variations and abundances to be determined, and revealed a variety of depositional environments, including in-situ shelf deposits not previously recorded. The combination of drill cores from the TDP and outcrop sampling therefore provides a good overview of the LBF of the Paleogene of Tanzania. The Kiswere site is also a very important new discovery and has high potential for more detailed future study.

The TDP cores studied do not span the Miocene but fluctuating relative sea during this period means many sequences contain clay levels which were used for independent dating of the LBF. Within this study a large number of Miocene LBF localities and occurrences have been documented accurately for the first time, and analysis of genera present and facies has been carried out.

Initial comparisons with Tethyan and Indo-Pacific faunas have been carried out, showing perhaps an intermediate assemblage in the Eocene and some similarities with the Indo-Pacific in the Miocene. Although, much more detailed work with species level identifications is needed to look at migration events and accurate comparisons, this study provides a solid basis for such further work to be carried out. With further work, there is therefore a high potential for using the TDP data along with outcrop data to help improve global LBF stratigraphy and provide links between LBF and climatic events. The EOT is explored in detail using the TDP sites in chapter 4.

Chapter 4:

Extinction of Larger Benthic Foraminifera at the Eocene / Oligocene boundary.

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4.1 Introduction

The Eocene - Oligocene transition (EOT) was a time of profound climatic and oceanographic change associated with the first major continental-scale glaciation of Antarctica (see Coxall and Pearson, 2007, for review). This environmental disruption led to a global peak in biotic turnover, seen in both terrestrial and marine records and in shallow-water and deep-sea environments. This complex series of events occurred over an extended period between about 33.5 Ma and 34.0 Ma. The Eocene / Oligocene boundary (EOB) itself is located at the extinction of the planktonic foraminiferal Family Hantkeninidae at 33.7 Ma on the timescale of Cande and Kent (1995; also see Berggren et al., 1995; Wade et al., 2011). The boundary significantly pre-dates, by about 200 kyr, the largest shift in global oxygen isotope curves which is interpreted as representing the most rapid phase of ice expansion in Antarctica and hence sea-level fall (Zachos et al., 1996; Coxall and Pearson, 2007; Lear et al., 2008). The period of most positive oxygen isotope values following this shift is referred to as the Early Oligocene Glacial Maximum (EOGM; Liu et al., 2004; Coxall and Pearson, 2007). This period coincides with the base of an isotope stage referred to as the Oi-1 isotope zone (Miller et al., 1991). The most detailed study of extinctions within the larger benthic foraminifera (LBF) through the EOT was carried out by Adams et al. (1986). Those authors suggested that these global environmental changes, in particular the sea-level fall, could have caused a rapid mass extinction within the LBF including the disappearance of long ranging and widespread Families such as the Discocyclinidae and Orbitoclypeidae (collectively referred to as the orthophragmines), Pellatispiridae, and a number of species in the Nummulitidae.

Thick Cenozoic limestones containing LBF are common within the Indo-Pacific region (e.g. Adams, 1965, 1970; Adams et al., 1986; Renema, 2002; Wilson, 2002; Renema, 2007). However, because global sea level decreased during the EOT, many sections are incomplete, with hiatuses or unconformities in the transition interval. The most complete sections reported from the Indo-Pacific region are thought to be the Melinau limestone of Sarawak (Adams, 1965, 1970; Adams et al., 1986), the Amravati Formation of Cambay, India (Mukhopadhyay, 2003) and in the Fulra formation of Kutch, India (Sarangi et al., 1998, 2001; Sarkar et al., 2003a, 2003b). However, lack of dating evidence independent of the LBF ranges, along with species endemism, makes global correlation problematic and the exact timing of LBF extinctions difficult to determine.

The Kilwa District of south Tanzania contains an excellent and apparently complete succession through the EOT that has recently been studied in outcrop section and three boreholes drilled by the Tanzania Drilling Project (TDP; Pearson et al., 2004, 2006; Nicholas et al., 2006, 2007; Pearson et al., 2008; Bown et al., 2008; Dunkley Jones et al., 2008a, 2008b; Lear et al., 2008; Wade and Pearson, 2008; Pearson et al., 2009). The dominant lithology is hemipelagic clay with limestone beds rich in LBF (Nicholas et al., 2006, 2007). The stratigraphy of this succession has been established using extensive planktonic foraminiferal, nannofossil and isotope studies of the clays (Pearson et al., 2008; Dunkley Jones et al., 2008a, 2008b; Lear et al., 2008; Wade and Pearson, 2008).

A preliminary study of the LBF within the clay residues was carried out by Pearson et al. (2008). Extinctions of several genera such as *Discocylina*, *Asterocyclina*, *Pellatispira* and *Spiroclypeus*, were found to approximately coincide with the extinction of the planktonic foraminiferal Family Hantkeninidae which marks the EOB in the type section at Massignano, Italy (Coccioni, 1988; Coccioni et al., 1988). Here we carry out a more detailed study of the palaeontology and sedimentology utilising petrological thin sections and oriented thin sections of LBF specimens from both clay and limestone samples. The succession provides an excellent opportunity to examine the precise timing of the LBF extinctions in relation to climatic events and global isotope and biostratigraphy providing a tie point for global LBF stratigraphy.

4.2 Biostratigraphic framework for larger benthic foraminifera

There are currently two main biostratigraphic schemes for Paleogene LBF: i) the Shallow Benthic Zonation which is applied principally to the Tethys and ii) the East Indian Letter Classification used in the Indo-Pacific region, primarily Indonesia (see below for references). Neither scheme is directly applicable to Tanzania but both contain key elements that are relevant to the Tanzanian record and identify fauna that go extinct during the critical EOT interval.

Cenozoic Tethyan LBF biostratigraphy was revised by Cahuzac and Poignant (1997) and Serra-Kiel et al. (1998). The Paleocene to Eocene was divided into 20 shallow benthic zones (SBZs; Serra-Kiel et al., 1998) and the Oligocene to Late Miocene into 5 SBZs (Cahuzac and Poignant, 1997). In the Tethyan region the boundary between SBZs 20 and 21 correlates with the broad EOT interval and is defined by the last occurrence of the orthophragmines, and various species of *Heterostegina* and *Nummulites* including *N. fabianii* and the first occurrence of *N. vascus* and *N. fichteli* (Cahuzac and Poignant, 1997; Serra-Kiel et al., 1998). The precise correlation of the SBZ 20/21 boundary to the EOB and the EOGM remains ambiguous.

The Indo-Pacific region contains several important carbonate successions which have been the subject of considerable stratigraphic investigation and work is ongoing (Adams, 1970; Adams et al., 1986; Boudagher-Fadel and Banner, 1999; Renema, 2002; Renema et al., 2003; Sharaf et al., 2006; Renema, 2007). The correlation of these sections has long been problematic (see Renema, 2002; McGowran, 2005; Renema, 2007 for overviews). Problems arise largely due to a lack of species in common with the Tethyan region and many of the Indo-Pacific carbonates contain very few planktonic foraminifera (Renema, 2007).

The East Indian Letter Classification consists of zones or stages defined by assemblages of LBF. Several revisions in the number and ranges of the stages have taken place since their origins in the 1920s (e.g. van der Vlerk and Umbgrove, 1927; van der Vlerk, 1955). Within the East Indian Letter Classification the EOT corresponds to the boundary between Stages Tb and Tc and is largely defined by the last occurrence of *Pellatispira* and first occurrence of *Nummulites fichteli* (Adams, 1970; Renema 2007). This species is the same as is used in the Tethyan zonation (see above), however the closely related Priabonian species *N. fabianii*, which is common in the Tethyan region, is not found anywhere east of India (Renema et al., 2003). Because of this, and the fact that boundary is not tied to global plankton biostratigraphy nor the global isotope curve it is uncertain how the Tb-Tc transition relates to the SBZ 20 / 21 boundary and the globally defined EOB and transition.

If the LBF extinctions can be accurately correlated to global isotope stratigraphy, they could provide a clear tie-point between the two schemes for further work on their correlation. The Tanzanian site, which clearly shows the extinction and is correlated well with global stratigraphy, is therefore important in linking the zonal schemes of the Tethys and Indo-Pacific both to each other and to global plankton and isotope stratigraphy.

4.3 Materials and methods

Marine sediments of Aptian to Oligocene age crop out along a broad coastal belt in Tanzania south of the Rufiji River, from the Kilwa Peninsula to Lindi Creek (Nicholas et al., 2006; Figure 4.1). These sediments are formally defined as the Kilwa group and are split into four formations: the Nangurukuru, Kivinje, Masoko and Pande formations (Nicholas et al., 2006). The Pande formation spans the Upper Eocene to Lower Oligocene and contains an apparently conformable sequence through the EOB.

Three TDP sites (TDP 11, 12 and 17) were drilled in 2004 and 2005 in the Pande formation to recover the EOB sediments (Nicholas et al., 2006; Pearson et al., 2008). These three sites were positioned approximately along strike within 3 km of each other (TDP 17 – UTM 37L; 560539 8984483; TDP 11 – UTM 37L; 560250 8983211; TDP 12 – UTM 37L; 560222 8981309; Nicholas et al., 2006; see Figure 4.1). The drill sites are estimated to be approximately 50 km from the palaeo-shoreline, distal of a narrow shelf (Kent et al., 1971; Nicholas et al., 2006, 2007). The sedimentary facies and smaller benthic foraminiferal biofacies and suggest that the sediment was deposited in a bathyal outer shelf to slope setting, at ~300-500 m water depth (Nicholas et al., 2006, 2007) although maximum depths are difficult to determine and it is possible the palaeoenvironment was deeper than this. The sediment is primarily a succession of dark greenish grey clays with <10% $CaCO_3$ (Nicholas et al., 2006). The clays contain exceptionally well-preserved calcareous microfossils (Pearson et al., 2008; Bown et al., 2008; Wade and Pearson, 2008). Limestone beds, deposited allochthonously with the clays, are present throughout the succession and are rich in LBF. In addition to the boreholes, the EOT succession is also intermittently exposed on a hillside close to the TDP 12 drill site (UTM 37L; 560034, 8981434; see Figure 4.1, 4.2). Limestones of the

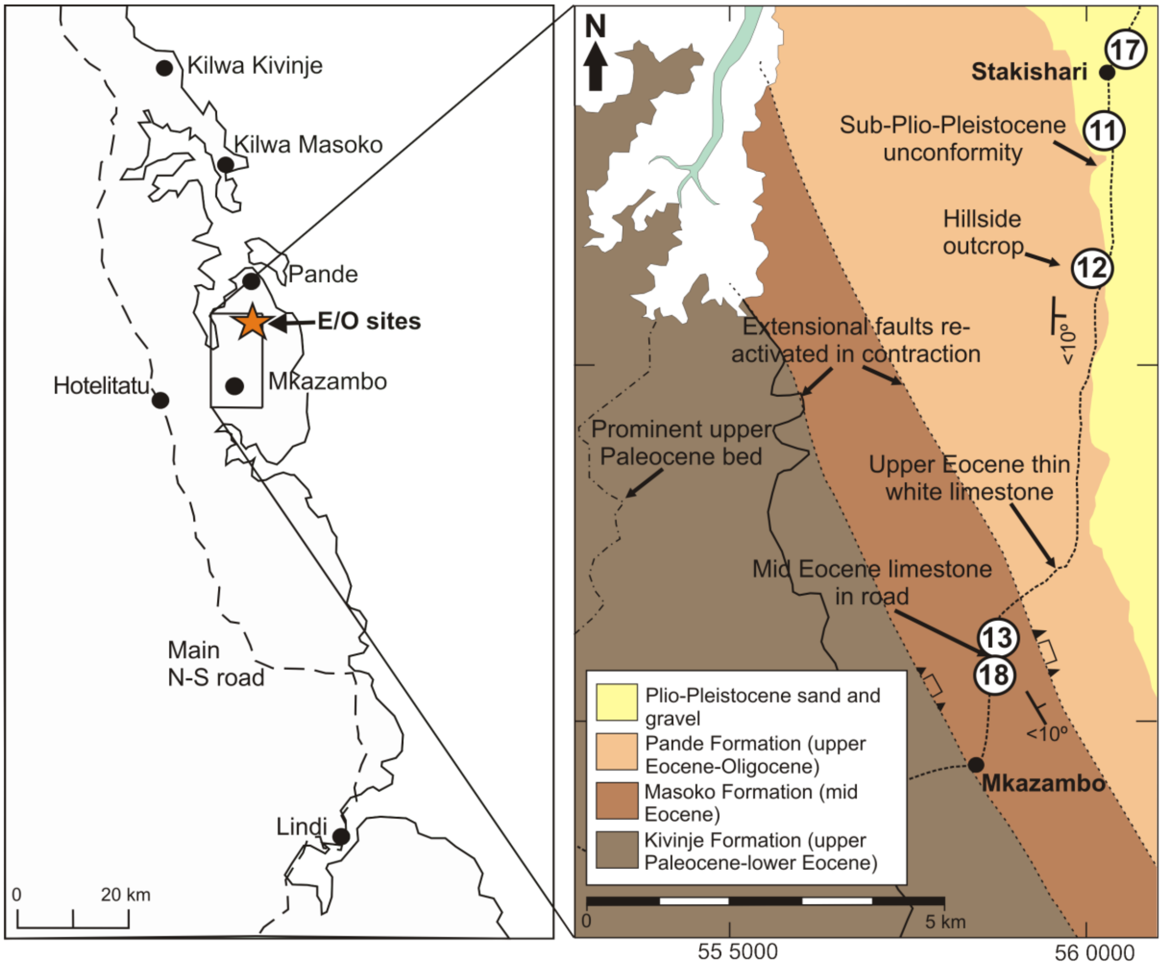

Figure 4.1 . Location and geological maps of the Tanzanian Drilling Project Eocene / Oligocene boundary sites (TDP 11, 12 and 17), additional Tanzanian Drilling Project sites in the area are also shown. Modified from Nicholas et al. (2006).

upper Eocene and lower Oligocene at this site were collected and were correlated to the limestone beds in TDP 12 using the LBF assemblages present and plankton biostratigraphy from the surrounding clays.

For the hemipelagic clays, half-round samples approximately 10 cm in length were washed though a 63 μm sieve and the residues dried (Pearson et al., 2008; Lear et al., 2008; Wade and Pearson, 2008). Oriented sections of the LBF were made for identification. A combination of randomly orientated petrological thin sections, acetate peels (prepared according to Dickson, 1965, 1966) and oriented individual LBF thin sections were used in the study of limestones. The limestones are well cemented, hence free LBF specimens are rare; therefore most LBF in the limestones have been identified to generic level only using petrological thin sections. Identification to species level is by comparison of sections with the orientated sections of clay specimens, from rare free specimens or equatorial sections occurring within the petrological sections.

Figure 4. 2. The Eocene / Oligocene boundary in outcrop. a) Hillside exposure close to TDP 12, the lower arrow indicates the highest *in situ* Type 1 “Eocene” bed, the upper arrow indicates the lowest *in situ* Type II “Oligocene” bed; b) astrocoeniid coral weathered out of the Type II beds; c) *Nummulites*-rich Type I limestone.

4.5 Correlation and isotopes

The EOB is formally defined at the Global Stratotype Section and Point (GSSP) at Massignano, Italy at a level corresponding to the extinction of the planktonic foraminiferal Family Hantkeninidae (Coccioni, 1988; Premoli Silva and Jenkins, 1993). This occurs slightly above (~60 kyrs) another planktonic extinction, that of the *Turborotalia cerroazulensis* group of species. In Tanzania five hantkeninid morphospecies are present (Wade and Pearson, 2008). The extinction level was originally placed at approximately 102.7 meters composite depth (mcd; Wade and Pearson, 2008), but by re-sampling at higher resolution we have constrained the extinction level to be between 102.28 and 102.22 mcd, with all five species disappearing in an interval of less than 10 cm. The *Turborotalia cerroazulensis* group disappears ~5.6 m below this (Wade and Pearson, 2008). The clear gap between these events suggests good stratigraphic completeness through this critical interval.

A stable isotope stratigraphy was constructed from overlapping intervals of TDP 12 and 17 using shells of the mixed layer planktonic foraminifera *Turborotalia* *ampliapertura* by Pearson et al. (2008). The oxygen and carbon records are both similar to deep-sea sites and have been used to correlate the succession to the global isotope curve. The oxygen isotopes show two main steps that lead to the most positive values of the EOGM. The Hantkeninidae extinction occurs in the plateau between the two steps, i.e. preceding the maximum oxygen isotope shift (Pearson et al., 2008; Wade and Pearson, 2008). The age model was generated using a combination of biostratigraphic and geochemical tie-points from the clays. The correlation of the clays ties the LBF extinction events across the boundary to global stratigraphy, which has not been possible at other sites in the Indo-Pacific region.

4.6 Results

4.6.1 Sedimentology

A microfacies study of the gravity sediment flow beds in the three cores reveals that there are two distinct lithologies, which we refer to as Type I and Type II beds (Figure 4.3). Type I beds are 0.1-1.5 m thick and are present in TDP 11 and 12, but not in TDP 17. Their absence in TDP 17 may be due to palaeobathymetry; if the area was a slight topographic high then the sediment gravity flows might not be deposited there. The Type I beds are found exclusively within the top 25m (124.88 to 103.16 mcd) of the Eocene part of the succession, plus one thin bed ~2 m above the EOB. The Type II beds are found higher in the Oligocene part of the succession, between 62.96 to 20.76 mcd.

Type I beds are coarse bioclast- and quartz-rich packstones (see Figure 4.3a). The grains are composed of approximately 35% coarse angular, quartz grains (up to ~1.5 mm in size, though most 0.5-1 mm) with 65% bioclasts and occasional peloids. The matrix is partly micritic and partly sparry calcite or ferroan calcite cement.

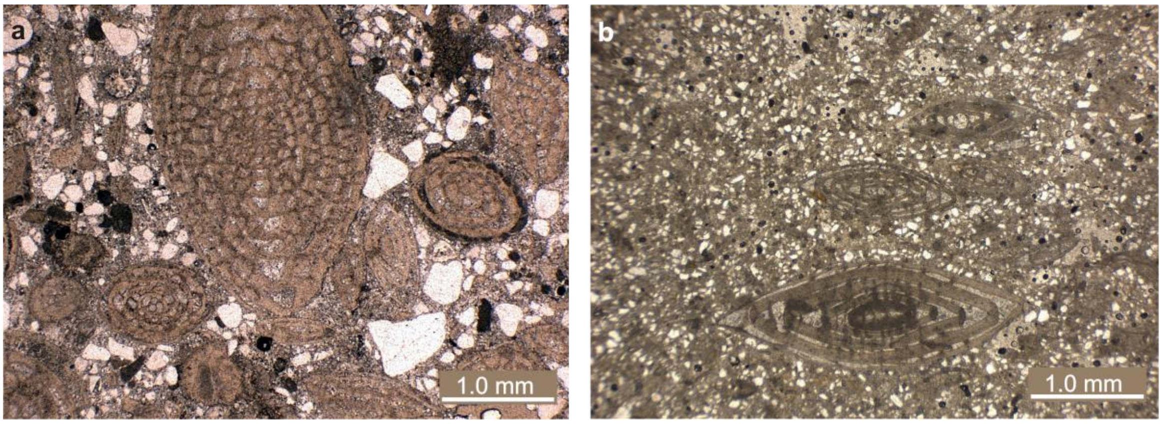

Figure 4.3. a) Typical thin section view of Type I lithology, with large numbers of LBFs and coarse quartz grains; b) Typical thin section view of Type II lithology, with rare LBFs (radiate *Nummulites*) and finer quartz rich matrix.

Bioclasts are mostly LBF tests, but also present are echinoid test and spine fragments, coral and red algae fragments along with smaller benthic foraminifera (including miliolids). The *Nummulites* and other LBF are heavily abraded, with the test periphery broken in most cases and the outer whorl frequently broken or, in some cases, completely removed. When compared with the scale of abrasive damage of Beavington-Penney (2004), the level of abrasion indicates they have undergone extensive transport or transport within turbidity currents. The packstone contains several compaction features, indicating that the material was re-deposited as loose sediment. The LBF are orientated approximately horizontally due to compaction prior to cementation. Thin disk-shaped LBF show brittle fracturing due to compression against harder quartz grains. No cemented lithoclasts were seen in any of the samples, although clay rip-up clasts are present. Some beds fine upwards.

The Type II beds are yellowish calcareous sandstones containing occasional LBF (Figure 4.3b). The calcareous sandstones contain a high percentage of medium sand-sized quartz grains, with a calcite cement and, in some samples, a clay-rich matrix. The bioclasts are far fewer, lower diversity and smaller sized than the Type I packstones, with the exception of on the hillside outcrop close to TDP12 where large astrocoeniid corals were found weathered out (see Figure 4.2b). The change in lithology from LBF rich pack-grainstones to calcareous sandstones may indicate a decrease in sea level. The increase in quartz content suggests a closer shoreline and decrease in skeletal carbonate material suggests at least a partial shut-down of shallow-water carbonate production in the Early Oligocene, although reasons for the decrease in quartz grain size remain uncertain. This interpretation is consistent with the observation that the highest Type I bed occurs in the lowermost Oligocene in the interval before the inferred major sea-level fall associated with the main isotope shift.

4.6.2 Palaeontology

The clay residue samples contain mostly small LBF specimens (most <2 mm but up to ~1 cm). Preservation is good, with exceptionally well-preserved tests present in some levels: In occasional samples with a high amount of pyrite, foraminifera are only present as pyrite moulds or are highly dissolved, possibly related to sea-floor anoxia. The LBF are found in low concentrations throughout the length of the succession, occurring within wisps of shallow carbonate material in the clays which also contain

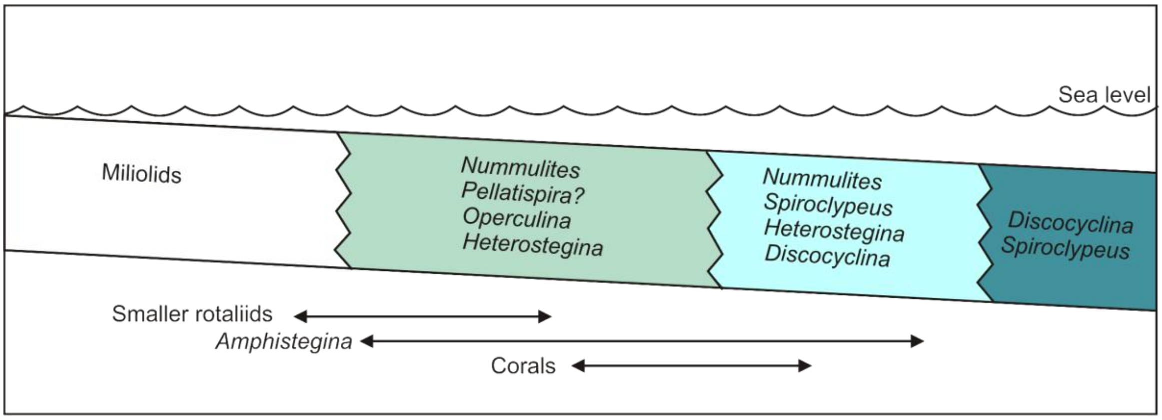

Figure 4.4. Schematic diagram showing depth zoning of LBF present in the Tanzanian Eocene / Oligocene section across a carbonate ramp (modified from Beavington-Penney and Racey, 2004).

bryozoan, echinoderm and coral fragments. Aragonitic micro-molluscs are also present but are likely to have been part of the in-situ benthos. LBF inhabited the photic zone, generally less than 130 m water depth (Hottinger, 1983; Hallock, 1984; Beavington-Penney and Racey, 2004), therefore all specimens are interpreted as having been transported from the shallow carbonate platform onto the continental slope, probably during storm events. Large storms or hurricanes cause mixing of platform sediments and transportation onto the slope (Hohenegger and Yordanova, 2001; Beavington-Penney, 2004; Jorry et al., 2006). *Nummulites* may be particularly susceptible to transportation by suspension due to their high porosity (Aigner, 1982; Beavington-Penney, 2004).

It is generally accepted that LBF were strongly zoned across platforms due to many factors including light levels and energy (see Beavington-Penney and Racey, 2004; Renema, 2005, 2006; Figure 4.4). The assemblages present are dominated by *Nummulites*, with pellatispirids, *Sphaerogypsina*, *Spiroclypeus* and rare *Discocyclina* suggesting a mainly mid-outer platform source for the sediment. As the platform is thought to have been narrow (Kent et al., 1971; Nicholas et al., 2006, 2007) LBF assemblages would therefore change rapidly across the shelf and a mix of shallow and deeper faunas would be expected in debris flow deposits.

The packstone beds are rich in LBF; however preservation is poor in comparison to the surrounding clays, with abraded and infilled specimens being common. The assemblage found within the limestones is likely to be skewed by the transportation mechanism; robust lenticular forms are more likely to survive intact than flattened disk shaped morphologies such as *Discocyclina* (see Beavington-Penney and Racey, 2004, for review of influences on test shape). This accounts for the absence or very low

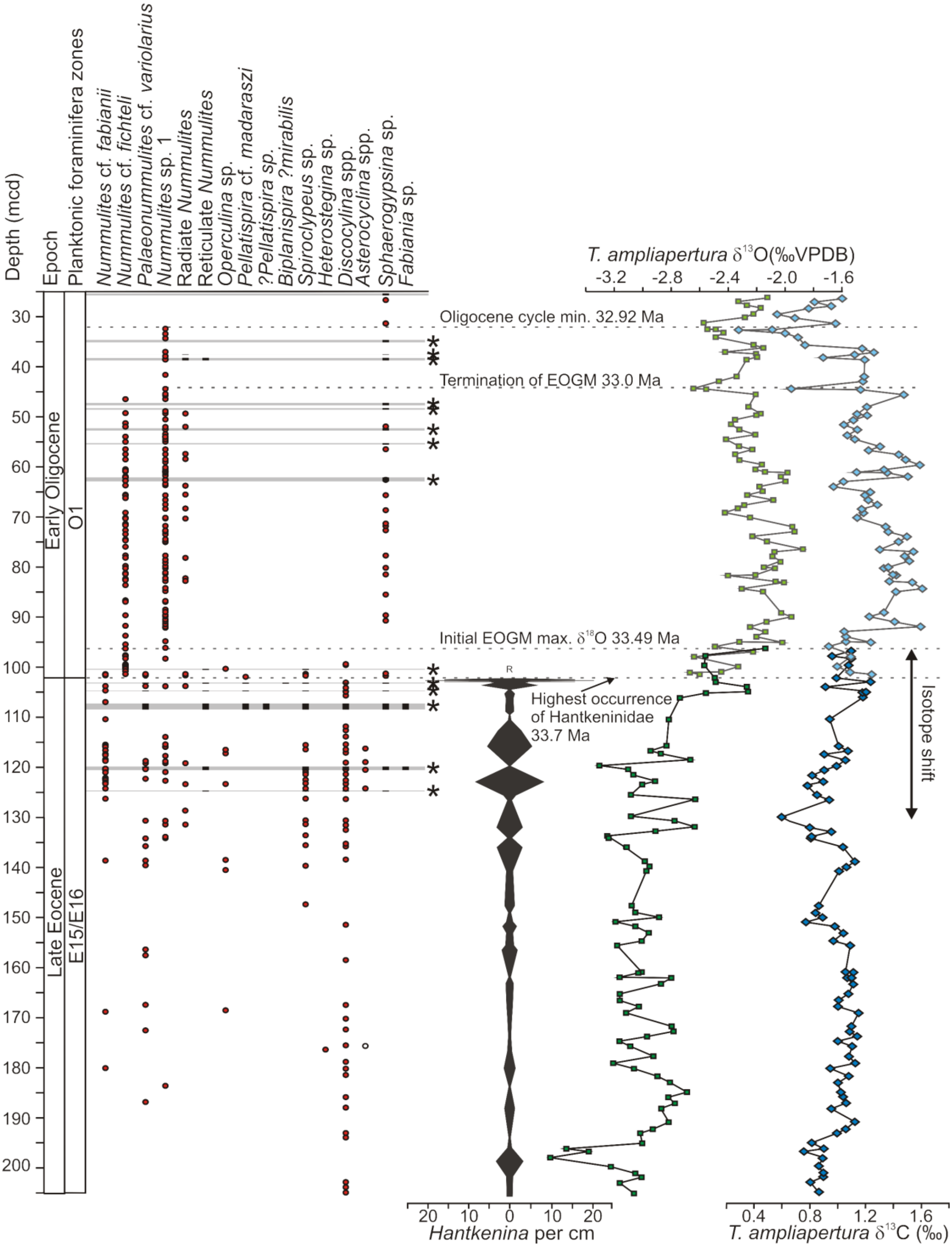

Figure 4.5. Range chart of LBF found in both clay residue and limestone samples plotted against isotope data from Pearson et al. (2008; isotope records from TDP 12 are plotted in black and from TDP 17 plotted in grey), the abundance of Hantkeninids per cm through the clay succession (Wade and Pearson, 2008; this study) and the planktonic foraminifera zones of Berggren and Pearson (2005). Circles represent occurrences within the clay sediment of LBF. Horizontal bands represent packstone beds, drawn to scale; black bars within these show occurrences of LBF in the packstones.

occurrence of the more fragile genera in the limestones, which are present in the clay residues.

The stratigraphic occurrence of LBF in both the primary clay samples and packstones are summarised in Figure 5 along with the stable isotope stratigraphy and the abundance of the planktonic Hantkeninidae which are used to correlate the EOB. *Discocyclina* (Figure 4.9, c-f; 4.13, e), *Pellatispira* (Figures 4.11, d; 4.13, a-c), *Spiroclypeus* (Figure 4.11, a; 4.12, g-h), *Palaeonummulites* (Figure 4.10, g-h; 4.12, f), *Fabiania* (Figure 4.13, g), *Operculina* sp. (Figure 4.11, c) and a number of species of *Nummulites* all have last occurrences between 102.14 mcd and 99.55 mcd, close to the EOB at 102.28 mcd. *Asterocyclina* (Figure 4.9, a-b) has a lower last occurrence at 116.5 mcd but is rare in the core samples with less than five complete individuals found in this study. *Heterostegina* (Figure 4.11, b) is only represented by one specimen, which was found at 175.50 mcd and *Biplanispira* (Figure 4.13, d) by a single specimen in the packstone at 103.16 mcd.

Nummulites is the most commonly found genus in the cores. It can be divided into reticulate and radiate groups of species on the basis of their morphology, particularly their external ornamentation. Reticulate *Nummulites* (Figure 4.10, a-c; 4.12, a-d) are present throughout the succession, but show a change across the boundary interval. The external morphology appears near identical before and after the boundary but there is a change in both the proloculus size and the tightness of the coiling (Figure 4.6), which likely indicates a change in the reticulate *Nummulites* species. Specimens below 101.39 mcd have a proloculus size of 140-220 μm (with a mean value of 175 μm), while those above this level have a proloculus of 180-330 μm (with a mean value of 250 μm), forming two distinct clusters. The sample at 101.39 mcd in TDP 17 contains both types. To compare the geometry of the whorls between the two *Nummulites* groups, graphs of whorl number against radius (coiling diagrams) have been plotted as in previous studies (e.g. Blondeau, 1972; Schaub, 1981; Racey, 1995; Renema, 2002; Renema et al., 2003; Figure 4.6b-d). All specimens in this study were A forms, as B forms are rare. These show a clear difference between the two groups, with the older group being slightly more tightly coiled with less variance between individuals. The younger specimens are comparatively more loosely coiled and more variable. Given the external similarity between the two groups, these are likely to be

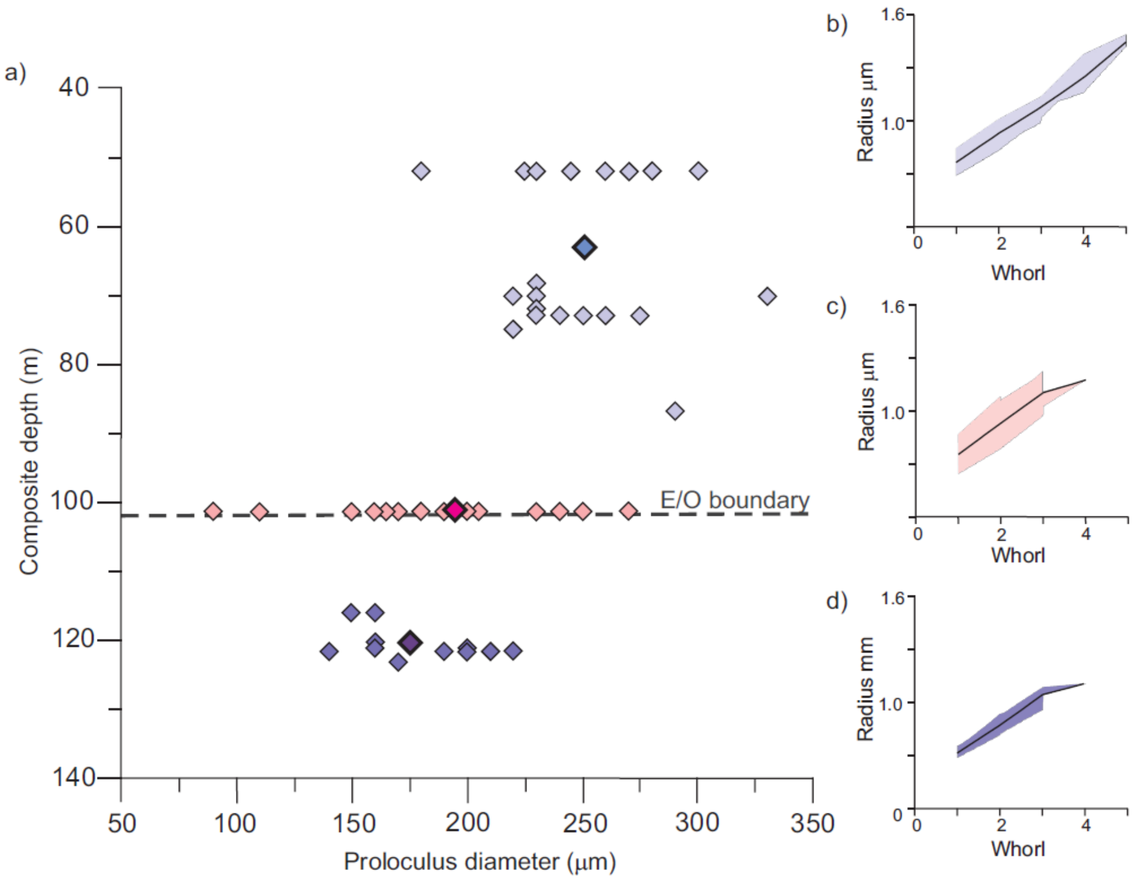

Figure 4.6. Proloculus size and corresponding coiling diagrams of reticulate *Nummulites* across the Eocene / Oligocene boundary. Mean plot on coiling diagrams is shown as single line; the shaded area represents the spread of individual plots, a) Proloculus diameter against depth; larger darker symbols show mean values, b) coiling diagram of Oligocene *Nummulites* specimens (corresponding proloculus measurements shown in light purple), c) coiling diagram of specimens from sample at 101.39 mcd *Nummulites* specimens (corresponding proloculus measurements shown in pink), d) coiling diagram of Eocene *Nummulites* specimens (corresponding proloculus measurements shown in dark purple).

two separate but closely related species and have been identified as *N.* cf. *fabianii* (Figure 4.10, a, b) and *N.* cf. *fichteli* (Figure 4.10, c). The reason why these are not assigned directly to *N. fabianii* and *N. fichteli* is that there are slight differences in the range of proloculus size compared with the Tethyan material of Schaub (1981) and Papazzoni (1998). This variation from Tethyan forms is interesting and potentially important in the study of reticulate *Nummulites* evolution, but requires further investigation. Reticulate *Nummulites* are also widely used in LBF biostratigraphy, therefore the change from *N.* cf. *fabianii* to *N.* cf. *fichteli* may be useful as an EOB indicator; however this is complicated by the morphological variation between regions and again requires further work. Other nummulitids including *Spiroclypeus* sp., *Operculina* sp. and *Palaeonummulites* cf. *variolarius* are also present. All these have last occurrences close to the Hantkeninidae extinction (see Figure 4.5). Extinctions within these genera are known to occur globally during the EOT (Adams et al., 1986) so the Tanzanian record seemingly reflects the global extinctions of these groups. *Palaeonummulites* cf. *variolarius* is similar to forms from Indonesia (see Figure 4.7) which also became extinct during the EOT (Renema, 2002). Orthophragmines are found as rare, small specimens of *Discocyclina* and *Asterocyclina.* Specimens of *Discocyclina* show similar characteristics to *D. trabayensis* and *D. augustae* from Turkey, but have a smaller protoconch and deuteroconch (compare Figure 4.9, c, f with Özcan et al., 2006 - Plate 2, 3, Text Fig. 12, Özcan et al., 2007 - Fig. 8, 9, Özcan et al., 2010b – Fig. 27).

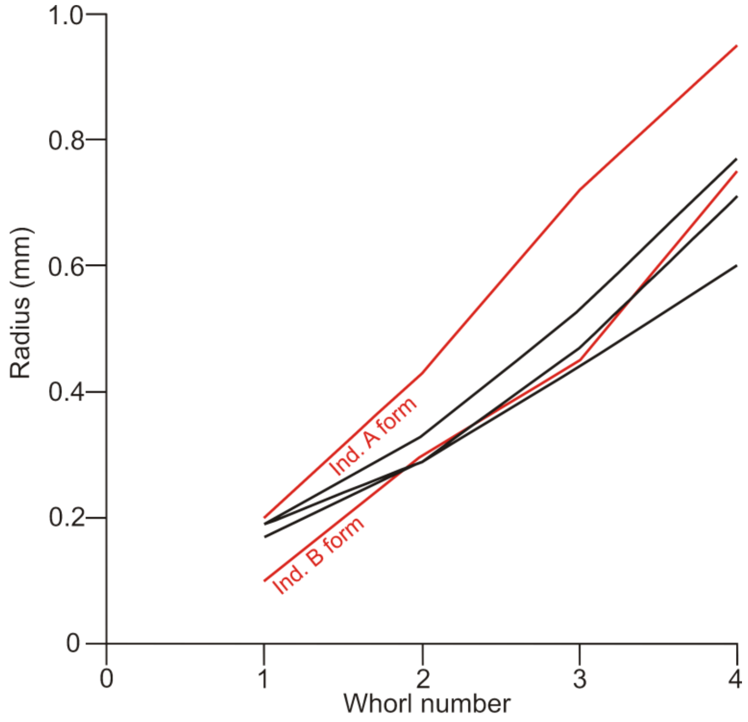

Figure 4.7 Coiling diagram of *Palaeonummulites* cf.. *variolarius*. Tanzanian specimen values are shown in black, average values for Indonesian *P.variolarius* from Renema (2002) are shown in grey for comparison.

Radiate *Nummulites* spp. (including sp.1; Figure 4.10, e-f) and *Sphaerogypsina* sp. (Figure 4.11, e; 4.13, f) are the only LBF which pass through the transition apparently unaffected. These surviving groups and newly occurring species above the EOB event appear to be generalist forms. *Nummulites* is known to have lived in a range of environments on the platform (Beavington-Penney and Racey, 2004), and *Sphaerogypsina* has been recorded from the Miocene-Pliocene of the Dominican Republic as possibly occurring below the photic zone and recent *Sphaerogypsina* have no symbionts (Hottinger et al., 2001). From this it can be inferred that the Eocene / Oligocene extinctions appear to be mainly within the deeper photic zone specialists.

4.6.3 Synthesis

The sedimentological and palaeontological evidence across the EOT in Tanzania shows that during the Eocene there was an active carbonate factory on the platform with diverse biota including corals, red algae, echinoids, bryzoans and LBF. Frequent storms caused mixing and suspension of the shelf sediment and washed smaller individuals of the LBF taxa onto the slope, where they settled out in the clays. This process continued throughout the deposition of the sediment – in both the Eocene and Oligocene. Meanwhile carbonate sediment built up on the platform which periodically destabilised and spilt off the platform edge as sediment gravity flows, forming the packstone deposits (Figure 4.8a).

At the EOB proper (between 102.28 and 102.22 mcd) there was a co-ordinated extinction of the planktonic Hantkeninidae. This closely coincided with the extinction of several important genera of LBF (see Figure 4.5). The last Type I (Eocene style) bed is above this at 100.23-100.28 mcd, but with a much reduced fauna indicating that the extinctions seem to have occurred before the switch from Type I to Type II sedimentation. At 96.64 mcd is the maximum δ^{18}O value of the transition (Pearson et al., 2008). This signifies not only a decrease in temperature, but also a drop in sea level due to ice growth (Lear et al., 2008). It seems that above this level the carbonate factory was severely reduced and there was a pause in the debris flow deposition: With a lower sea level and closer shoreline, terrestrial quartz built up and was subsequently deposited as Type II debris flows (Figure 4.8b). LBF in these beds are rare, and those present appear to be unspecialised forms. Orthophragminines, *Spiroclypeus*, pellatispirids, *Fabiania* and some species of *Nummulites* are all known to have suffered global extinction at the EOT (Adams et al., 1986). Our record from Tanzania shows that these extinctions did not occur at the isotope shift as we would expect following Adams (1965), but are all coincident with, or rapidly following, the Hantkeninidae extinction. The clear offset between these extinctions and the sedimentary change in the samples supports that the last occurrences are not an artefact of sedimentation. The relatively sharp and well-defined disappearance horizon indicates that the LBF sedimentation was penecontemporaneous with the clay and there was little significant reworking into younger deposits.

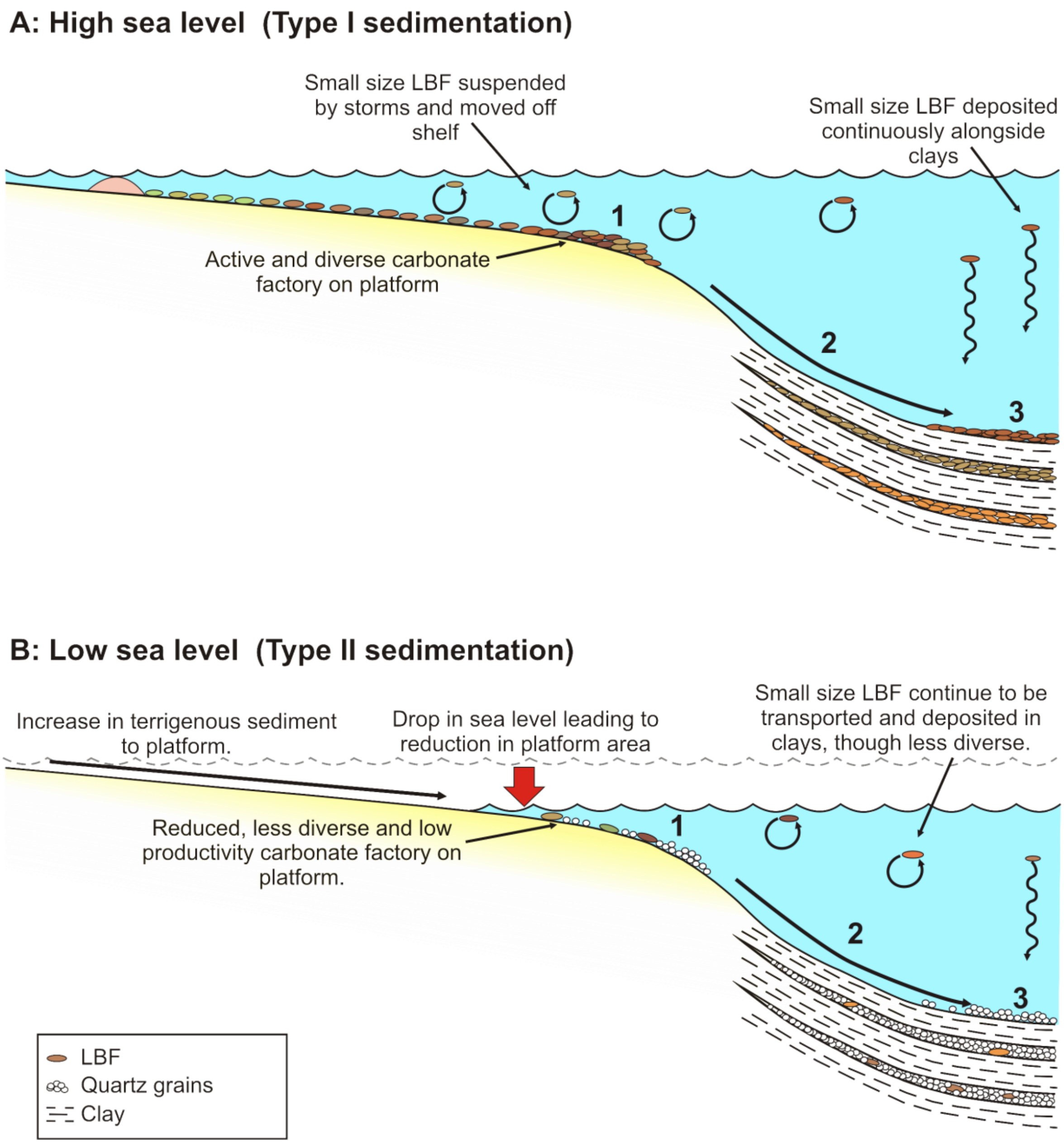

Figure 4.8. Conceptual model of shelf sedimentary processes before and after the early Oligocene sea-level drop. A) Carbonate factory builds up sediment (1) and destabilises resulting in periodic sediment gravity flows into deeper water (2) forming occasional limestone beds within the clay succession (3); B) Terrigenous sediment builds up (1), destabilises (2) and forms sediment gravity flow beds containing only occasional LBFs (3).

4.7 Extinction mechanisms

Several large overturning events took place within the LBF and planktonic foraminifera over an extended period of ~20 million years from the middle Eocene to the Oligocene. The extinctions have been linked to long-term climatic trends (e.g. Hallock et al., 1991). The results discussed above clearly show that the end-Eocene extinctions in the LBF, while arguably part of this long term trend, are not spread out but instead occur nearly simultaneously (at least within a few thousand years). This leads us to speculate that the causes of these extinctions may be directly linked to each other and with the extinction of the planktonic Hantkeninidae.

The relative suddenness of the event seems to demand a rapid kill mechanism, whether the trigger was environmental or ecological. The widespread biogeographic distribution of the groups in question indicates a global cause. The records also indicate it must be a very rare occurrence with a repeat time of at least millions or tens of millions of years or more and duration of much less than 100 kyrs. Further clues to the nature of the extinction are its apparent selectivity: Those LBF that became extinct and the Hantkeninidae lived in oligotrophic waters, in the deeper part of the photic zone and all may have relied on photosynthetic algal symbionts (see Coxall et al., 2000 for a discussion of hantkeninid ecology; Wade and Pearson, 2008); moreover all the extinct species were relatively specialised forms. The survivors among both the LBF (e.g. *Sphaeorogypsina*, some *Nummulites*) and the planktonic foraminifera (e.g. dentoglobigerinids) seem to have been tolerant of a wide range of habitats and had a more generalist morphology. Here we discuss potential mechanisms for these sudden extinctions.

In general the EOT (34.0-33.5 Ma) was a period of cooling and ice growth resulting in the lowering of global sea levels, but the changes were pulsed and occurred over an extended period of time (Zachos et al., 1996; Coxall et al., 2005; Coxall and Pearson, 2007; Pearson et al., 2008; Lear et al., 2008). However, the precise extinction level of the LBF and Hantkeninidae does not correspond to a noticeable step in the oxygen isotope stack or other climatic records (see Figure 4.5). It is appreciably earlier (by an estimated 200 kyrs on the Tanzanian age model) than second large δ^{18}O shift in the early Oligocene which is thought to represent the major phase of ice growth and a significant sea-level fall (Lear et al., 2008). This global sea-level fall therefore cannot be the cause of the extinction, as previously suggested by Adams et al. (1986). This is further supported by the change from Type I to Type II lithology, which occurs above the extinction level.

Sudden and dramatic perturbations in the Earth system that would not necessarily be seen in the oxygen isotopes include bolide impact, massive volcanism and a supernova explosion relatively close to the Earth. The first two of these potential mechanisms can easily be dismissed through lack of geological evidence at the appropriate biostratigraphical interval. High levels of volcanism are known from around the EOT but are too long lived to specifically be linked with the extinction (Berhe et al., 1987; Hofmann et al., 1997; Jicha et al., 2009) and there is no geological evidence for an especially large singular event. Likewise, though there is abundant evidence for major bolide impacts in the late Eocene, no large ones have been shown to coincide with the Eocene - Oligocene extinction events (Keller, 1986; Coccioni et al., 2000; Spezzaferri et al., 2002; Molina et al., 2006). Within the Tanzanian cores no microtektites or other evidence for an extraterrestrial impact were observed and there is no iridium anomaly (Pearson et al., 2008). The effects of a supernova would be more difficult to detect. It has been suggested that a nearby supernova (within 10 parsecs of the Earth) would produce ionising radiation causing ozone destruction of between 20 and 95% at the equator leading to a large influx of solar radiation to the Earth's surface (Ruderman, 1974; Crutzen and Brühl, 1995; Ellis and Schramm, 1995; Fields and Ellis, 1999; Gehrels et al., 2003). However the effect of a supernova would probably be more widespread among the Earth's biota, both terrestrial and marine, than is observed.

Increased nutrient supply into shallow water has been suggested as a mechanism for a number of similarly timed extinctions in LBF and planktonic foraminifera, such as the mid Eocene extinction of *Alveolina*, large *Nummulites* and muricate planktonic foraminifera (Hallock et al., 1991). At the Cenomanian / Turonian boundary a similar coincident extinction occurred between LBF and the planktonic rotaliporids (Parente et al., 2008). This is thought to have been caused by thermal destabilisation of a highly stratified water column, leading to upwelling of nutrient rich deep waters, destroying the surface oligotrophic environment (Parente et al., 2008). A sudden increase in nutrients to the surface waters at the EOB could cause extinctions in oligotrophic foraminifera, both planktonic and benthic, particularly among more specialist genera. Increased nutrients in the surface waters could lead to increased biomass and organic particles, and decreased water transparency (Hallock, 1986; Riley, 1956). It may also cause overfeeding stress and increased competition for space (Hallock, 1986). However, though there are indications of a general increase in nutrients across the transition (Diester-Haass and Zachos, 2003; Dunkley-Jones et al., 2008), we do not have evidence for a sudden increase at the extinction level.

The net effect of cooling and ice growth in the interval preceding the EOB would have reduced living space on the continental shelves and may have caused latitudinal restriction in carbonate platform and pelagic environments. These changes may have stressed the various groups and preconditioned them for extinction. Weakening of ecosystem linkages may have eventually reached a tipping point and caused sudden catastrophic extinctions in groups of specialist species with commonalities of life strategy, even without a major sudden external perturbation in the Earth system.

4.8 Conclusion

The record of the EOT shallow carbonate environments is exceptionally well correlated to global isotope and plankton biostratigraphy in the Tanzanian cores. We show that the extinction of important genera of LBF, including *Discocylina*, *Asterocyclina* and *Pellatispira*, occurred before the major sea-level drop and was closely coincident with the extinction of the planktonic foraminiferal family Hantkeninidae. This has implications for the global correlation of LBF biozonations. The extinction levels correlate both the top of letter stage Tb (Adams, 1970) and shallow benthic foraminiferal (SBZ) zone 20 (Serra Kiel et al., 1998) with the EOB (top of planktonic foraminifer Zone E16; Berggen and Pearson, 2005) in the stratotype section at Massignano, Italy, providing a clear tie point between the regional larger benthic zonations and global stratigraphy.

The co-ordinated extinction within the two foraminiferal groups also raises questions about the mechanism responsible. It seems likely that the climatic changes in the early stages of the EOT may have preconditioned the LBF for extinction. A sudden nutrient supply at the EOB may have been the push that caused the extinction of various LBF and the planktonic Hantkeninidae all of which occupied relatively specialised deep photic zone environments.

4.9 Taxonomy

Classifications and descriptions of the Nummulitoidea are based on Schaub (1981), Racey (1995) and Renema (2002), with the exception of the Pellatispiridae which are based on the work of Hottinger et al. (2001). The classification and descriptions of the orthophragmines – Discocylinidae and Asterocyclinidae are based on the work of Özcan et al. (2006, 2007, 2010). The remaining genera follow Loeblich and Tappan, (1987).

Order Foraminiferida Eichwald, 1930
Suborder Rotaliina Delage and Hérouard, 1896
Superfamily Nummulitoidea de Blainville, 1827
Family Nummulitidae de Blainville, 1827
Subfamily Nummulitinae de Blainville, 1827
Genus *Nummulites* Lamarck, 1801

Nummulites cf. *fabianii* (Prever 1905)
Figure 4.6; Figure 4.10, a-b

1905 *Bruguieria fabianii* Prever, p. 1805, 1825 (*fide* Schaub 1981).
1981 *Nummulites fabianii* Prever, Schaub, Fig. 88; Plate 49, 57-69; Plate 50, 1-4; Table 15, i.
1995 *Nummulites fabianii* Prever, Papazzoni and Sirotti, Plate 2, 8-10.
1995 *Nummulites fabianii* Prever, Racey p. 43; Plate 4, 8-13; Text Fig. 37.
1998 *Nummulites fabianii* Prever, Papazzoni p. 165-168; Plate 1, 1-15; Plate 2, 1-15.

Material: 20 orientated sections, comprising of 19 equatorial and 1 axial sections, along with numerous unsectioned specimens, all from clay residues. Reticulate *Nummulites* are abundant in the packstones, but have not been identified beyond genus level due to a lack of clear oriented sections.

Description: Tests are lenticular, mostly 1-2 mm in diameter with a rounded periphery and strongly reticulate septal filaments. The spire is regular and opens steadily, coiling is looser than that of *N.* cf. *fichteli*. Chambers are regular, sub-rectangular, and almost isometric in innermost whorls but become wider than high in outer whorls. Septa are straight to very slightly curved and slightly inclined. Pillars are visible in axial section. The proloculus is 140-220 μm. All sectioned specimens are A forms.

Remarks: External morphology appears near identical with *N.* cf. *fichteli*, but *N.* cf. *fabianii* can be distinguished in equatorial thin section by smaller proloculus diameter and looser coiling (see discussion in section 4.6.2).

Stratigraphic range: *N.* cf. *fabianii* is common in the clay samples of all three cores and has a last occurrence at 101.39 mcd, just above the EOB. Within the Type I lithology reticulate *Nummulites* are common, whereas in the Type II lithology a single specimen in oblique section is seen (Figure 4.12, d). *N. fabianii* has a Priabonian range and is used to define SBZ 19 (early Priabonian) in the Tethyan region (Serra Kiel et al., 1998), but is not known from anywhere east of India (Renema et al., 2003).

Geographic range: Wide distribution, common throughout Europe and the eastern Tethyan region. Known from Tanzania (this study); Libya, Rhodes, Algeria, India (Blondeau, 1972); Northern Italy, Swiss and French Alps, Romania, Spain and Somalia (Schaub, 1981); India (Samanta, 1968); Oman (Racey 1995); Turkey (Özcan et al., 2006).

Nummulites cf. *fichteli* (Michelotti, 1841)
Figure 4.6; Figure 4.10, c

1841 *Nummulites fichteli* Michelotti, p. 44; Plate III, 7 (*fide* Schaub 1981)
1970 *Nummulites fichteli* Michelotti, Adams, p. 122.
1981 *Nummulites fichteli* Michelotti, Schaub, p. 128; Plate 50, 5-18; Table 15, k,l.
1995 *Nummulites fichteli* Michelotti, Racey, p. 44.
2002 *Nummulites fichteli* Michelotti, Renema, Fig 6.8; Plate 12, D-E.

Material: 25 individuals, comprising of 24 equatorial and 1 axial sections, along with numerous unsectioned specimens all from the clay residues. Reticulate *Nummulites* are abundant in the packstones, but have not been identified beyond genus level due to a lack of clear oriented sections.

Description: Tests are lenticular, mostly 1-2 mm in diameter, with a rounded periphery and strongly reticulate septal filaments. The spire is regular, opens steadily and is tightly coiled. Chambers are sub-rectangular, isometric to 1.5x wider than high in innermost whorls and up to ~3x wider than high in the outermost whorls of the largest specimens. Septae are straight or very slightly curved and slightly inclined. Pillars are visible in axial section. The proloculus is 180-330 μm in diameter. All sectioned specimens are A forms.

Remarks**:** External morphology near identical with *N.* cf. *fabianii*, it is distinguished in equatorial section by a larger proloculus size and tighter coiling. Chambers are also wider in the outer whorls and the test is slightly flatter, though this is less noticeable in smaller specimens. The coiling diagrams (Figure 4.6) show measurements of *N.* cf. *fichteli* cluster less closely together than those of *N.* cf. *fabianii*.

Stratigraphic range: *N.* cf. *fichteli* has a first occurrence at 101.39 mcd just above the EOB and continues to the top of the core. The first occurrence level of *N.* cf. *fichteli* coincides with the last occurrence of *N.* cf. *fabianii* and this is the only sample in which the two species are found together. This suggests *N.* cf. *fichteli* is replacing *N.* cf. *fabianii*. Within Indonesia *N. fichteli* is a characteristic species of Tc and Td (Early Oligocene age). The last Indonesian occurrence is at 29.4 Ma in Java (Renema, 2002). Within the Tethys *N. fichteli* is characteristic of SBZ 21 and 22 (Rupelian- Middle Chattian), and has a range from the EOB to within the lower part of SBZ 23 (Cahuzac and Poignant, 1997).

Geographic range: Widespread within both the Tethyan region (Blondeau, 1972; Schaub, 1981) and Indo-Pacific (Adams, 1965, 1970; Renema, 2002; Renema et al., 2003).

Nummulites sp. 1
Figure 4.10, e-f

Material: 25 individuals, comprising of 21 naturally split equatorial sections, 2 equatorial thin sections and 2 axial sections along with numerous unsectioned specimens within the clay residues.

Description: Tests are flattened lenticular (with a diameter/thickness ratio of ~3), and up to 2.5 mm in diameter. Septal filaments are sigmoidal, in some specimens the septal filaments in the umbilical region form granules and there is an umbilical plug,. The spire is regular, loosely coiled and rapidly opening. Chambers in innermost whorls are ~isometric, but become ~2.5x higher than wide in outer whorls. The proloculus is 43 - 77 μm in diameter.

Remarks: Sub axial sections show similarity to some of the radiate *Nummulites* seen in the Type II beds (Figure 4.12, e).

Stratigraphic range: *Nummulites* sp. 1 has a first occurrence at 185.81 mcd and last occurrence at 32.54 mcd, making it one of the few species that passes through the EOB. This species is especially common in TDP 17, with counts of over 250 individuals in a 14 cm clay sample.

Nummulites spp. (radiate)
Figure 4.9, d

Material: 3 equatorial sections, along with unsectioned specimens from the clay samples.

Remarks: A small number of other radiate *Nummulites* occur in the samples, including some larger examples (up to 7 mm). Multiple species appear to be present, but further detailed sectioning is required to distinguish between them.

Stratigraphic range: *Nummulites* spp. (radiate) occur in the clays between 131.48 mcd and 47.95 mcd.

Genus *Palaeonummulites* Schubert, 1908

Palaeonummulites cf. *variolarius* (Lamarck, 1804)
Figure 4.10, h-g

1804 *Lenticulites variolaria* Lamarck, p. 187 (*fide* Renema 2002).
1972 *Nummulites variolarius* Lamarck, Blondeau, p. 143; Plate XIX, 1-14.
2002 *Palaeonummulites variolarius* Lamarck, Renema, p. 155; Fig 6.18; Plate 11, E-H.

Material: 3 equatorial thin sections, 1 axial section and 1 sub axial specimen from the clay layers, along with several unsectioned specimens.

Description: Small, biconical test up to ~ 1.5 mm in diameter and up to ~0.8 mm in thickness, giving a diameter to thickness ratio of ~ 1.7. Septal filaments are straight or slightly curving radiating from a distinct polar pillar, which forms a clear umbilical pillar in axial section. Sectioned specimens have 4 whorls, which are tightly coiled and open very regularly. Septa are perpendicular to the marginal chord and slightly curved. The proloculus is very small, 0.07-0.08mm in diameter.

Remarks: It is unclear whether this is the A or B form of the species, as both have very small proloculus diameter. Comparison of whorl radii with those measured in Indonesian specimens by Renema (2002) show a strong similarity with the Indonesian B form (see Fig. 7), but more specimens would be needed to confirm this and show the variation within the population. The septae appear straighter than the Indonesian specimens (see Renema, 2002). *P*. cf. *variolarius* is also seen within the Type I packstones (Figure 4.12, f), but is rare.

Stratigraphic range: *P*. cf. *variolarius* has a first occurrence at 187.00 mcd and last occurrence at 101.39 mcd. Within Indonesia the range is estimated to be Middle-Late Eocene, Letter Classification zone Ta_3-Tb (Middle Lutetian to Priabonian; Renema, 2002).

Geographic distribution: Rarely included in studies dealing with the Nummulitidae (Renema, 2002). Blondeau (1972) reports it from Somalia, Mozambique and Egypt along with England, France, Belgium, the former Soviet Union and New Caledonia. Renema (2002) reports it as being widely distributed throughout Indonesia, including Java, Borneo, Timor, Sulawesi, Nias and Sumba.

Genus *Operculina* d’Orbigny, 1826

Operculina sp.
Figure 4.11, c

Material: <10 unsectioned specimens from clay residue samples; often fragmented.

Description: Specimens up to ~1 mm in diameter. Test flat and evolute, with whorls rapidly opening. Granules are visible along septae and marginal cord.

Stratigraphic range: *Operculina* sp. has a first occurrence at 187.00 mcd and a last occurrence at 101.32 mcd. Specimens are rare in the clays, often occurring only as fragments and have not been found in the limestone beds.

Subfamily Heterosteginінae Galloway, 1933
Genus *Heterostegina* d’Orbigny, 1826

Heterostegina sp.
Figure 4.11, b

Material: Single unsectioned specimen from clay residues.

Description: Specimen is ~1 mm in diameter. Test is lenticular with an inflated central region. Central pile is clearly visible with slightly sigmoidal sutures. Chamberlets are visible on broken edge of test.

Remarks: Only a single specimen has been identified from the clays and *Heterostegina* sp. has not been found in the packstones. External ornamentation resembles that of *H. armenica* from the Western Tethys (Less et al., 2008; Fig. 11). Further specimens and sections are required for species level identification

Stratigraphic range: The specimen is found at 173.68 mcd.

Genus *Spiroclypeus* Douville, 1905

Spiroclypeus sp.
Figure 4.11, a; Figure 4.12, g-h

Material: 4 equatorial sections, plus additional sub axial and oblique sections in peterological thin sections from the Type I packstones and a number of unsectioned specimens from the clays.

Description: Tests are lenticular and 0.6-2.9 mm in diameter, with an inflated central region and thin flange, though the flange is often missing probably due to damage during transportation. Pillars occur over the inflated region, decreasing in size and density away from the centre and not visible on the flange. These can be seen in axial section. The spire is coiled tightly for ~ 3 whorls and then opens rapidly. The proloculus is ~ 0.05 mm. Chambers are higher than wide, their height increasing rapidly after the first 2-3 whorls. Primary septae are strongly curved backwards. Following the embryon there are 3-4 undivided (operculine) chambers and all successive chambers are subdivided into chamberlets, with 5 chamberlets in the 14th chamber. The chamberlets are largely rectangular to trapezoidal in shape.

Remarks: Similar to “older” *Spiroclypeus* forms such as *S. carpaticus* (see Less and Özcan, 2008, for discussion), although flange appears to be narrower than *S. carpaticus* but this may be due to preservation.

Stratigraphic range: *Spiroclypeus* sp. has a first occurrence at 147.60 mcd and last occurrence at 101.39 mcd and is found within both the clay residues and Type I packstones. It is especially common in the limestone bed at 108.55 mcd.

Family Pellatispiridae Hanzawa, 1937
Subfamily Pellatispirinae Hanzawa, 1957
Genus *Pellatispira* Boussac, 1906

Pellatispira cf. *madaraszi* (Hantken, 1876)
Figure 4.11, e; Figure 4.13, a-b

1876 *Nummulites madaraszi* Hantken, p. 86; Plate 16, 7 (*fide* Hottinger et al., 2001).
1928 *Pellatispira madaraszi* Hantken, Umbgrove, p. 17; Figs. 27-33.
1999 *Pellatispira madaraszi* Hantken, Romero et al., p. 91; Plate 1, 7, 9-11.
2001 *Pellatispira madaraszi* Hantken, Hottinger et al., p. 44-46; Text Figs. 3, 4, 5A, 6; Plate 7, 1-4; Plate 8, 1-5.

Material: 11 equatorial sections within petrological thin sections of Type I packstones, along with a number of oblique and sub-axial sections. One specimen found in clay residues.

Description: Tests are up to 5mm in diameter and are discoidal to lenticular. The chambers are arranged in an evolute, near planispiral form with ~ 8 chambers in the first whorl and ~ 15 chambers in the second whorl. In equatorial section the marginal crest reaches a height roughly equivalent to the height of the chamber. In vertical section piles are clearly visible and can be seen as pustules on the surface of specimens, along with pores. In some specimens preserved within sparite cement small spines are visible. The proloculus is spherical with a diameter of 110-117 μm. The deuteroconch is slightly smaller than the proloculus ~112 μm mean diameter.

Remarks: The proloculus size is slightly smaller than in the specimens described by Hottinger et al. (2001) and Umbgrove (1928), who give averages of ~ 256 μm and 200 μm respectively.

Stratigraphic occurrence: Specimens of *P.* cf. *madaraszi* have a first occurrence in the limestones at 108.55 mcd and last occurrence at 103.16 mcd, with a single specimen in the clays at 102.14 mcd. The genus *Pellatispira* is known from Bartonian to Priabonian age, becoming extinct during the EOT (Umbgrove, 1928; Adams, 1970; Hottinger et al., 2001).

Geographic range: *Pellatispira madaraszi* is common within the Tethyan region (Hottinger et al., 2001) and *Pellatispira* is found throughout Indonesia (Adams, 1965, 1970; Renema, 2002) and in India (Sarangi et al., 2001).

Pellatispira sp.
Figure 4.13, c

Material: Single specimen in oblique axial section.

Description: The test is lenticular and ~3mm in diameter. The specimen shows what appears to be biplanar growth in the initial spiral and planispiral growth in the outer whorls.

Remarks: The growth pattern is the opposite of Indonesian material showing intermediate growth patterns: These display biplanispiral growth in the outer whorls and pellatispiral growth in the inner whorls (W. Renema pers. comm.).

Stratigraphic range: Single specimen found at 103.16 mcd.

Genus *Biplanispira* Umbgrove, 1937

Biplanispira ?mirabilis (Umbgrove, 1936)
Figure 4.13, d

1936 *Heterospira mirabilis* Umbgrove, p. 155; Figs. 1-11 (*fide* Hottinger et al., 2001).
1984 *Biplanispira mirabilis* Umbgrove, Samanta, p. 316; Figs. l, 2, 6.
2001 *Biplanispira mirabilis* Umbgrove, Hottinger et al., p. 50; Plate 16-17.

Material: 2 sub axial section within petrological thin section of Type I packstone.

Description: The test shows a biconvex lenticular shape with pellatispirine architecture. The test has a width of ~140 μm and height of ~40 μm. Piles forming pustules on the surface of the test are clearly visible. Two layers of lateral chamberlets are present, one on either side of the marginal crest.

Remarks: The specimen shows a strong resemblance to the sub axial sections of *B. mirabilis* illustrated by Hottinger et al (2001; Plate 17).

Stratigraphic range: *Biplanispira ?mirabilis* is very rare in the cores, with two specimens found in the limestone bed at 103.16 mcd. The genus *Biplanispira* is known globally from Bartonian to Priabonian age (Adams, 1970; Hottinger et al., 2001; Renema, 2002).

Geographic range: *Biplanispira* is common within Indonesia (Adams, 1970; Hottinger et al., 2001; Renema, 2002).

Family Discocylinidae Galloway, 1928
Genus *Discocylina* Gümbel, 1870

Discocyclina cf. *augustae* (van der Weijden, 1940)
Figure 4.9, f

1940 *Discocyclina augusta*e van der Weijden (*fide* Özcan et al., 2006)
2006 *Discocyclina augustae* Özcan et al., p. 493-494; Plate 4, 19-20.
2010 *Discocyclina augustae* Özcan et al., p. 53-54; Fig. 27, g-m.

Material: single equatorial thin section from clay residue samples.

Description: Small flattened test, unribbed with granules on surface. Nephrolepidine embryon (protoconch is semi-enclosed by deuteroconch; see Özcan et al. (2006) for detail on orthophragmine terminology), with rectangular, low adauxilliary chamberlets. The chamberlets increase in height towards the outer edge of the test. The deuteroconch 130µm and protoconch 60 µm in diameter.

Remarks: Tanzanian specimens show similarities to *D. augustae* from Turkey (Özcan et al., 2006, 2010), but have a smaller embryon size.

Stratigraphic range: The specimen of *Discocyclina* cf. *augustae* occurs at 122.74 mcd. *D. augustae* ranges from the middle Ilerdian to the end of the Priabonian (Özcan et al., 2006).

Geographic range: *D. augustae* extends from North East Spain to India (Özcan et al., 2006).

Discocyclina cf. *trabayensis* (Neumann, 1955)
Figure 4.9, c

1955 *Discocyclina trabayensis* Neumann, (*fide* Özcan et al., 2006)
2006 *Discocyclina trabayensis* Neumann, Özcan et al., p. 494-495; Plate 2, 7-9; Text Fig. 12.

Material: single equatorial thin section from clay residue samples.

Description: Small flattened test, unribbed, with granules on surface – very similar to *Discocyclina* cf. *augustae* in external morphology. Nephrolepidine embryon with low, wide adauxilliary chamberlets which are slightly arched at the top. Chamberlets are narrow and tall, increasing in height towards the edge of the test. Deuteroconch 105 μm and protoconch 50 μm in diameter.

Remarks: The Tanzanian specimens are very similar to *D. trabayensis* from Turkey (Özcan et al., 2006), but have a smaller embryon size.

Stratigraphic range: The specimen of *Discocyclina* cf. *trabayensis* occurs at 120.41 mcd. *D. trabayensis* ranges from the early Cuisian to the end of the Priabonian (Özcan et al., 2006).

Geographic range: *D. trabayensis* occurs from South West France to Anatolia (Özcan et al., 2006).

Discocyclina sp. 1
Figure 4.9, e

Material: Single equatorial thin section from clay residue samples.

Description: Small flattened test, with granules on surface. In thin section 7 or 8 ribs are visible, these were only faintly seen in the external morphology, but this could be influenced by erosion on the test during transportation. Nephrolepidine embryon with rectangular, tall adauxilliary chamberlets which are slightly arched at the top. Chamberlets slowly increase in height towards the outer edge of the test. Deuteroconch 310 μm and protoconch 150 μm in diameter.

Remarks: Shows some similarity to *D. radians* (Özcan et al., 2006; Özcan et al., 2010) and *D. nandori* (Özcan et al., 2010) from Turkey, but more specimens are needed for further identification.

Stratigraphic range: The specimen of *Discocyclina* sp. 1 occurs at 120.41 mcd.

Discocyclina spp.
(Figure 4.13, d)

Remarks: Some specimens of *Discocylina* currently remain identified to only generic level and do not appear to belong to the species described above, further measurements and comparisons are required to fully identify them. A number of specimens from the clay residues also currently remain unsectioned. Additionally, specimens from the Type I limestones are largely fragments in oblique section and so identification beyond generic level is not possible.

Stratigraphic range: *Discocyclina* specimens have a first occurrence at 205.03 mcd and last occurrence at 99.55 mcd. Globally, *Discocyclina* is known from the Middle Paleocene to top of the Late Eocene (Loeblich and Tappan, 1987).

Family Orbitoclypeidae Brönniman, 1945
Genus *Asterocyclina* Gümbel, 1870

Asterocyclina stellata (d'Archiac, 1846)
Figure 4.9, b

1846 *Asterocyclina stellata* d'Archiac (*fide* Özcan et al., 2006).

2006 *Asterocyclina stellata* d'Archiac, Özcan et al., p. 507; Plate 4, 8-12; Text Fig. 12.
2010 *Asterocyclina stellata* d'Archiac, Özcan et al., p.61; Fig. 29, o-t.

Material: Single equatorial thin section from clay residue samples.

Description: Star shaped test with 5 rays. Granules are clearly visible on test surface. Nephrolepidine embryon, with clear "stellata" arrangement of adauxiliary chamberlets - with 5 large chamberlets corresponding to the 5 rays, and narrower chamberlets between (see Özcan et al., 2006). Equatorial chamberlets are arranged into ateroidal annuli. Deuteroconch is 200 μm and protoconch is 130 μm in diameter.

Stratigraphic range: The specimen of *Asterocyclina stellata* occurs at 119.01 mcd. This species is known from the early Cuisian to the end of the Priabonian (Özcan et al., 2006).

Geographic range: *A. stellata* is know from North East Spain to India and may occur in Indonesia (Özcan et al., 2006).

Asterocyclina sp.
Figure 4.9, a

Material: Single equatorial thin section from clay residue samples.

Description: Star shaped test with 5 rays. Nephrolepidine embryon, adauxiliary chamberlets are not clear in the section. Equatorial chamberlets arranged into ateroidal annuli. Deuteroconch is 135 μm and protoconch is 90 μm in diameter.

Stratigraphic range: The specimen of *Asterocyclina* sp. occurs at 120.41 mcd.

Asterocyclina spp.

Remarks: A number of specimens of *Asterocyclina* remain unsectioned and are therefore not identified beyond generic level.

Stratigraphic range: Globally, the genus *Asterocyclina* is known from the Middle Paleocene to the top of the Eocene (Loeblich and Tappan, 1987).

Superfamily Acervulinoidea Schultze, 1854
Family Acervulinidae Schultze, 1854
Genus *Sphaerogypsina* Galloway, 1933

Sphaerogypsina sp.
Figure 4.11, d; 4.13, f

Material: 1 sub equatorial section, ~ 20 un-sectioned individuals from clay residue samples and a number of sub equatorial sections within petrological thin section from both Type I and Type II beds.

Description: Spherical test with a diameter of 0.55-1.3 mm. Chambers in numerous layers, with between 6 and 10 rings in the outer “aligned” section of the test, with a flower-like arrangement in the centre. Chambers in successive layers are aligned one above each other, adjacent chambers alternate with a brick-like arrangement. The chambers are rectangular in shape with a height of ~30 µm and width of 50-90 µm, with the width increasing in successive rings. The proloculus is ~20 µm in diameter. Pores are visible on the external surface of the test.

Stratigraphic range: *Sphaerogypsina* sp. has a first occurrence at 120.43 mcd and continues to the top of the cores. The genus *Sphaerogypsina* is known from the Palaeocene to Recent (Loeblich and Tappan, 1987).

Family Cymbaloporidae Cushman 1927

Subfamily Fabianiinae Deloffre and Hamaoui, 1973
Genus *Fabiania* Silvestri, 1924

Fabiania sp.
Figure 4.13, g-h

Material: 15 sub axial and oblique sections within petrological thin sections of Type I packstone.

Description: Test is conical with a diameter of 1.5-2.5 mm and height of 0.5-1.0 mm. The cone has a deeply excavated centre, with large inner chambers. Outer chambers are split vertically and horizontally into small chamberlets. Chamber walls are thick.

Remarks: *Fabiania* sp. is only found within the Type I packstones.

Stratigraphic range: *Fabiania* sp. has a first occurrence at 120.43 mcd and last occurrence at 103.16 mcd. *Fabiania* globally ranges from the Late Paleocene to Late Eocene (Loeblich and Tappan, 1987).

Geographic range: The genus *Fabiania* is known from France, Italy, Spain, Turkey, W. Pacific, India, New Caledonia, Japan and the Caribbean (Loeblich and Tappan, 1987).

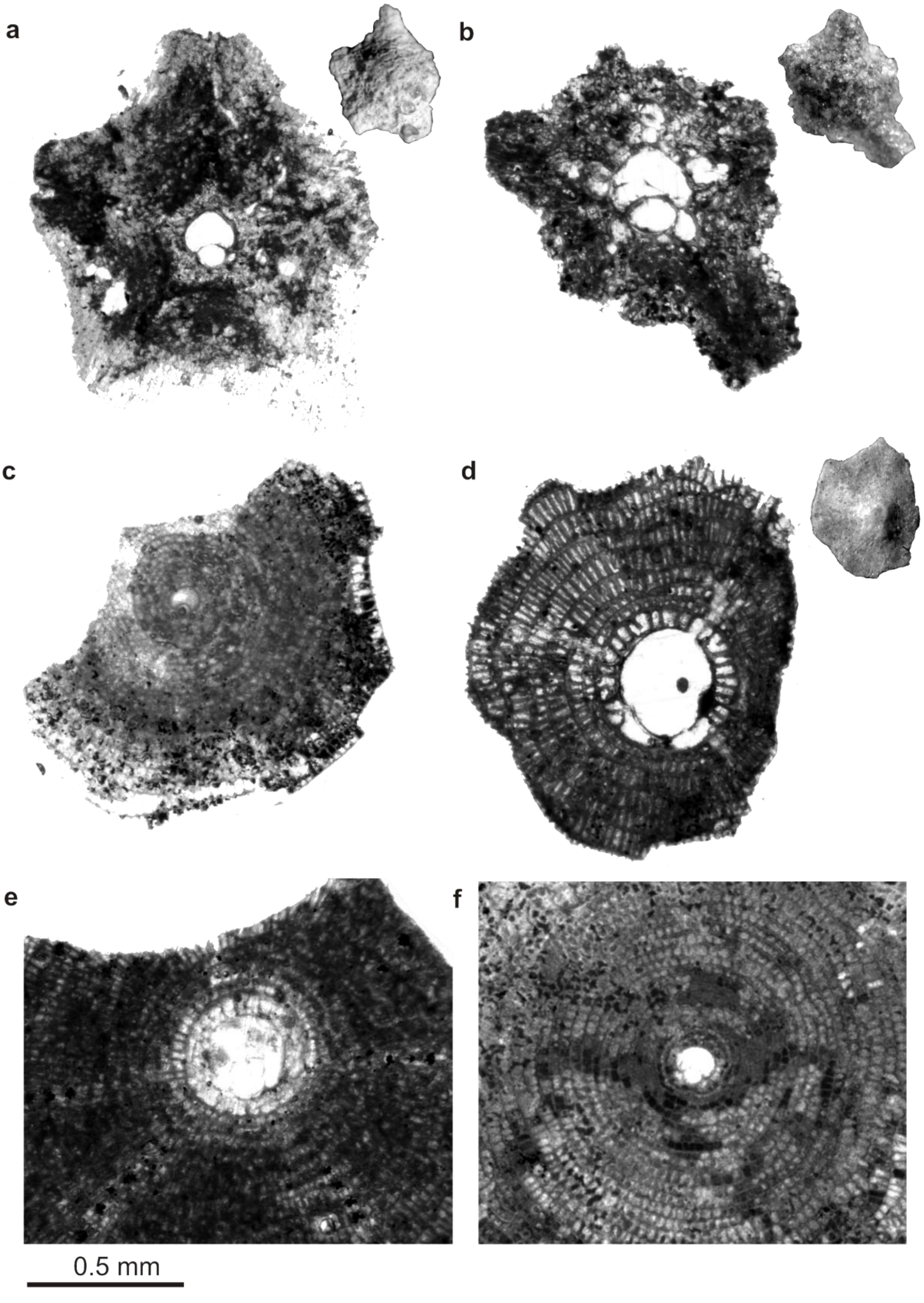

Figure 4.9. Clay specimens: a) *Asterocyclina* sp., equatorial section, external view also shown, TDP 12/20/1 41–50 cm (4); b) *Asterocyclina stellata* (d'Archaic, 1846), equatorial section, external view also shown TDP 11/34/1 71-81 cm (1); c) *Discocyclina* cf. *trabayensis* (Neumann, 1955), equatorial section, TDP 12/20/3 74-83 cm (2); d) *Discocyclina* sp., equatorial section, external view also shown, TDP 12/20/1 41-50 cm (3); e) *Discocyclina* sp. 1, equatorial section, TDP 12/20/1 41-50 cm (2).. f) *Discocyclina* cf. *augustae* (van der Weijden, 1940), equatorial section, TDP 12/20/3 74-83 cm (1).

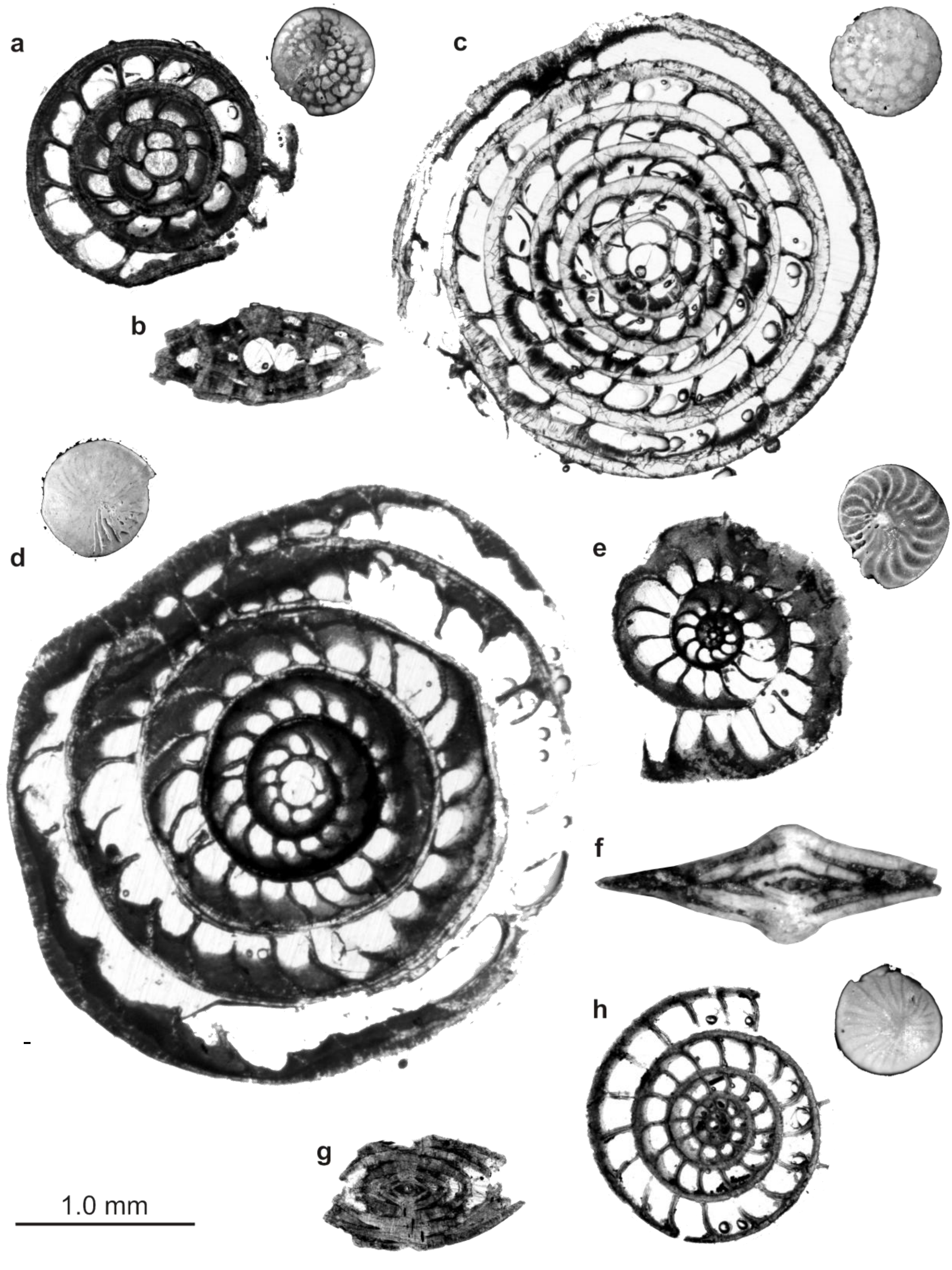

Figure 4.10. Clay specimens: a) *Nummulites* cf. *fabianii* (Prever, 1905), equatorial section, external view also shown, TDP 17/16/2 63-75 cm (21); b) *Nummulites* cf. *fabianii* (Prever, 1905), axial section, TDP 17/35/1 49-55 cm (23); c) *Nummulites* cf. *fichteli* (Michelotti, 1841), equatorial section, TDP 17/24/1 20-35 cm (1); external view of TDP 12/12/2 80-90 cm (3) d) *Nummulites* sp. (striate), equatorial section, external view also shown, TDP 17/16/2 63-75 cm (13); e) *Nummulites* sp. 1, equatorial section, external view also shown, TDP 17/15/2 87-97 cm (1); f) *Nummulites* sp. 1, axial section, TDP 17/14/1 0-14 cm; g) *Palaeonummulites* cf. *variolarius* (Lamarck, 1804), axial section, TDP 17/35/1 49-55 cm (28). h) *Palaeonummulites* cf. *variolarius* (Lamark, 1804), equatorial section, external view also shown, TDP 17/35/1 49-55 cm (26).

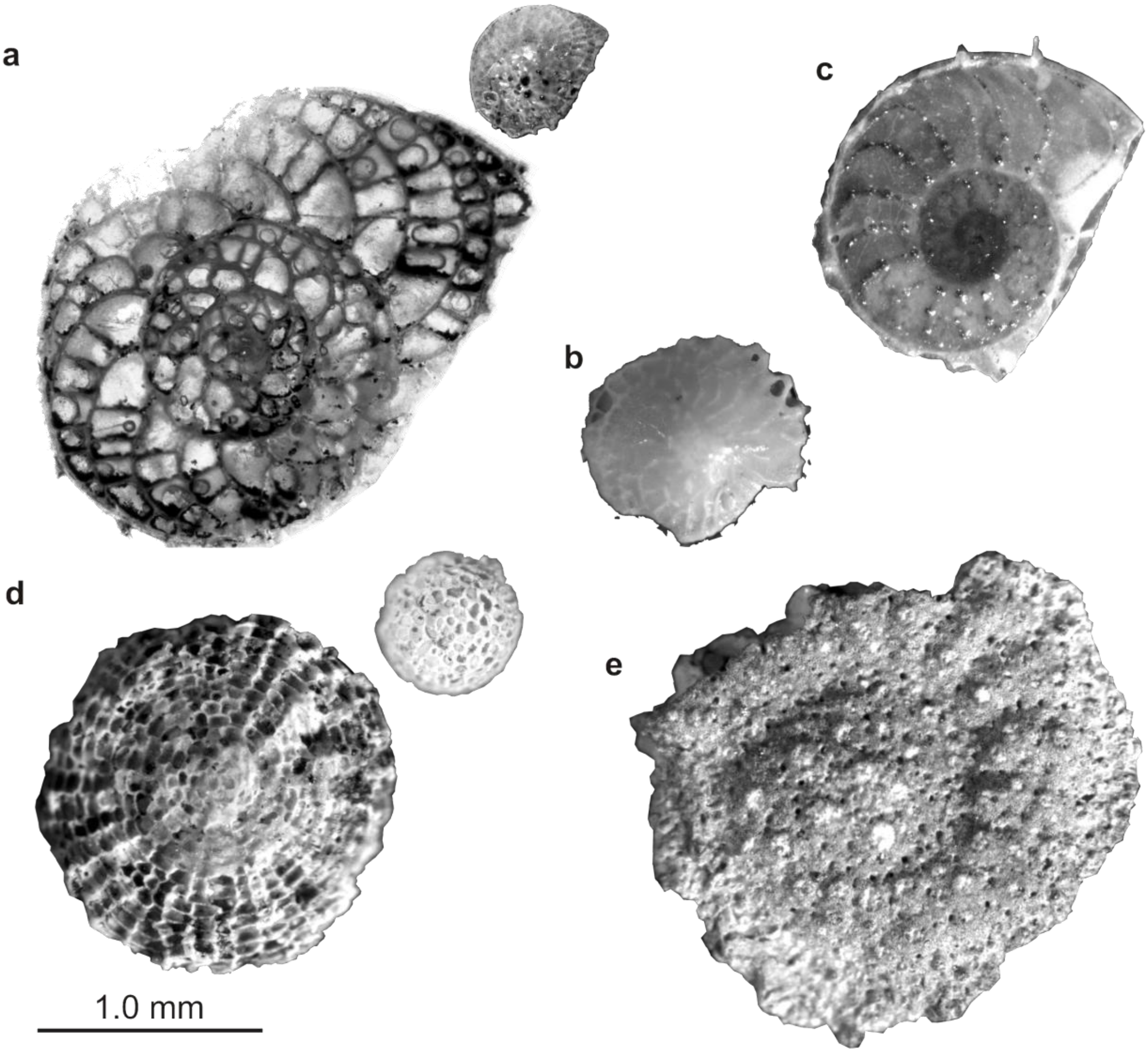

Figure 4.11. Clay specimens: a) *Spiroclypeus* sp. equatorial section, external view also shown, TDP 12/20/1 41-50 cm (1); b) *Heterostegina* sp., external view, TDP 12/38/3 83-93 cm; c) *Operculina* sp., external view, TDP 12/19/1 22-34 cm; d) *Sphaeorogypsina* sp., sub axial section, external view also shown, TDP 17/25/2 48-59 cm e) *Pellatispira* cf. *madaraszi* (Hantken, 1876), external view, TDP 12/14/1 14-22 cm;

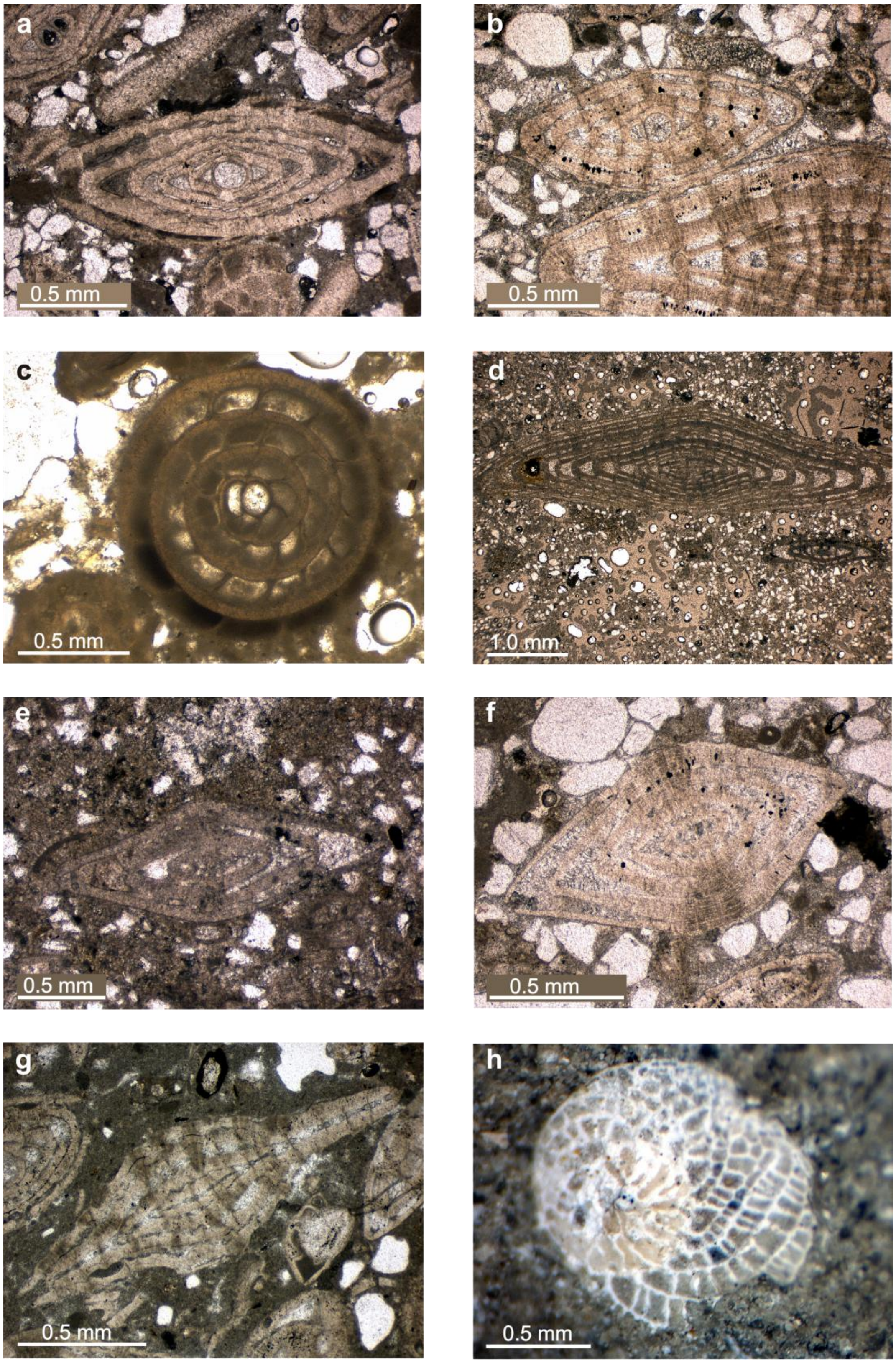

Figure 4.12. Limestone specimens: a) Reticulate *Nummulites* sp., axial section, TDP 11/28/1 64-68 cm; b) Reticulate *Nummulites* sp., axial section TDP 11/34/2 60-71 cm; c) Reticulate *Nummulites* sp., equatorial section, TDP 12/15/3 74-78 cm; d) Reticulate *Nummulites* sp., sub axial section, TDP 11/4/1 61-108 cm; e) Striate *Nummulites* sp., sub axial section, TDP 11/3/1 50-53 cm, f) *Palaeonummulites* cf. *variolarius* (Lamarck, 1804), oblique section, TDP 11/34/4 ; g) *Spiroclypeus* sp. sub axial section, TDP 12/16/1 0-55 cm; h) *Spiroclypeus* sp., specimen on rock surface TDP 12/21/2 66-88 cm.

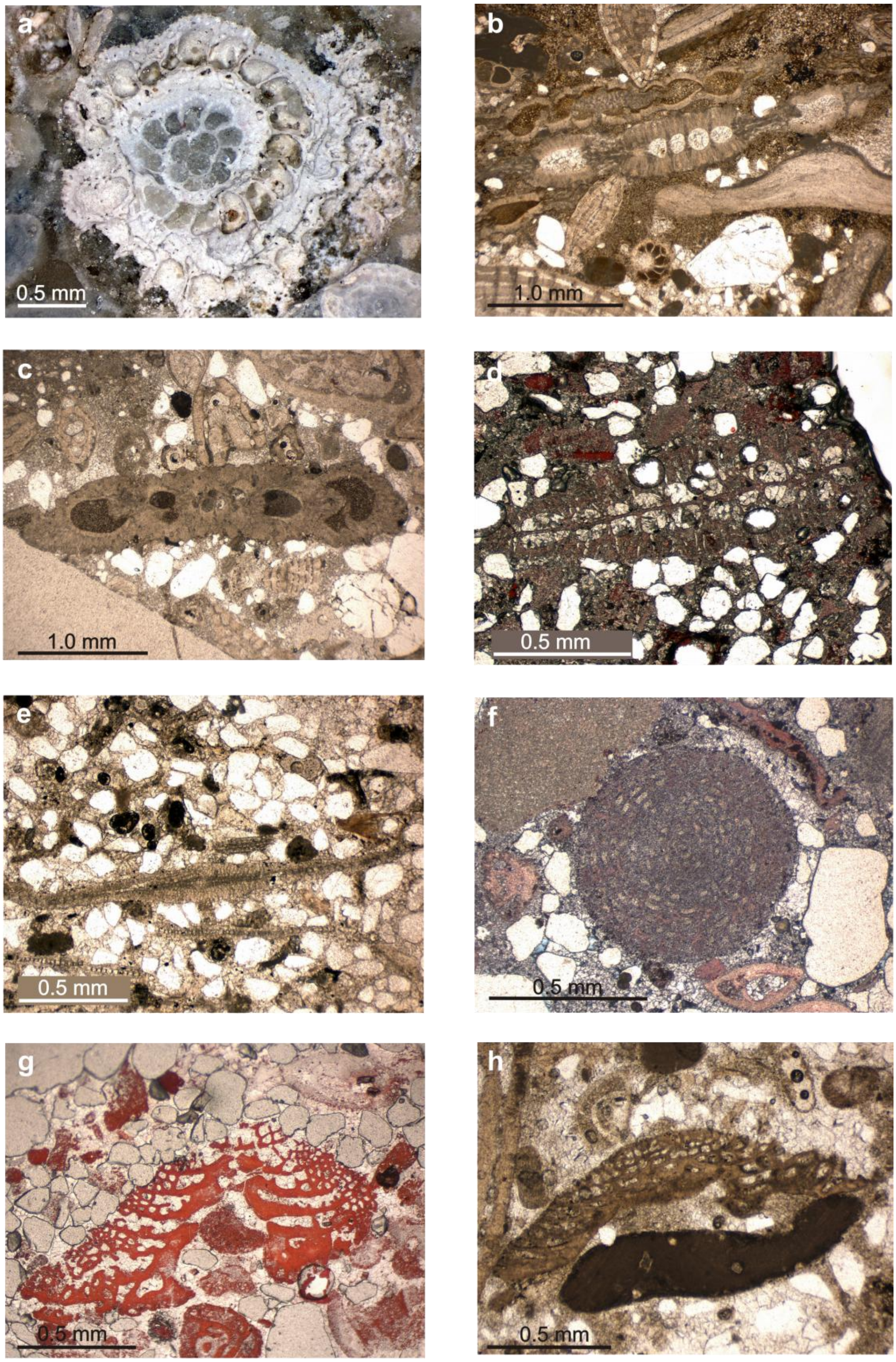

Figure 4.13. Limestone specimens: a) *Pellatispira* cf. *madaraszi* (Hantken, 1876), equatorial section TDP 12/15/4 0-7 cm; b) *Pellatispira* cf. *madaraszi* (Hantken, 1876), sub axial section sample K18; c) *Pellatispira* sp., oblique section TDP12/16/1 0-55cm; d) *Biplanispira* cf. *mirabilis* (Umbgrove, 1936), sub axial section TDP 12/14/2 1-10 cm; e) *Discocyclina* sp., axial section, TDP 12/14/2 1-10 cm; f) *Sphaerogypsina* sp., sub axial section, TDP 11/35/1 0-63 cm; g) *Fabiania* sp., sub axial section TDP 12/15/2 15-25 cm; h) *Fabiania* sp., sub axial section, TDP 11/35/1 51-63 cm.

Chapter 5:

Testing the theory: The Melinau Limestone, Sarawak and Fuente Caldera and Cortes Zarabanda sections, Spain.

The work on the section of Cortes Zarabanda was part of a collaborative integrated micropalaeontological study, which has been published as a paper. The reference for this is Fenero, R., Cotton, L., Molina, E. and Monechi, S., 2013. Micropaleontological evidence of the late Oligocene Oi-2b global glaciation at the Zarabanda section, Spain. Palaeogeography, Palaeoclimatology, Palaeoecology 369, 1-13. Within this work analysis of planktonic foraminifera was carried out by EM, benthic foraminifera by RQ, nannofossils by SM and LBF by LJC. Only the parts of the study carried out by LJC are included in this chapter as modified versions from the paper.

5.1 Introduction

Within the Tanzanian Eocene - Oligocene Transition (EOT) section discussed in the previous chapter the extinction of the LBF occurs at the Eocene / Oligocene boundary (EOB), coincident with the extinction of the Hantkeninidae. This precedes the global sea-level fall by 200,000 years, indicating it is not the cause. In this chapter studies of two further EOT sites were carried out for comparison with the results of the Tanzanian study to ascertain whether this is a truly global phenomenon. The two sections are the Melinau Limestone section of Sarawak and Fuente Caldera section in Spain. Additionally, an upper Rupelian site close to Fuente Caldera was studied to determine the potential of using integrated studies including LBF in identifying links between other climatic events and LBF. Both the Melinau Limestone and Fuente Caldera are reported to continuously span the EOT and contain LBF across this interval. However both sections have different but unresolved questions relating to the LBF events at the boundary which this chapter aims to address.

The Melinau Limestone, like Tanzania, is within the Indo-Pacific region but is located in Sarawak on the opposite side of the Indian Ocean. This succession is thought to be one of the most complete shallow water sections across the EOT (Adams, 1965; Adams et al., 1986; Renema, 2002). Both its location and completeness make it a good comparison to Tanzania, to determine if the same extinction pattern is found across the Indo-Pacific region. However, previous studies have been unable to determine the exact boundary level (Adams, 1965; Adams et al., 1986). Bulk isotope studies were therefore carried out as part of this study to identify major isotopic shifts associated with the EOT and constrain the timing of LBF events.

The Fuente Caldera section is a succession of hemipelagic marls with turbiditic LBF rich limestones within the Tethyan region. The section is known to continuously span the EOT, but an extended range of orthophragmines has been reported from the site (Molina, 1986; Molina et al., 2004; Molina pers. comm.). Orthophragmines are generally thought to become globally extinct at the EOT (e.g. Serra-Kiel et al., 1998; BouDagher-Fadel, 2008) and in Tanzania this has been found to occur at the EOB (Chapter 4; Cotton and Pearson, 2011). The extended range reported from Fuente Caldera is therefore highly unusual. The LBF and sedimentation of this site were therefore examined firstly to confirm the occurrence of the orthophragmines and secondly to determine if different events within the LBF were occurring during the EOT of the Tethyan region or whether it is an artefact of sedimentation.

Close to the site of Fuente Caldera is Cortes Zarabanda, which also contains LBF in limestone beds within a hemipelagic marl succession. In collaboration with researchers at the University of Zaragoza and University of Firenze an integrated micropalaeontological study was carried out to determine biostratigraphy and palaeoenvironmental changes in this section. This shows the potential of studies beyond the EOT linking changes in LBF assemblages with smaller climatic events in the Oligocene.

5.2 Melinau Limestone, Sarawak

5.2.1 Introduction

The Melinau Limestone of Sarawak is thought to be one of the most complete shallow water Cenozoic sections in the Indo-Pacific region (Adams, 1965; Adams, 1970; Adams et al., 1986). The succession consists of ~2000 m of continuous shallow water carbonate sedimentation from the Bartonian to Miocene and spans the EOT (Adams, 1965). An extensive biostratigraphic study was carried out by Adams (1965), however, the exact level of the EOB remained uncertain largely due to the lack of independent dating. Adams (1965) found that the Eocene faunas disappear rapidly, followed by an interval containing no LBF before the Oligocene faunas gradually emerged. The EOT could therefore only be constrained to this interval. Here bulk stable isotope analysis is carried out on the section for the first time, using the samples of Adams (1965) as provided by the Natural History Museum, London. The resulting isotope record allows for comparison with global chemostratigraphy and clarifies the events of the EOT. This enables the extinction pattern to be determined and compared to the results from Tanzania.

The Melinau Limestone is located in Sarawak, just south of Brunei (Figure 5.1). It is named after the river Melinau which cuts through its centre and provides one of the best sections through the stratigraphy in the Melinau Gorge (Adams, 1965). The limestone is approximately 37 km in a NE-SW direction and 8 km at its widest with a thickness of ~2000 m (Adams, 1965). The Melinau Limestone contains an LBF succession from Bartonian to Miocene within almost a single facies, making it exceptionally important for biostratigraphy (Adams, 1965). It therefore provides a standard section against which shorter sections from Indo-Malaysia can be compared, and was used extensively within revisions of the East Indian Letter Classification (Adams, 1965; Adams, 1970; Adams et al. 1986). However, few age-diagnostic fossils other than LBF are present in the section (Adams, 1965). The biostratigraphy is determined from the LBF, which can be problematic due to species endemism and migration events (see discussion in section 4.2). Though broad correlations can be made with planktonic biostratigraphy and climatic events, exact correlations are more difficult.

The EOT is recognised within the Melinau Limestone due to a large overturning of LBF (Adams 1965; Adams et al., 1986), but the exact EOB level remains uncertain. Adams (1965) constrains the EOB to occurring between sample 10085 and 10093, in a zone labelled “?Tc” on his biostratigraphy chart. Taxa that are recorded as disappearing are *Discocyclina*, *Fabiania saipanensis*, *Pellatispira*, *Spiroclypeus vermicularis* and at least one species of striate *Nummulites* (Adams, 1965; Adams et al., 1986). The last occurrences of these taxa are all within a short stratigraphic interval in the uppermost Eocene whilst the new Oligocene assemblages appear gradually after the boundary (Adams, 1965). Between the last age-diagnostic late Eocene assemblages and the first datable Oligocene assemblages there is a thick succession of algal limestones (~60 m) devoid of age diagnostic fossils, which has been interpreted as representing a sea-level

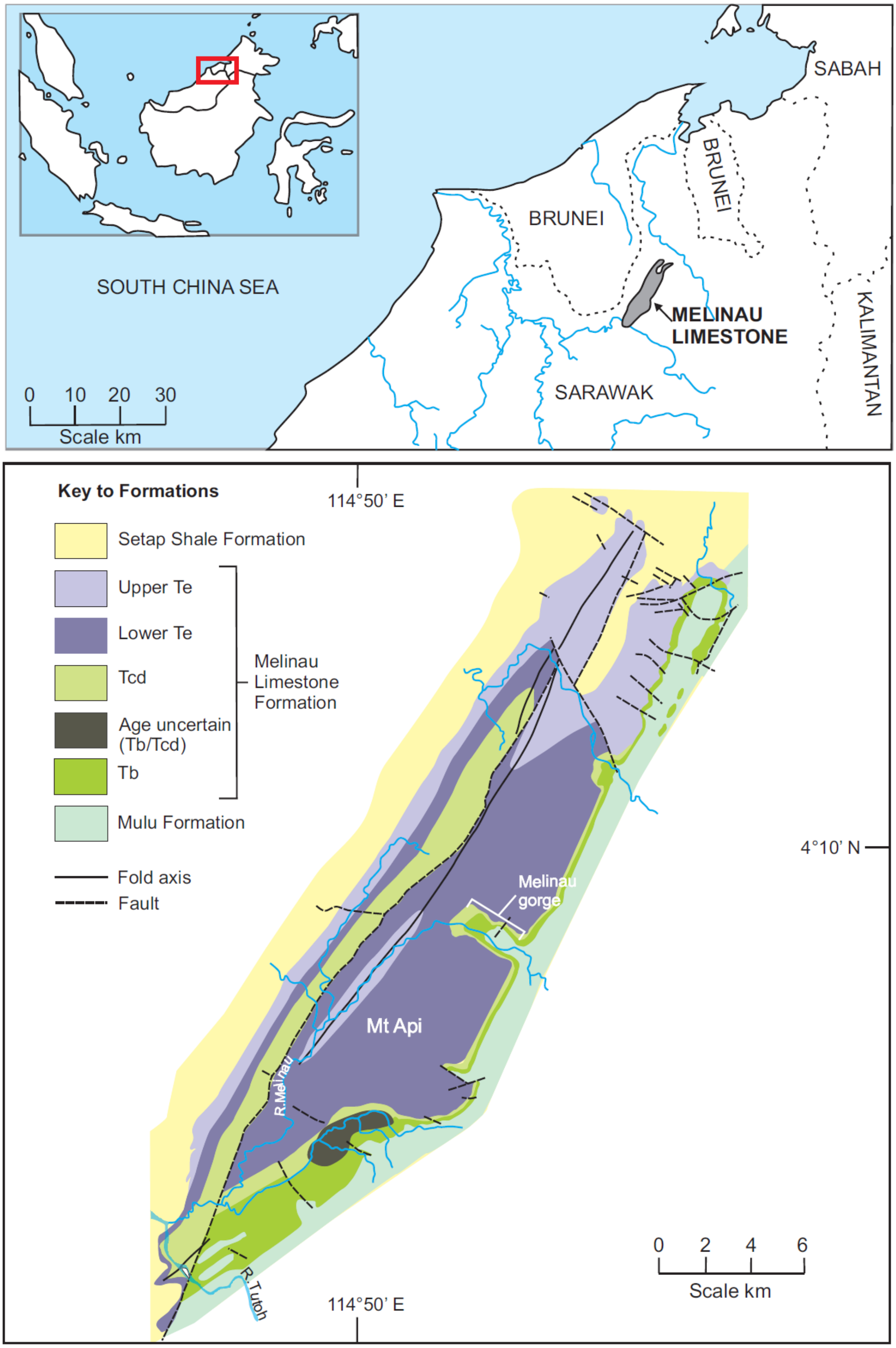

Figure 5.1. Location and geological maps of the Melanau Limestone, Sarawak modified from Adams (1965).

fall across the transition (Adams, 1965; Adams, 1970; Adams et al., 1986). Adams et al. (1986) proposed this sea-level fall as a potential extinction mechanism for the LBF at the EOT, though the results from the Tanzanian EOT section show this is not the case in Tanzania (Chapter 4; Cotton and Pearson, 2011)

Using the samples of Adams, which have already been studied extensively in terms of biostratigraphy, bulk oxygen and carbon stable isotope analysis was used to provide an independent age constraint on the LBF events and determine the extinction pattern within the Melinau Limestone. This enables a comparison with the results from Tanzania to determine if the same events are visible across the Indo-Pacific, in one of the most complete EOT sections known from the Indonesian region.

5.2.2 Materials and methods

Samples were collected by G.E.Wilford and studied by Geoffery Adams during the 1960s. Detailed biostratigraphic and lithological data was published in Adams (1965). The samples are currently held at the Natural History Museum in London, in their Wandsworth store. In total 195 samples were collected in sequence from the Melinau gorge section which cuts the Melinau Limestone perpendicular to bedding and provides the greatest exposed section, spanning from the Upper Eocene to Miocene. For this study only the Upper Eocene and Oligocene samples were used, a total of 165 samples (numbers S10000 to S10165) over 1036 m. Adams numbered the samples in order along the Melinau Gorge, but only gives stratigraphic heights for a small number of them in Adams (1965). The data has therefore been plotted against sample number.

For the bulk carbonate stable isotope analysis a microdrill was used to grind powder from several areas on fresh surfaces of samples and these were mixed together to homogenise the sample. Between 200 and 400 μg of powder from each sample was weighed and placed into vials. The samples were run on a MAT251 mass spectrometer at Cardiff University, and carbon and oxygen isotope values measured. Values are reported as a permil deviation from the Vienna Pee Dee Belemnite (VPDB). Internal precision, based on replicates of a limestone standard was better than 0.08‰ and 0.06‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively.

5.2.3 Stable Isotope Results

The bulk limestone $\delta^{18}O$ and $\delta^{13}C$ values are shown plotted against the range

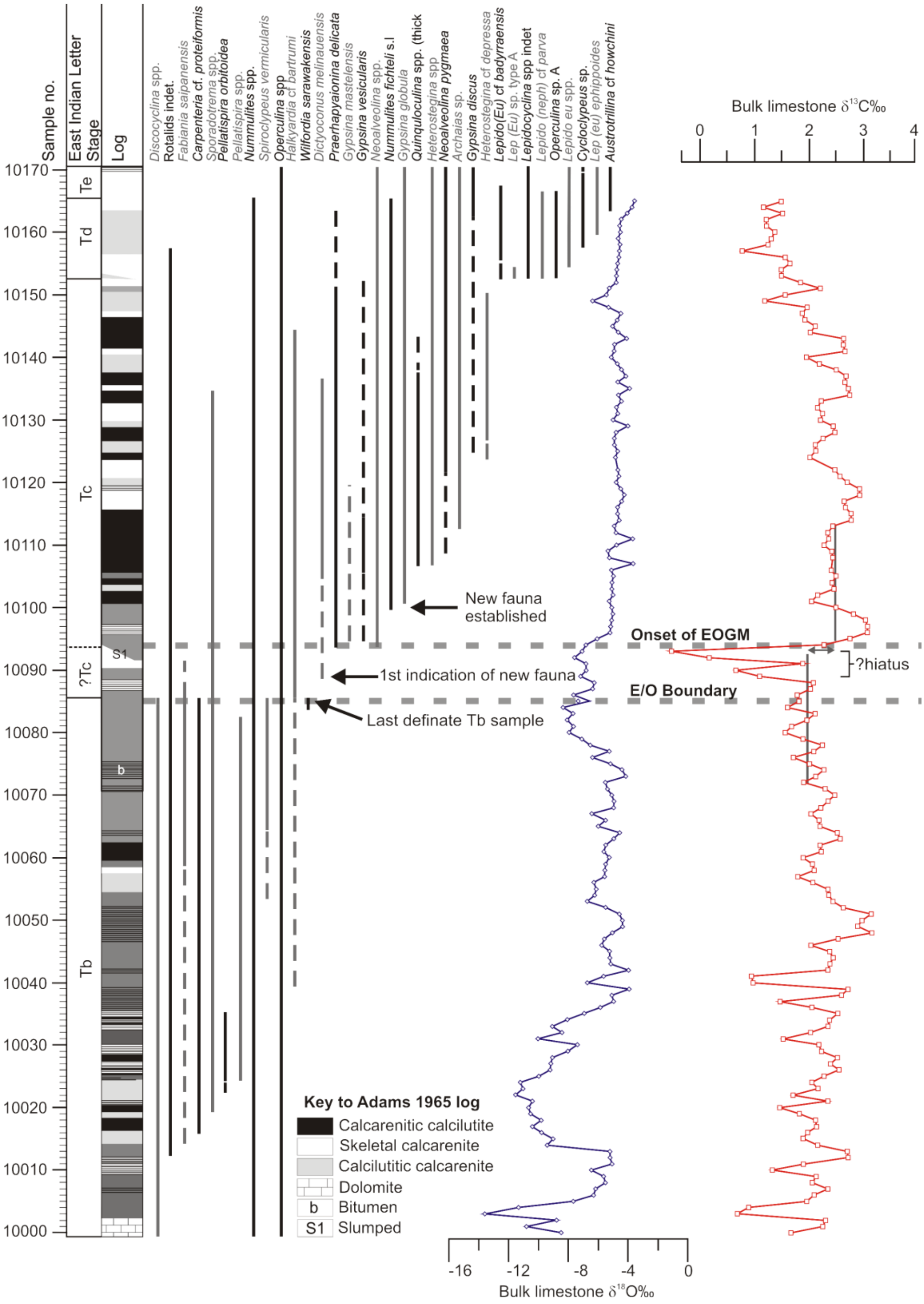

Figure 5.2. Bulk isotopes plotted against the range chart and log of Adams (1965). δ^{18}O values are shown in blue and δ^{13}C in red, the shift in δ^{13}C isotopes across the onset of the EOGM is indicated by grey bars.

chart, assigned letter stages and log of Adams (1965) in Figure 5.2. The $\delta^{18}O$ values range between -3.5 and -13.5 ‰. The most negative values occur towards the base of the section between samples 10000 and 10034 with a value of -13.6 ‰ in sample 10003. From sample 10034 to 10085 values are more stable and are in the range of -4 ‰ to -6 ‰. There is then a decrease in values forming a plateau between sample 10086 and 10096 of values around -7 ‰. Following this the isotope record is stable with values of around -5 ‰, with only a slight negative excursion in sample 10152.

The $\delta^{13}C$ record shows a range of values between -0.5 ‰ and 3.2 ‰. The initial Tb section of the $\delta^{13}C$ record, from 10000 to 10054, is variable with values of ~0.5 ‰ to 3.2 ‰. From 10055 to 10088 values are more stable and show an overall slight increase. This is followed by a sudden negative spike of ~-0.5 ‰ in sample 10093 and then a smaller positive overshoot immediately afterwards of ~3 ppm, before returning to values of around 1.5 ‰ to 2.5 ‰. Values then begin to decrease towards the top of the section. There is a general increase in the $\delta^{13}C$ values of 0.5 ppm between the record before and after the spike in sample 10093, this is marked by the grey bars on Figure 5.2.

When plotted against the range chart of Adams (1965) the plateau in the $\delta^{18}O$ record and overall shift with negative spike in the $\delta^{13}C$ record broadly correlate with the interval which was referred to as Tc? by Adams (1965), in which the EOB was thought to occur. The last definite Tb assemblage occurs within the stable period in the $\delta^{13}C$ record, with no large shift in the isotopes at this level. The first indication of the new "Oligocene" assemblage occurs above this in sample 10089, just preceding the spike in the $\delta^{13}C$ values. The Oligocene assemblage is more apparent in sample 10094, immediately above the spike and becomes fully established in sample 10100, immediately after the overshoot. The results therefore appear to show possible correlations between the two records.

5.2.4 Comparison to EOT stable isotope records

The $\delta^{18}O$ record shows very negative values, particularly toward the lower part of the section this is likely to be related to diagenesis, as Adams (1965) reports extensive recrystallisation and some dolomitisation in the section. The very flat $\delta^{18}O$ values in the Oligocene further suggest that they have been reset during a later event. There appear to be several sections to the curve which may be related to preferential diagenesis of particular beds or diagenetic events may affect particular parts of the sequence. The high diagenetic alteration of the $\delta^{18}O$ values therefore means they offer little insight into determining the boundary level.

The carbon isotope data are, however, more promising. The $\delta^{13}C$ values were plotted against $\delta^{18}O$, but no co-variance was visible (Figure 5.3). This indicates that the $\delta^{13}C$ are likely to be less altered and have not been reset by the same processes affecting the $\delta^{18}O$ values. The step of +0.5 ‰ in values seen just after sample 10093 is comparable to the $\delta^{13}C$ shift seen at the Early Oligocene Glacial Maximum (EOGM) in both Tanzania (Pearson et al., 2008) and deep sea ODP sites (Coxall et al., 2005; Coxall and Pearson, 2007). Additionally the record also shows a small initial overshoot of $\delta^{13}C$ to more positive values, which is also recognised in both the global records and Tanzania (Coxall et al., 2005; Coxall and Pearson, 2007; Pearson et al., 2008). The general trend of the Melinau Limestone $\delta^{13}C$ record therefore appears consistent with other EOT records within the boundary interval.

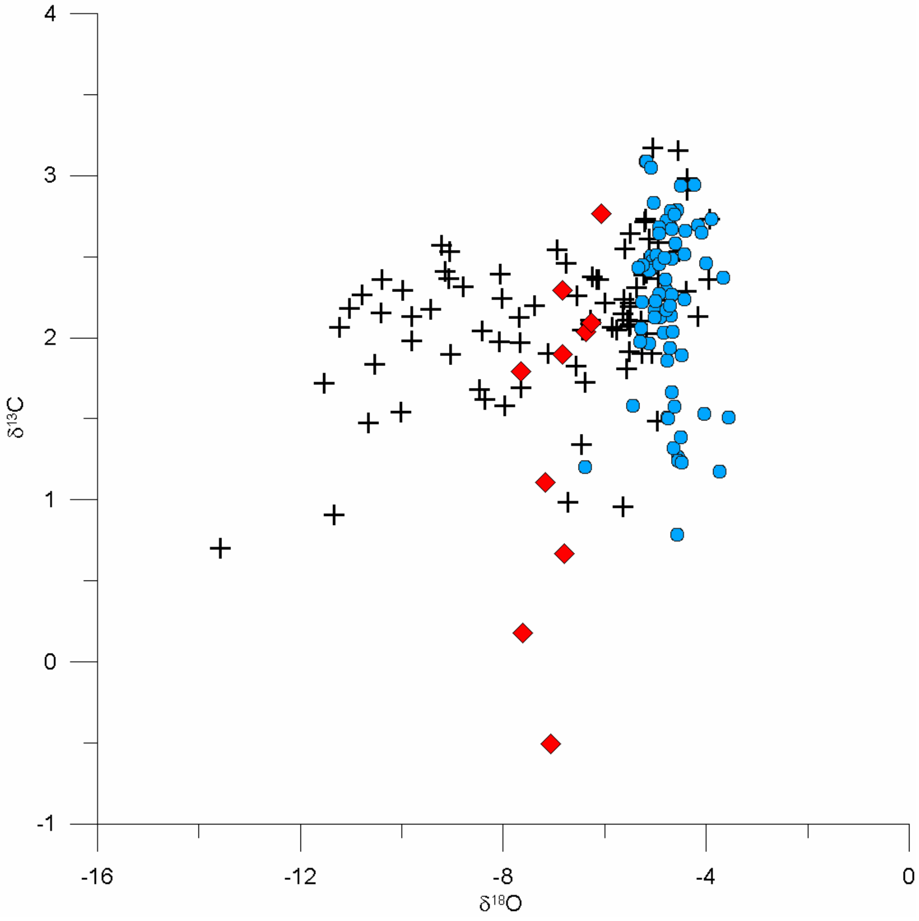

Figure 5.3. Plot of $\delta^{13}C$ against $\delta^{18}O$; crosses represent samples 10096 to 10165, red diamonds samples 10086 to 10095 and blue circles 10000 to 10085.

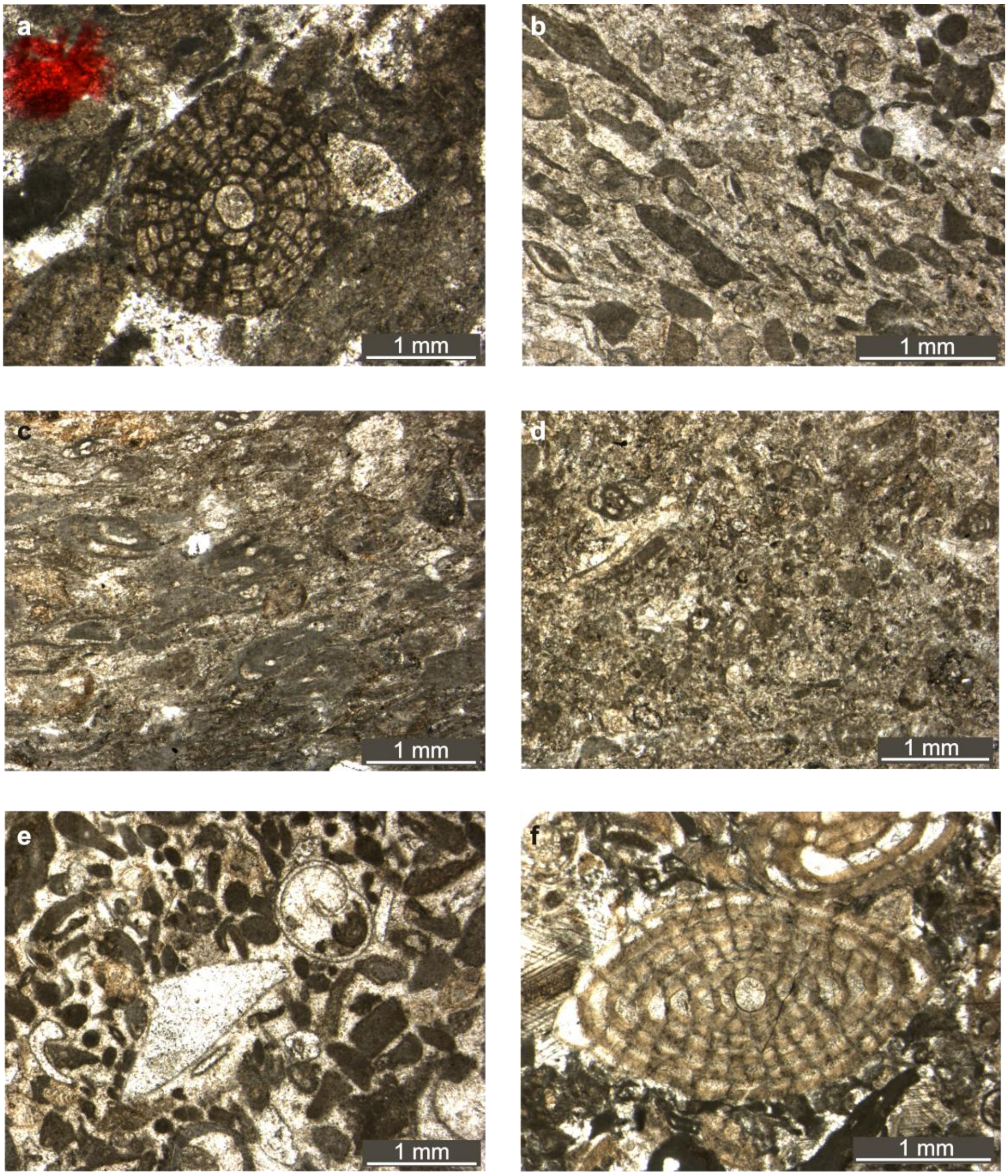

Figure 5.4. a) Image from thin section 10084 showing holotype of *Wilfordia*, common in the Priabonian of the Melinau Limestone; b) thin section 10092 showing lineation and recrystalisation of the limestone; c) thin section 10093 showing strongly deformed limestone; d) thin section 10094 showing recrystallisation of the limestone; e) thin section 10095 algal rich grainstone showing no obvious deformation; f) *Nummulites fichteli* in sample 10100

However the $\delta^{13}C$ spike in sample 10093 does not match with complete records seen elsewhere. This spike occurs just beneath the overall $\delta^{13}C$ shift, which represents the onset of the EOGM. The EOGM is a period of major ice growth it is associated with major sea-level fall (see Chapter 4). Adams (1965) noted a facies change to more algal dominated limestones during the ?Tc interval, which was interpreted as being due to shallowing of the shelf. The excursion in $\delta^{13}C$ may therefore represent a short disconformity due to sea-level fall. Thin sections from the Natural History Museum of samples S10090 to S10095 were examined, but no definite evidence of an exposure surface was found. However, this does not necessarily mean there was no exposure surface; lithological indicators of exposure are environmentally specific and so if the palaeoenvironment in Melinau was either too dry or too wet no indications of its exposure would be preserved (V. P. Wright pers. comm.). The thin sections from samples within this interval all lack LBF, as reported by Adams (1965) and are largely composed of miliolid foraminifera and algae. They also show considerable recrystallisation and deformation (Figure 5.4b-d). Sample 10093 appears to be most deformed with an almost schist like foliated texture in thin section (Figure 5.4c). The limestones on either side of this interval appear undeformed and LBF rich. The $\delta^{13}C$ spike therefore coincides with the most deformed samples, but there is no co-variant spike in the $\delta^{18}O$ values which would be likely if caused by diagenetic processes. The cause of the $\delta^{13}C$ spike therefore remains uncertain. One possibility is that an exposure surface did form and created a weakness along the rock allowing a fault plane to occur along it. This would then account for both the $\delta^{13}C$ spike and the deformation visible in thin section. However, the site would need to be visited to determine whether this occurred.

5.2.5 EOT Extinction pattern

The extinction level in Adams' (1965) study occurs between sample 10085 and 10086 (see Figure 5.2). Several major groups of LBF including orthophragmines and pellatispirids become rapidly extinct between 10085 and 10086. A new assemblage starts to appear slightly above this in sample 10089. This is then followed by the onset of the EOGM and associated sea level-fall at sample 10093, this perturbation in the shallow water environment may prevent the Oligocene assemblage from becoming established initially. The Oligocene fauna then becomes more established from sample 10100 onwards. Due to the lack of planktonic foraminifera within shallow facies along with the poor δ^{18}O record it is not possible to determine if the LBF extinction coincides with the level of the Hantkeninidae extinction. However, the LBF extinction in the Melinau Limestone is appears to occur below the δ^{13}C isotope shift indicating the level of the EOGM and associated sea-level fall, as also recognised in Tanzania. This supports the conclusion that sea-level fall and associated decrease in platform space is not the major cause of their extinction and further supports that the extinction pattern found in Tanzania is likely to be a global phenomenon. This enables the extinctions of LBF that occur at the EOB to be used as a global biostratigraphic tie point between the regional LBF zonal schemes, planktonic biostratigraphy and the global isotope curve.

5.3 Fuente Caldera

5.3.1 Introduction

Fuente Caldera is a well-known Tethyan EOT site in southern Spain which has been subject to detailed micropalaeontological study (Molina 1986; Molina et al., 1986; Molina et al., 2004; Molina et al., 2006; Robin and Molina, 2006; Alegret et al., 2008; Fenero et al., 2008;). The majority of work at this site has been carried out on the planktonic and smaller benthic foraminifera through the Priabonian of the section and across the EOT. More recent works by Fenero et al., (2008) and Alegret et al., (2008) examine the upper part of the section from the EOT to the lowermost Chattian, primarily using smaller benthic foraminifera. However, little remains published on the LBF of the section, despite apparently very unusual occurrences. Orthophragmines are considered to become globally extinct at the EOT (Serra-Kiel et al., 1998; BouDagher-Fadel, 2008) but in the Fuente Caldera section a number of orthophragmines, including *Discocyclina,* are reported to extend well beyond the EOB to the Upper Rupelian (Molina, 1986; Molina et al., 2004; Alegret et al., 2008). Additionally there appears to be an apparent replacement of orthophragmines by lepidocyclinids in the Upper Rupelian (E. Molina pers. comm.) which is also not known to occur elsewhere. The last occurrence of the orthophragmines and the first occurrence of the lepidocyclinids in both the Tethys and Indo-Pacific regions are separated by the duration of most of the Rupelian. Due to these unusual occurrences and lack of previous detailed study, we were invited by E. Molina of the University of Zaragoza to sample and study the LBF of the section. The range of the orthophragmines is identified, along with the ranges of associated LBF, and the nature of the sedimentation within the sequence is assessed to determine whether the extended range of the orthophragmines is a true occurrence or an artefact due to reworking of older material.

The Fuente Caldera section is located in the township of Pedro Martinez in the northern Granada province, Southern Spain (Figure 5.5). This location is within the median Subbetic realm, which was a subsiding trough during the Eocene, and makes up part of the Betic Cordillera – the most western mountain system of the European Alpine chains (Comas et al., 1985; Molina, 1986). The Fuente Caldera succession consists of a 460 m thick succession of hemipelagic marls with limestone and sandstone beds, spanning the Priabonian to late Chattian. This includes an apparently complete section across the EOT. The hemi-pelagic marls are rich in both planktonic foraminifera, smaller benthic foraminifera and nannofossils, which are generally well preserved enabling detailed biostratigraphic and assemblage studies to be carried out (Molina, 1986; Molina et al., 2004; Molina et al., 2006; Alegret et al., 2008). LBF are present in the limestone beds, which have been redeposited from the carbonate platform into deeper water. These beds occur throughout the section and are considered penecontemporaneous by Molina (1986 and subsequent publications). If this is the case, LBF ranges can be constrained by micro-and nanno-fossil biostratigraphy from the marls. However, two olistostrome levels are present in the Rupelian (Alegret et al., 2008) showing that large scale reworking has occurred in at least some levels.

The biostratigraphy of the lower 106 m of the section and was established in Molina (1986) later refined in Molina et al., (2004) and Molina et al., (2006). The planktonic biostratigraphy shows that the section is apparently complete without known unconformities. The EOB is marked by a faunal turnover including the last occurences of *Turborotalia cocoaensis, T. cunialensis, Hantkenina alabamensis, H. brevispira, Cribohantkenina lazzarii* and *Pseudohastigerina micra* at, or a few 10s of cm below, the boundary (Alegret et al., 2008). An increase in the percentage of high latitude species in the assemblage also occurs towards the early Oligocene (Alegret et al., 2008). A high amount of reworked and epiphytic smaller benthic foraminifera are found thoughout this part of the succession, due to the nearby shallow photic environment. The upper part of the section, approximately 330 m from the EOB to the Upper Chattian has been studied in detail by Alegret et al., (2008). These authors identify several events within the Oligocene of the succession, from benthic and planktonic foraminiferal assemblage

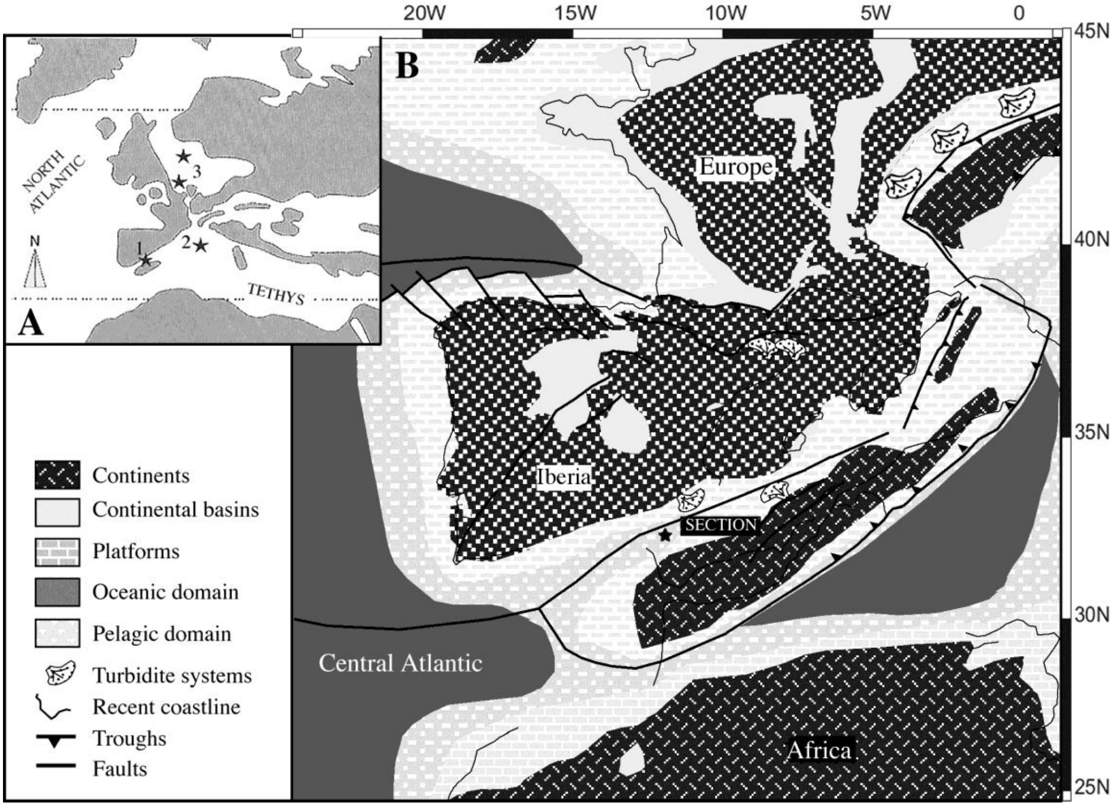

Figure 5.5. Location map of Fuente Caldera, from Alegret et al., (2008).

studies: in the upper part of Zone O1 warming and sea-level rise are recognised; a sea-level fall resulting in the 37 m thick intensively bioturbated layer seen at ~ 235 m, probably due to tectonics; and a warming event in the lower part of O6 which may correspond to the Late Oligocene Warming event.

Despite these extensive foraminiferal studies, there remains little work on the LBF. Molina et al., (2004) found that the LBF assemblage consists of mainly discocyclinids (orthophragmines) nummulitids, pellatispirids and amphisteginids. *Nummulites* and *Spiroclypeus* are recorded as rare, *Heterostegina* and *Pellatispira* as frequent and *Discocyclina* and *Asterocyclina* common (Molina et al., 2004). Additionally occurrences of *Atkinocyclina* and *Gypsina* are reported in Molina (1986). Red algae is also reported to commonly occur (Molina et al., 2004). Molina (1986) writes that the orthophragmines decrease gradually in the upper part of the series but are still well represented in the biozone of *G. tapuriensis*, but does not include them in range charts. The discocyclinids are then reported as being replaced by the lepidocyclinids, but the exact level at which this happens is not explicit in publications. The turnover from discocyclinids to lepidocyclinids is also reported from the nearby site of Molino de Cobo, which has a very similar setting also in the median Subbetic realm (Molina et al., 1988).

5.3.2 Methods

A total of 41 samples were collected from the levels shown in Figure 5.7, spanning the Priabonian through to the Upper Rupelian. Samples were from the limestone beds or from immediately beneath the beds where LBF had been weathered out. Petrological thin sections were made from 12 of these samples to gain an overview of sedimentation and assemblages. Orientated sections of individual foraminifera were made from all samples with LBF to establish the presence or not of orthophragmines. In total 42 oriented sections were used.

5.3.3 Results

5.3.3.1 Sedimentation

The limestone beds in the section vary between fine grained limestones, calcareous sandstones with little or no LBF and LBF rich limestones with LBF clearly visible on the surface in outcrop (Figure 5.6). Rubbly algal material is seen towards the bottom of the limestone beds from 155 m upwards and a considerably thicker limestone occurs at ~320 m (Figure 5.6; 5.7).

The thin sections from the Priabonian samples are located at the base of the section and just below the EOB (samples A and N; see Figure 5.7). Both were composed primarily of LBF (dominated by orthophragmines) and red algae, which appear to have been deposited as uncemented grains. The sediment is highly compacted with very little matrix and strongly sutured grain boundaries between bioclasts. There are occasional pockets of micrite containing planktonic foraminifera. Definite lithoclasts are visible in sample N. They may also be present elsewhere, but this is uncertain due to the lack of matrix for comparison and the suturing of the edges of grains.

Samples Q, R, S and T are from the four limestone beds immediately following the boundary. Q and S are fine-grained, generally well sorted limestones and composed of primarily planktonic foraminifera, smaller benthic foraminifera, red algae fragments and fragments of LBF and bryozoan with very little matrix or cement. Sample S additionally contains quartz grains and occasional larger fragments of (>2 mm) of LBF and red algae within the finer grained matrix. Samples R and T are both very similar to the Priabonian samples; they are largely composed of LBF and red algae, with high compaction, little matrix and sutured grain boundaries. Orthophragmines strongly dominate the assemblage in R, along with nummulitids whilst in sample T orthophragmines are present but a smaller component and nummulitids including *Heterostegina*, *Operculina* and *Nummulites* make up a larger proportion of the assemblage. Planktonic foraminifera are found within micritic pockets in both samples. In sample R small pockets of sparite cement and lithoclasts were also observed.

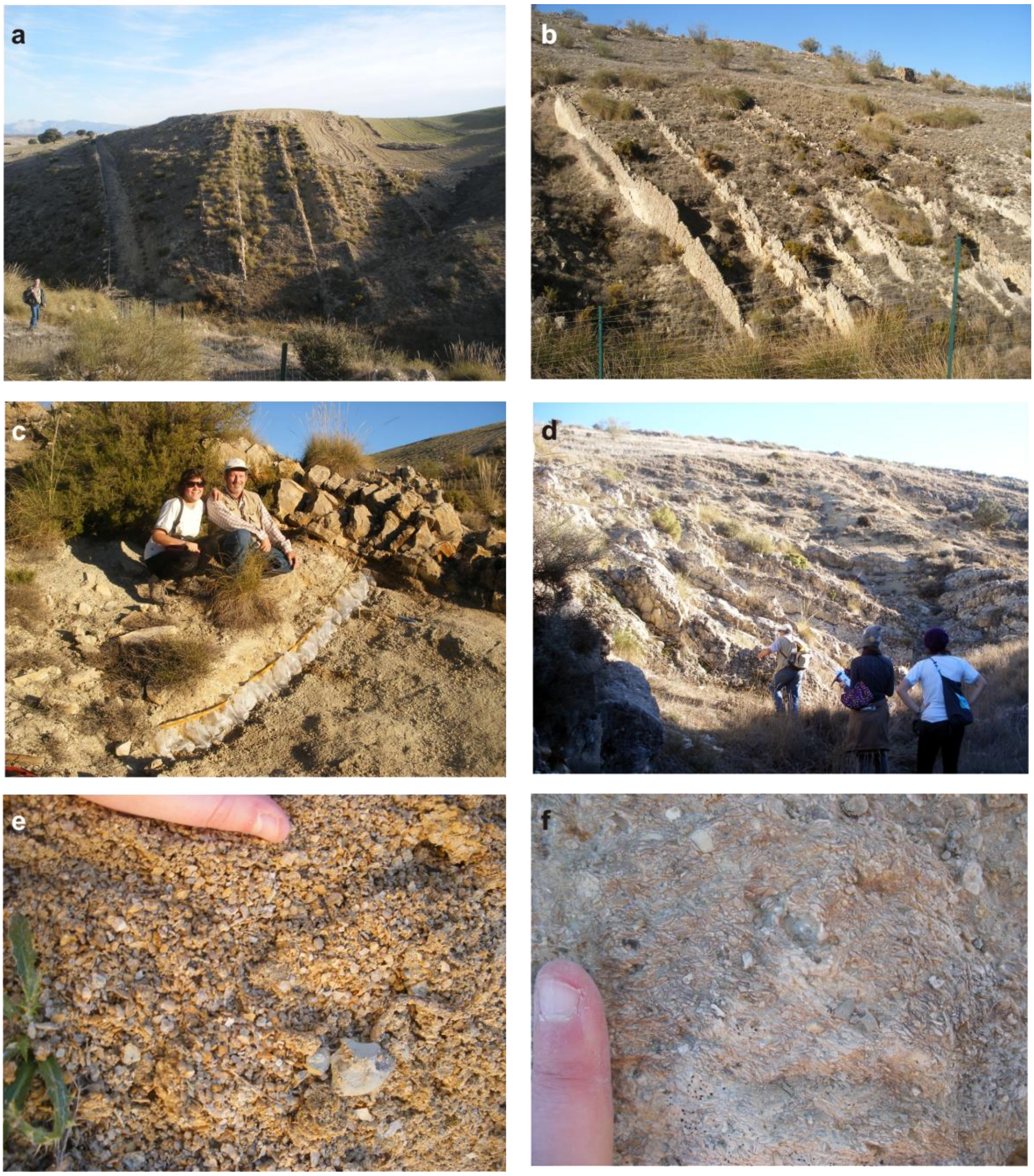

Figure 5.6. a) View of lower part of Fuente Caldera site; b) lower part of Fuente Caldera site showing prominent limestone beds; c) the EOB, marked by hammer; d) thicker rubbly limestone beds in the upper part of the Rupelian; e) loose LBF weathered out underneath limestone beds; f) surface of LBF rich limestone.

The remaining thin sections are spaced through the Rupelian of the succession. With the exception of AJ and AL which are both fine grained grainstones, these samples show a distinct difference in lithology to those found within the Priabonian and just after the EOB (see images in Figure 5.7). These limestone beds are bioclastic packstones with red algal layers and rhodoliths up to ~5 mm in size, coral fragments and LBF. Red algae are the major bioclastic component in these packstones and there is a much larger amount of micritic matrix with little compaction. LBF are present but much less numerous than in previous samples. Planktonic foraminifera can be seen within the micritic areas. Lithoclasts are also frequently observed throughout. In sample AB red algae is observed overgrowing a micritic clast and in AM can be seen overgrowing a reworked LBF. Samples AJ and AL are both fine grained, well sorted pack-grainstones, composed of smaller foraminifera and other carbonate fragments including LBF within little matrix. They are very similar to the fine grained limestones found after the EOB.

The Priabonian and Lower Rupelian limestones are typical of turbidite deposits with little matrix, strong compaction and a mix of shallow water and pelagic material due to extensive transportation. Finer grained limestones are likely to be smaller turbidites or from the upper part of the deposit. The change in sedimentation seen in sample AB is probably due to a change in source area for the sediment, likely related to the tectonically active nature of the region at this time.

5.2.3.2 Palaeontology

The occurrences of LBF are shown in Figure 5.7 plotted against the combined logs of Molina et al., (2006) and Alegret et al., (2008). LBF are found throughout the limestone beds of the Fuente Caldera section, although vary in abundance. In the Priabonian and earliest Rupelian they are the dominant component of the rock, whilst are much less abundant in the upper part of the section. The assemblage consists of mainly orthophragmines and nummulitids, with occasional other LBF. As the main aim was to determine the presence of orthophragmines, extensive sectioning of other groups was therefore not carried out. However, a number of individual sections were made and they are often clearly visible in the petrological sections, which allows for an overview of their occurrences.

The orthophragmines are almost continuous through the section from A at ~5 m to AI at ~270 m. A diverse assemblage is present with at least the genera *Asterocyclina*,

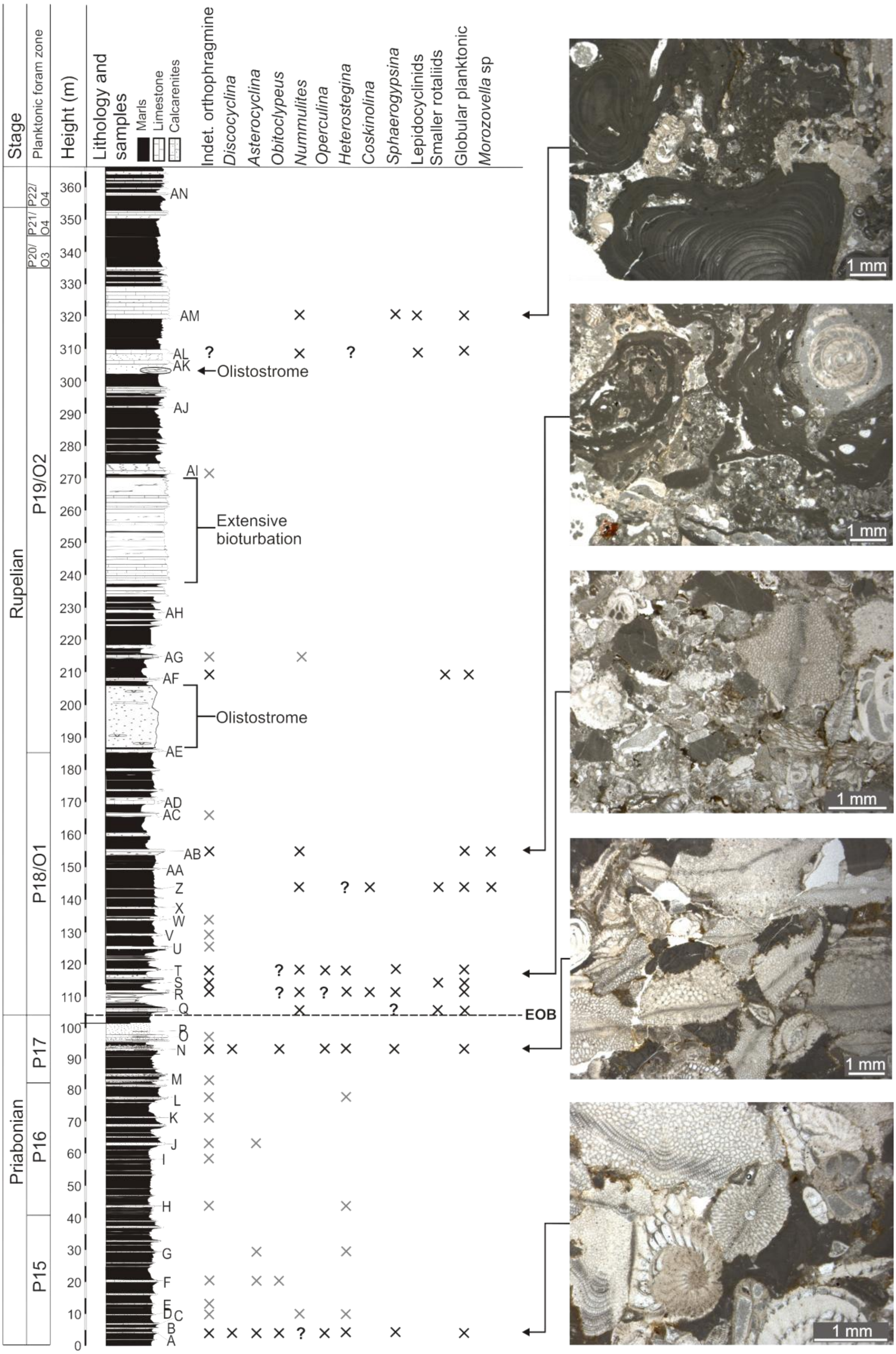

Figure 5.7. Occurrences of LBF and planktonic foraminifera plotted against the combined logs of Molina et al., 2006 and Alegret et al., 2008. Images show the change in sedimentation from orthophragmine rich grainstone with little matrix to more algally dominated packstone with a higher matrix content.

Discocyclina and *Orbitoclypeus* commonly occurring (Figure 5.8). The orthophragmines are abundant in the Priabonian forming ~ 80% of the limestone are abundant in the Priabonian forming ~ 80% of the limestone and appear to have been deposited as uncemented grains. This high abundance is maintained immediately across the EOB, but then begins to decrease from sample T onwards. Nummulitids are also common within the section and are represented by *Heterostegina*, *Nummulites* and *Operculina* (Figure 5.8). *Heterostegina* appears to occur most commonly in the Priabonian samples. *Nummulites* appear more common in the Rupelian, but are found throughout in low numbers. Several species of *Nummulites* are present in the section, but do not appear to occur continuously. *Operculina* is rare throughout. Genera from other groups of LBF also occasionally occur, but make up a minor component of the assemblage. These include *Sphaerogypsina* which is found in low numbers in the Rupelian and *Coskinolina* which occurs in samples Z and R in the lower part of the Rupelian, but is known to have a Paleocene to end Middle Eocene global range.

In the uppermost part of the section lepidocyclinids are found. There is a possible occurrence in sample AL at 310 m and a definite occurrence with multiple specimens within the 10 m thick limestone at 320 m (AM). This occurrence is just above the highest occurrence of the orthophragmines in the section. Planktonic foraminifera have been seen in all thin sectioned samples are likely to be present in the samples that were not sectioned. This indicates that planktonic material was being mixed in with the shallow water material. The majority of planktonic foraminifera seen in thin section appear to be globular forms which are typical of the Oligocene, but also present in sample Z and AB in the early Rupelian were specimens of the genus *Morozovella* (identified by P.N. Pearson).

5.3.4 Discussion

These results confirm the occurrence of orthophragmines throughout the Rupelian of the Fuente Caldera section. The apparent replacement of orthophragmines by lepidocyclinids (as recorded by E. Molina, pers. comm.) is also observed. However there is substantial evidence of reworking of older material which casts doubt as to whether these are true ranges and events. The Priabonian orthophragmines and those from immediately above the boundary appear to have been deposited as uncemented grains in high numbers. It is therefore likely they were either living abundantly on the platform or a build-up of dead tests not yet cemented or a combination of both. If

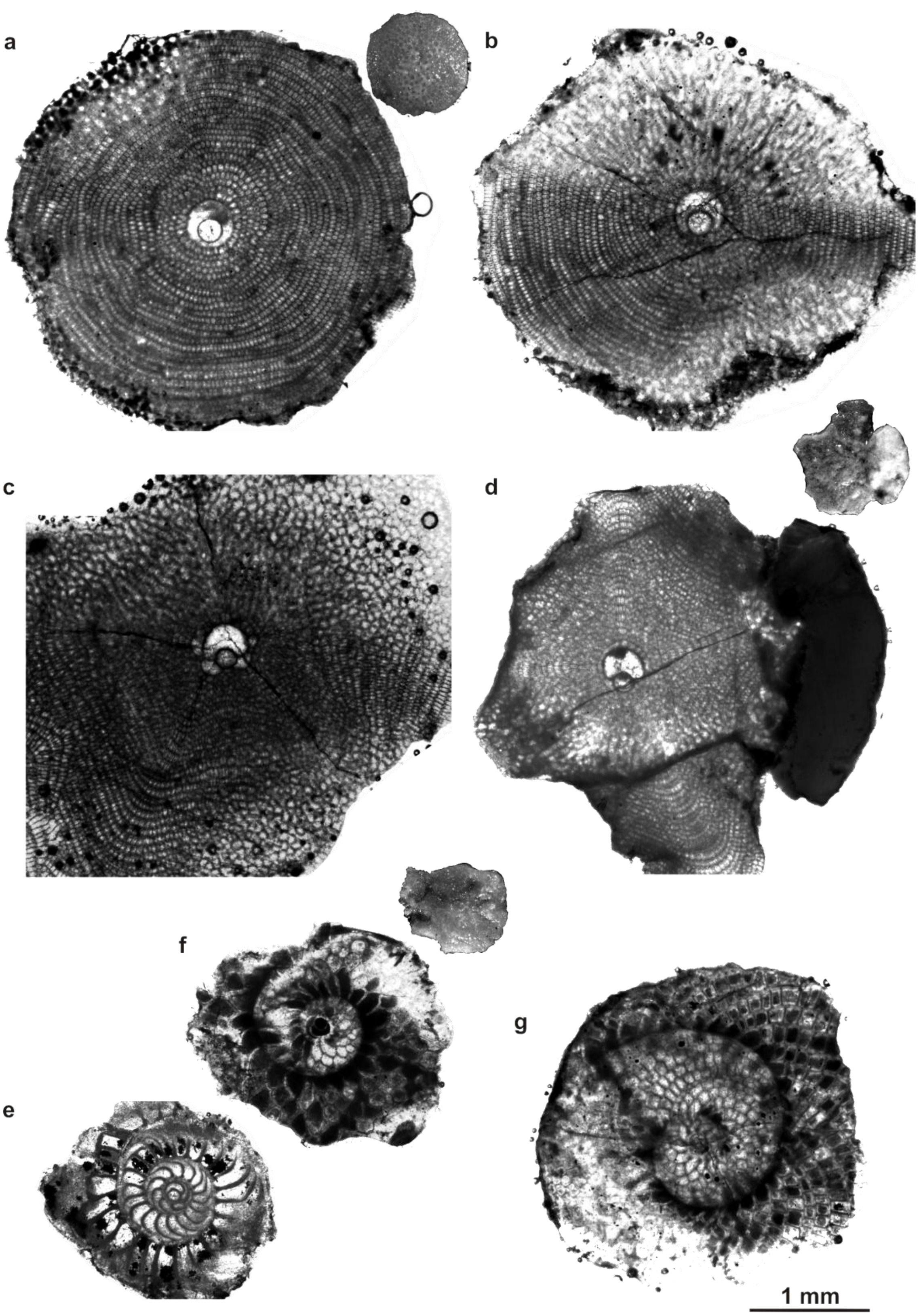

Figure 5.8. Oriented sections of LBF (numbers in brackets indicate oriented specimen number); a) *Orbitoclypeus ?varians* with external view, sample F (1) b) *Orbitoclypeus ?varians*, sample N (2) c) *Asterocyclina ? kecskemetii*, sample I (1) d) *Asterocyclina stella* with external view, sample J (2) e) *Operculina gomezi* sample D (3), f) *Heterostegina reticulata* with external view, sample H (1) g) *Heterostegina reticulata* sample L (1)

orthophragmines had inhabited that area of the platform for some time there may have been a build-up of dead tests beneath the living foraminifera. The abundance of orthophragmines decreases just after the EOB and they become rarer through the section. This indicates a decrease in the number of orthophragmines in the platform source and suggests they are either a significant decrease in their population or they are no longer present but occasional older tests are still being reworked. *Heterostegina, Nummulites* and *Operculina* both have long ranges at a generic level and are common in both the Eocene and Oligocene of the Tethyan region (Schaub, 1981; Banner and Hodgekinson, 1991; Serra-Kiel et al., 1998; BouDagher-Fadel, 2008). They therefore give little insight as to whether other LBF known to become extinct at the EOT also continue. *Heterostegina* shows a similar pattern to the orthophragmines, decreasing in abundance up section which may be due to a shared sediment source. However the presence of *Coskinolina* in the Rupelian is a strong indicator of reworking of older material (Figure 5.9). This genus has a range from the Paleocene to the end of the Middle Eocene (BouDagher-Fadel, 2008). Further evidence of the reworking of Middle Eocene or older sediments is seen in the planktonic foraminifera. *Morozovella* occurs within the Rupelian of the Fuente Caldera limestones. These planktonic foraminifera also became extinct within the late Middle Eocene (Pearson et al., 2006) and so have been reworked from older material. Orthophragmines were also abundant in the Middle Eocene of the Tethys and so may have been reworked from the same material as the *Coskinolina* and *Morozovella*. The lepidocyclinids, however, have a first occurrence consistent with their first occurrence in the Tethys (BouDagher-Fadel and Price, 2010). This also occurs in the thicker limestone bed, suggesting a change in sedimentation occurs at this level and may have begun to source more contemporaneous sediment.

Lithoclasts are frequently visible in hand specimen and thin section throughout the succession (Figure 5.9). Reworking of older sediments therefore occurred throughout the Priabonian and the Rupelian. The two olistostromes in the Rupelian also clearly show large scale reworking is occurring in the section, probably due to tectonic activity.

5.3.5 Summary

Within the Fuente Caldera section there is a large amount of evidence for reworking within the turbidite limestones, particularly during the Rupelian. This

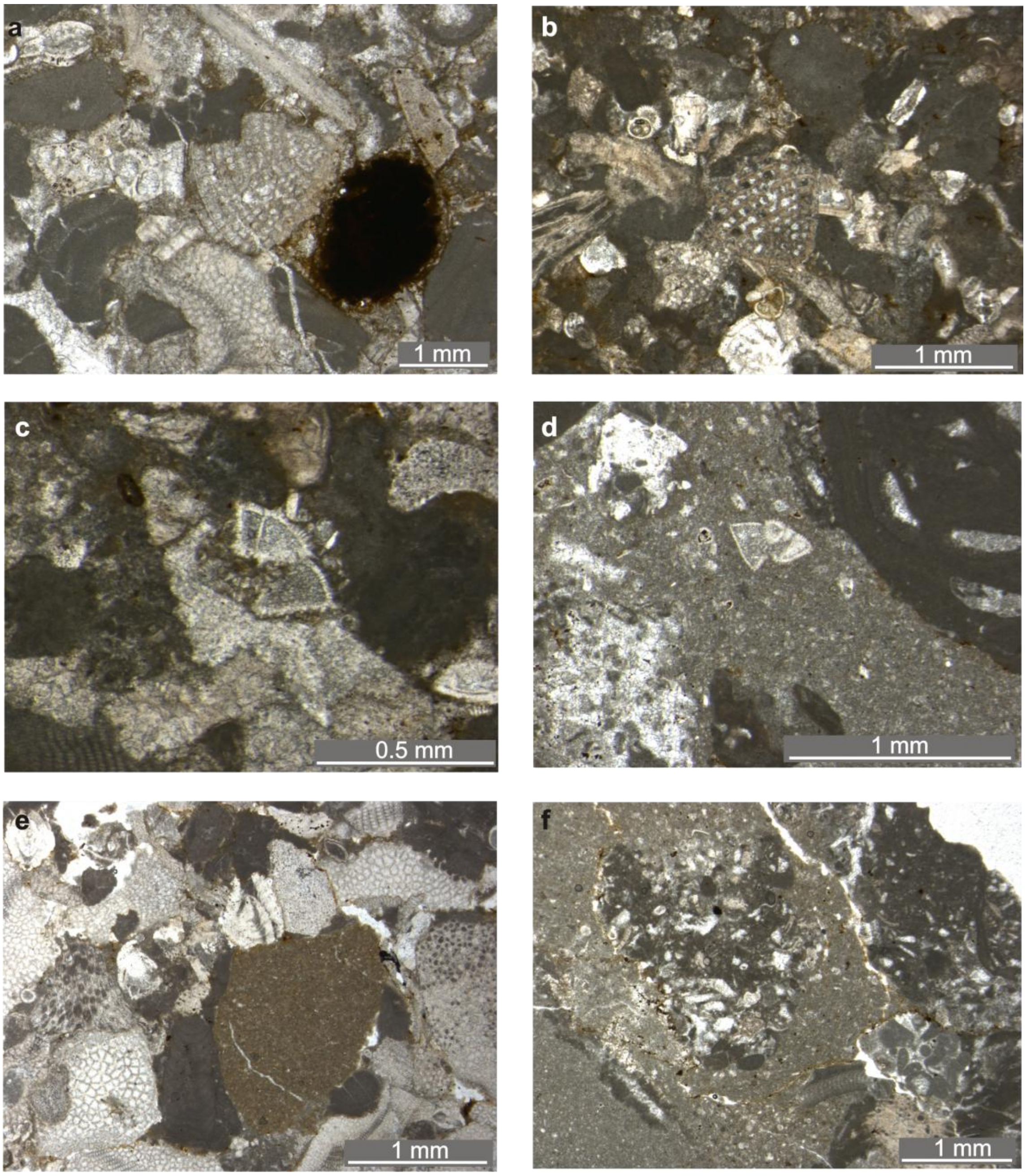

Figure 5.9. Evidence for reworking; a *Coskinolina* in sample R (Rupelian) b) *Coskinolina* in sample Z (Rupelian), c) *Morozovella* in sample Z (Rupelian) d) *Morozovella* in sample AB (Rupelian) e) Lithoclast in sample A, f) lithoclast in sample AB.

coupled with the lack of evidence for orthophragmines beyond the EOB from elsewhere means that although the abundance of orthophragmines in the Priabonian was probably near contemporaneous with the marl deposition, those in the Rupelian were reworked. The apparent replacement of orthophragmines by lepidocyclinds in the Rupelian is therefore an artefact of a change in sedimentation. As the area was tectonically active during the Paleogene this is likely to be related to faulting and/or eustatic sea-level changes. The reported occurrence of orthophragmines in the Rupelian of Molino de

Cobo (Molina et al., 1988) is likely due to the same sedimentary processes as the sites are close to each other and both within the median Subbetic realm.

A change from reworked to penecontemporous sediment appears to occur close to the Rupelian / Chattian boundary with the first occurences of lepidocyclinids. Further Chattian sites showing penecontemporaneous sedimentation are known within this region and a short investigation of one such site is carried out in the following section.

5.4 Cortes Zarabanda

5.4.1 Introduction

An integrated micropalaeontological study was carried out the Oligocene section at Cortes Zarabanda, in order to determine the biostratigraphy of the section and potential links to Oligocene climatic events. Following the events of the EOT the Oligocene climate was variable with several cooling events (Miller et al., 1991; Miller et al., 2008; Miller et al., 2009) linked fluctuations in the Antarctic ice sheet and the formation of cold deep water in the Southern Ocean (Zachos et al., 2001; Lawyer and

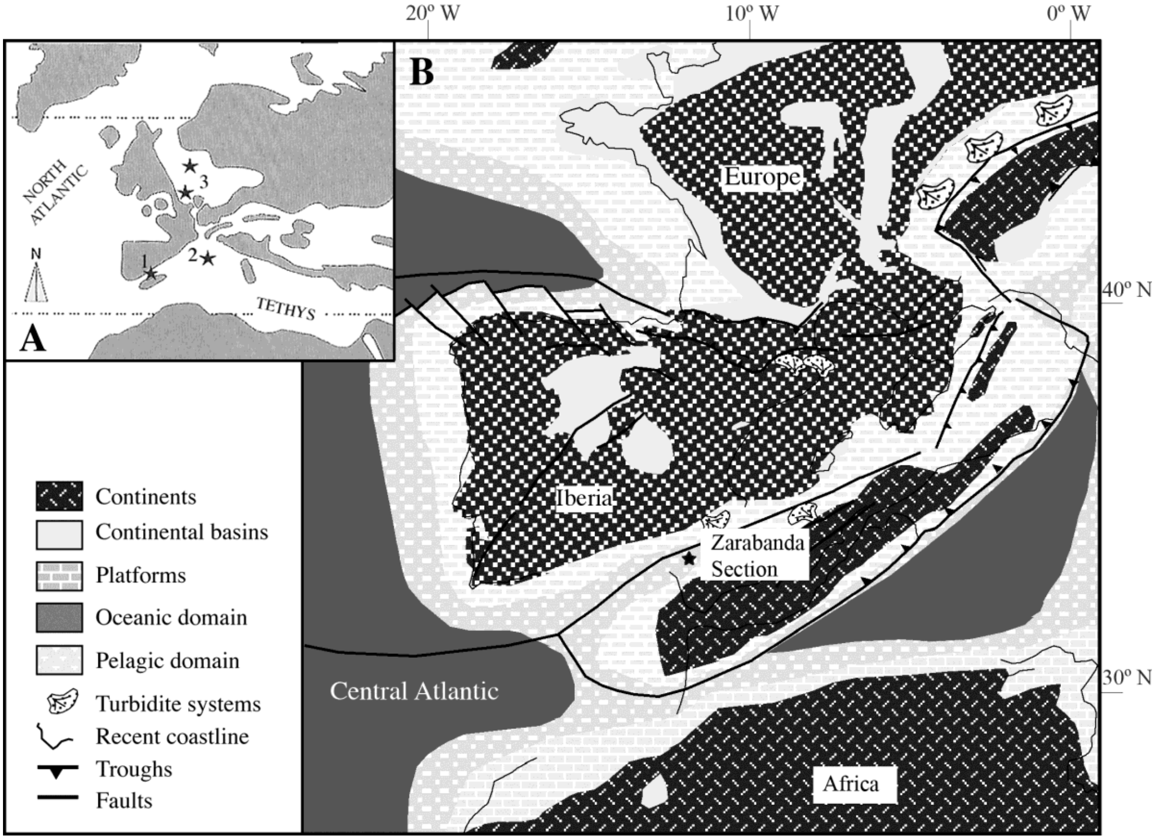

Figure 5.10. Location map of the Cortes Zarabanda site, from Fenerro et al., (accepted with revisions).

Gahagan, 2003). The largest of these events occurred at the EOGM ~ 33.5-33.7 Ma (Miller et al., 1998; Zachos et al., 2001; Coxall and Pearson, 2007; Eldrett et al., 2009). However this was followed by a second large $\delta^{18}O$ isotope excursion at approximately 26.7 Ma which is the Oi−2b glaciation event (Miller et al., 1998; Wade and Palike, 2004; Flower and Chisholm, 2006; Pekar et al., 2006). Two further decreases in $\delta^{18}O$ isotope values were also recognized in the late Oligocene, the Oi−2c (~25.1 Ma) and Mi−1 (~23.2 Ma) glaciation events (e.g., Pekar et al., 2006). Here the results from the LBF study of the Cortes Zarabanda section which were carried out by the author are presented and the compared with the results from studies of other calcareous microfossils from the section which were carried out as part of the collaborative work.

The Zarabanda section is situated very close to the site of Fuente Caldera also within the Subbetic realm (Figure 5.10). The site is from the upper Oligocene but detailed biostratigraphy has not previously been carried out. The section consists of an 82 m thick sequence of hemipelagic marls with limestone and turbiditic sandstone layers. The hemipelagic marls contain abundant planktic foraminifera and calcareous nannofossils, common small benthic foraminifera and rare ostracodes. The smaller foraminifera and calcareous nannofossils studied are from the autochthonous marls. The calcareous sandstone strata contain abundant larger foraminifera and small benthic foraminifera resedimented from the shelf, which appear to have been deposited penecontemporaneously with the marls. The preservation of calcareous nannofossils, planktonic and benthic foraminifera and LBF is moderate to poor.

The biostratigraphy of this site is therefore determined using planktonic foraminifera, LBF, nannofossil and benthic foraminiferal studies. This integrated approach is then used to see whether the cooling events of the Oligocene can be recognised in the section, in particular, whether it is possible to recognise these smaller events (when compared with the EOT) in the LBF record.

5.4.2 Methods

A total of 42 samples were collected at the Zarabanda section for an integrated study of the foraminifera and calcareous nannofossils. Eight of these samples were from the calcareous sandstone and limestone beds for the study of LBF. Samples were collected towards the base of beds, where foraminifera had been naturally weathered out and were clearly visible. The samples were then studied using petrological thin sections and oriented thin sections of individual foraminifera, with the exception of sample Zb A which was studied using oriented individual sections only. In total 15 petrological thin sections and 60 oriented individual thin sections were used in this study.

5.4.3 LBF Biostratigraphy

Within the marl sequence at Zarabanda section there are limestone beds composed of platform carbonate debris, primarily LBF. These beds, though redeposited, are believed to have been deposited as uncemented grains penecontemporaneous with the deposition of the surrounding clays. The limestones can therefore be used to examine the shallow water LBF assemblages and biostratigraphic age across the section and to compare them with the planktic and smaller benthic foraminiferal ages determined from the clays.

The larger benthic foraminiferal assemblage present in the limestone samples is fairly consistent through the log (Figure 5.11), and is common for the upper Oligocene of the Tethyan region. The key foraminifera present for determining the biostratigraphical age of the samples are the lepidocyclinids – *Eulepidina dilatata* and *Nephrolepidina morgani*, and the presence of miogypsinids (Cahuzac and Poignant, 1997). *Operculina?complanata*, *Heterostegina* and *Neorotalia* have long ranges though the Oligocene−Miocene (Cahuzac and Poignant, 1997).

In the lowermost bed, of the diagnostic species mentioned, only *E. dilatata* is present. This indicates that the lowermost bed has a maximum age of middle to lower Oligocene (within SB 22A following the Shallow Benthic Zonation of Cahuzac and Poignant, 1997), and can be no younger than uppermost Oligocene – just below the Oligocene/Miocene boundary (top of SB 23). In sample Zb B no *E. dilatata* are found, but *N. morgani* is present which ranges from the lower part of the upper Oligocene to ~mid lower Miocene (SB 22B to within SB 25). Sample Zb C contains an indeterminate miogypsinid fragment. Miogypsinids have a first occurrence in the upper Oligocene (base of SB 23) and continue to the top of the Lower Miocene (top of SB 25). Samples Zb D, Zb E and Zb G all contain *N. morgani* and are therefore upper Oligocene to the lower Miocene (SB 22B to within SB 25) in age. Sample Zb F contains lepidocyclinid fragments, it is likely that these also belong to *N. morgani*, however there were no clear equatorial sections of A forms for this sample for species level identification. Finally sample Zb H contains *N. morgani* and a miogypsinid specimen the maximum age of Zb H is therefore upper Oligocene – base of SB 23, and the minimum age ~middle to lower Miocene (mid SB25).

The age as indicated by the LBF from the sequence is therefore upper Oligocene to lower Miocene age, though it is possible for bed A to be slightly older – within the upper part of the lower Oligocene.

Planktonic foraminiferal studies indicate the studied section spans the upper part of Zone O5 to O7 of Wade et al. (2011) and does not include the Oligocene/Miocene boundary (Fenero et al., 2013). The calcareous nannofossil analyses support this and conclude the section belongs to the CP19b−CN1 zones of Okada and Bukry (1980) and to the Zone MNP25 and lower part of MNN1 of Fornaciari and Rio (1996) (Fenero et al., 2013). Therefore it is most likely that the larger benthic foraminiferal limestones are upper Oligocene in age, belonging to SB 23.

5.4.4 Palaeoenvironmental implications

As the deposition of the LBF is appears to be penecontemporaneous they can be used to give an insight into the palaeoenvironmental changes occurring on the shallow water platform during this interval.

The beds are coarse bioclastic packstones, with the majority showing strong pressure dissolution structures between grains. The LBF are highly abraded with significant test damage, and are comparable with category 3 in the scale of transportation damage as described by Beavington−Penney (2004). This category indicates extensive transportation by wave action or within turbidity currents (Beavington−Penney, 2004). There is very little matrix in the limestone samples, with only occasional clasts of micritic material which frequently contain planktic foraminifera and further suggests the limestones were deposited as true turbidites.

The limestones are primarily composed of LBF. Red algae fragments are also common thoughout and additionally peyssonnelid algae are seen in sample Zb C. Coral, echinoid, bryozoan, bivalve and worm tube (possibly of the genus *Ditrupa*) fragments also frequently occur in the samples all of which are common on the platform. Lepidocyclinids are the most commonly occurring LBF, tending to dominate assemblages, *Operculina* and *Heterostegina* occur frequently along with *Neorotalia* and *Amphistegina*. *Nummulites* are relatively uncommon but multiple species are present. Miogypsinids are very rare. It is generally accepted that LBF were strongly zoned across platforms due to many factors, including light levels and energy (see Beavington−Penney and Racey, 2004; Renema, 2005, 2006). This combination of LBF

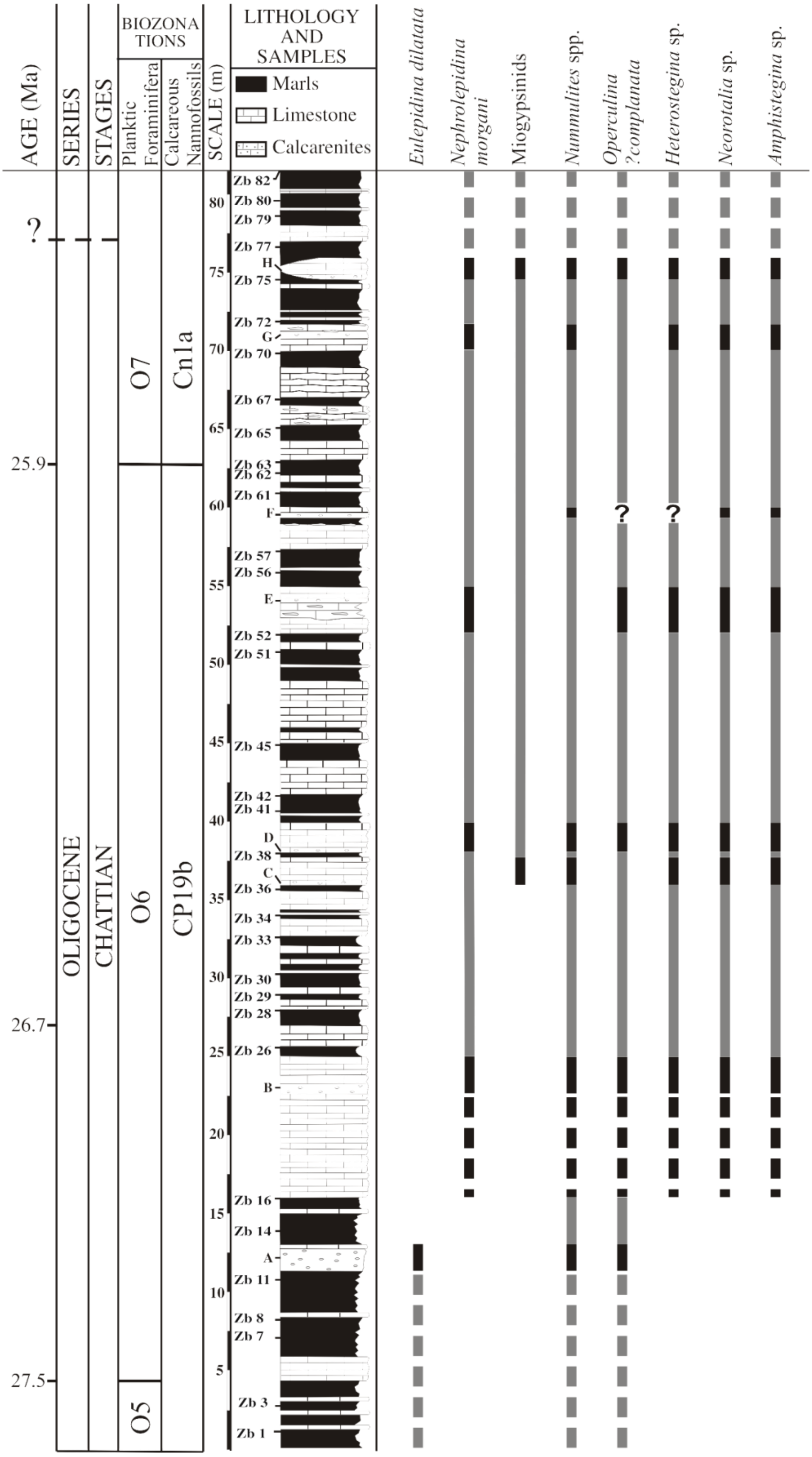

Figure 5.11. Stratigraphic column of the Zarabanda section showing limestone sample positions (A−H) and ranges of LBF. Due to the discrete nature of the beds, occurrences in the limestones are shown to scale in black, ranges between occurrences are in grey. Dashed lines show presumed continuation of the range, but where there were no further samples.

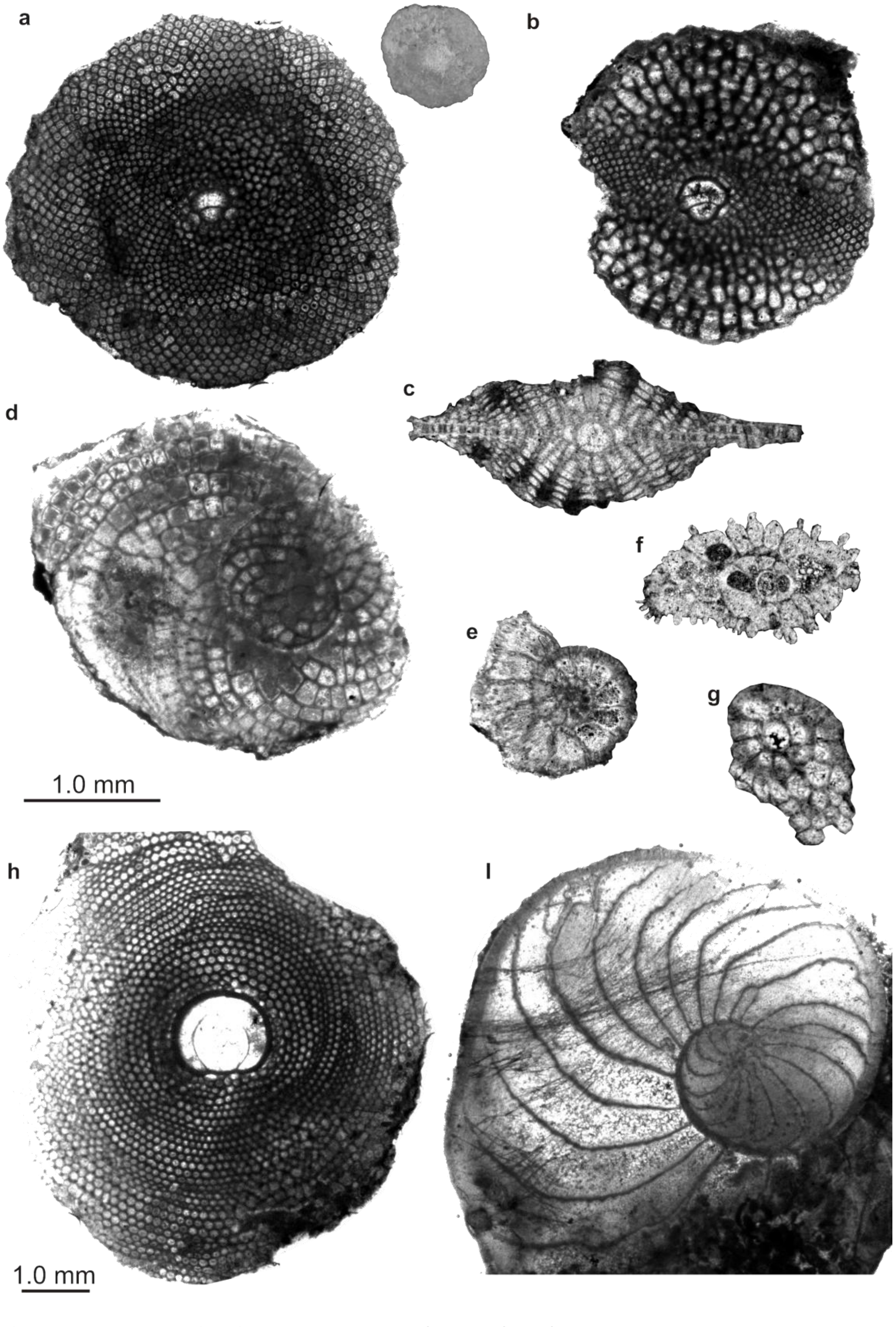

Figure 5.12. Plate showing larger benthic foraminifera from the Zarabanda section; a−g shown at same scale with scale bar below d; h and i shown at half this scale with scale bar below h; number in brackets is the oriented specimen number a) *Nephrolepidina morgani*, equatorial section; external view also shown, Zb D (4), b) *Nephrolepidina morgani*, equatorial section, Zb G (5), c) *Nephrolepidina morgani*, axial section from petrological thin section, Zb H. d) *Heterostegina* sp., equatorial section, Zb G (16), e) *Neorolatia* sp, (sub) equatorial section, Zb G (11), f) *Neorolatia* sp, axial slightly oblique section from petrological thin section, Zb C, g) Miogypsinid, equatorial or near equatorial section from petrological thin section, Zb H, h) *Eulepidina dilatata*, equatorial section, Zb A (10), i) *Operculina ?complanata*, equatorial section, Zb A (20).

is typical of an Oligocene−Miocene outer or mid to outer ramp assemblage (e.g., Beavington−Penney and Racey, 2004) suggesting this is the source of the carbonate sediment. The ramp itself is likely to be a distally steepened, rather than homoclinal ramp, to enable redeposition as gravity flow deposits. Turbidites therefore may have occurred due to destabilisation of the outer ramp sediment. The lack of miogypsinids in the limestone beds may therefore be due to them living outside of the source area of the turbidites (i.e. in shallower waters).

The major change in the assemblage is the disappearance of *E. dilatata* and appearance of *N. morgani* (see Fig. 6). The last occurrence of *E. dilatata* is in sample Zb A, before the 10 m thick limestone sequence and the first occurrence of *N. morgani* is in sample Zb B which is taken towards the top of this sequence. This is the same interval in which Fenero et al. (2013) find an increase in the shallow water, and decrease in the deep water smaller benthic foraminiferal taxa, which is interpreted as indicating a dramatic sea-level fall which would trigger redeposition of shallow material into deeper water. There is also a coeval increase in the relative abundance of the percentages of cool−water benthic species (Fenero et al., 2013).

Eulepidina is thought to have inhabited slightly deeper waters than *Nephrolepidina* (e.g., Schiavinotto and Verrubbi, 1994). A sea−level fall would cause an overall shallowing of the platform and therefore *Eulepidina* may not have been able to survive in the new shallower platform conditions and was replaced by *Nephrolepidina*. This change seen in the LBF therefore further supports that a sea−level fall occurred within the interval around 26.7 Ma.

5.4.5 Summary

Although significant cooling at this palaeolatitude would not be expected, comparison of the LBF and smaller benthic foraminiferal assemblages has shown a coeval relative change occurring at about 26.7 Ma. Both changes are indicative of a sea-level fall and can be correlated to the major expansion of the Antarctic ice sheet that occurred at approximately 26.7 Ma, the Oi−2b global glaciation event. Though the change in LBF assemblage is less dramatic than the changes seen at the EOT and appears to be a local rather than global event, it does show how integrated studies can be used to examine the effects of smaller climatic changes on LBF.

5.5 Conclusion

This chapter has presented new data on the LBF from two well-known EOT sites and a further section in the Oligocene. The study of the Melinau Limestone has provided new data on a stratigraphically very important section. The $\delta^{13}C$ record coupled with the existing biostratigraphy has allowed the extinction level and the EOGM isotope shift to be identified, which was not previously possible. This work has shown that the extinction clearly occurs before the EOGM and is therefore not caused by the most prominent sea-level fall. This is the same extinction pattern as seen in Tanzania and is therefore not a local phenomenon, but at least extends through the Indo-Pacific region and is likely to be global.

This study also shows the potential of using bulk isotope analysis to help constrain LBF ranges in shallow water sections. This is highly relevant for the Kiswere section in Tanzania (Chapter 3). The section appears to cover the late middle Eocene extinction event and the EOT continuously within shallow water facies. Bulk isotopes coupled with extensive sampling could be used in future to create a longer high resolution Eocene Tanzanian record.

The Fuente Caldera site from the Tethys displays the problems that can occur when dealing with turbiditic deposits. It appears likely that the orthophragmines suffer EOT extinction here, as they do elsewhere in the Tethys and Indo-Pacific regions and do not continue through the Rupelian. This is due to reworking of older, possibly Middle Eocene, material. It may be possible to further identify the extinction level of the orthophragmines, but this would require a much more detailed species level study. More detailed petrological examination of the beds would be needed, along with species level identifications of the orthophragmines to attempt to distinguish true occurrences from reworked material.

The Cortes Zarabanda site is an example of how integrated studies can be used to identify the effects of other climatic changes beyond the EOT on LBF. Though the events in this study appear localised, it shows how changes in assemblages from deeper to shallower species can be linked to sea-level changes and ice volume. It is uncertain if such studies would be successful for the younger Tanzanian sediments. Little Oligocene material is present in Tanzania and during the Miocene there appears to have been extensive faulting resulting in rapid facies changes (Chapter 2). Larger global climatic events such as the EOT, MECO and late Middle Eocene extinction therefore hold much more potential in creating tie points between the biostratigraphic and chemostratigraphic schemes.

Chapter 6:
Conclusions

In this thesis new data on larger benthic foraminiferal events across the Eocene - Oligocene Transition (EOT) and on longer range occurrences of larger benthic foraminifera (LBF) of Tanzania are presented from Tanzania Drilling Project (TDP) drill cores and field samples. The three TDP sites spanning the EOT have shed new light on the timing and potential mechanisms for the LBF extinction which occurs in this interval. The TDP records from the Lower Eocene to Oligocene coupled with extensive field samples have additionally provided a large amount of new data on occurrences, ages and distributions of LBF over the southern coastal region of Tanzania, providing a good foundation for future work. In this final chapter the aims given in Chapter 1 are addressed, the main aims of this work are summarised and future work is proposed.

6.1 Aims given in Chapter 1:

6.1.1 Study the EOT at high stratigraphic resolution using TDP records

The EOT from the Kilwa District of Tanzania has been studied at high resolution using three TDP records (sites 11, 12 and 17) which apparently continuously span the transition. These sediments contain a continuous record of LBF within the clay sediments, along with periodic limestone beds rich in LBF. The section is expanded due to a high sedimentation rate and therefore ideal for high resolution studies. The recent work by Pearson et al. (2008), Lear et al. (2008) and Wade et al. (2008) on the planktonic foraminiferal biostratigraphy and chemostratigraphy means the TDP records are exceptionally well correlated to global biostratigraphy and the global isotope curve. The timing of LBF events in these records can therefore be tied to global stratigraphy, something which is often not possible at other sites. This correlation has shown that the extinction of important groups of LBF, such as the orthophragmines, pellatispirids and some *Nummulites* occurs at the Eocene / Oligocene boundary (EOB), co-incident with the extinction of the planktonic foraminiferal Family the Hantkeninidae.

This has implications for the global correlation of LBF biozonations. The extinction levels correlate both the top of letter stage Tb (Adams, 1970) and shallow benthic foraminiferal (SBZ) zone 20 (Serra Kiel et al., 1998) with the Eocene / Oligocene boundary (top of planktonic foraminifer Zone E16; Berggen and Pearson, 2005) in the stratotype section at Massignano, Italy, providing a clear tie point between the regional larger benthic zonations and global stratigraphy. Additionally, within shallow carbonate sections, where planktonic foraminifera are often absent, LBF could be used to determine the boundary level.

6.1.2 Determine how the EOT larger benthic foraminiferal extinction correlates to the climatic record and implications for mechanisms.

The high resolution study of the EOT enabled the LBF extinction level to be tied to both planktonic foraminiferal biostratigraphy and chemostratigraphy. The extinction of LBF was found to be rapid and to occur at the EOB, closely coincident with the extinction of the Hantkeninidae. The EOB is within the plateau of the EOT $\delta^{18}O$ isotope curve, between the first step (largely due to temperature) and the second step (largely related to ice volume). This finding has important implications for the potential extinction mechanisms.

Sea-level fall was previously thought to be the responsible mechanism (Adams et al., 1986), however this study has shown the extinction precedes the large sea-level decrease by ~200,000 years. The rapidity of the extinction suggests a sudden event, such as a large volcanic eruption or bolide impact. However, there is no geological evidence for either at the EOB level. A supernova close to the Earth could also potentially cause sudden extinction, but effects would likely be more widespread among biota. The EOT is a period of global cooling and LBF distribution is known to be temperature dependent, but the cooling occurs over an extended period of time and so would be unlikely to cause a sudden extinction event. However, it may be a contributing factor. Changes in ocean stratification and increased nutrients in surface waters would be detrimental to both groups of foraminifera. General increases in surface water nutrients are seen across the transition (Diester-Haass and Zachos, 2003; Dunkley Jones et al., 2008b), however the exact mechanism for this remains uncertain. It therefore seems likely that the climatic changes in the early stages of the EOT may have preconditioned the LBF for extinction. An increase in nutrient supply at the EOB may have been the push that resulted in the extinction of both certain LBF and the Hantkeninidae.

6.1.3 To give an overview of the LBF distribution, facies and biostratigraphy of Tanzania using TDP technology and extensive additional fieldwork

A combination of existing TDP site records spanning the lower middle Eocene to Oligocene and extensive fieldwork spanning Lower Eocene to Upper Miocene have been used to give an overview of the LBF of southern coastal Tanzania. The records from TDP sites have been well studied in terms of plankton biostratigraphy and, in some sites, isotope stratigraphy. The age of LBF occurrences in these records is therefore well constrained. However, their geographical distribution is more limited. Extensive field sampling was therefore carried out. Field samples showed a similar overall assemblage to the TDP site samples, but also revealed a variety of depositional environments, including in-situ shelf deposits with LBF genera not present in the TDP material. A large amount of Miocene material from the Mchinga and Lindi regions was also sampled, with many localities documented for possibly the first time. Though the Miocene samples are from outcrop, they often occur with clay layers containing planktonic foraminifera, which allow independent dating of the LBF. The combination of drill cores from the TDP and outcrop sampling therefore provides a good overview of the LBF of the Eocene to Miocene of Tanzania and a solid basis for future work.

6.1.4 To compare both the longer range and the EOT Tanzanian records with the better known Tethyan and Indo-Pacific records

The longer range Tanzanian record has been compared with the LBF assemblage records of the Indo-Pacific and Tethyan regions. During the Eocene the assemblages of the Tethyan and Indo-Pacific regions have limited differences and therefore the Tanzanian record shows similarities to both regions with assemblages containing mostly *Nummulites*, orthophragmines and alveolinids. However, specimens of *Pellatispira* show more similarities to the flattened forms of the Tethys than the more rounded forms of the Indo-Pacific. At the Kiswere locality samples were found containing abundant *Somalina*, a genus known only from East Africa, parts of the Middle East and Greece. This suggests though there are shared components with the Indo-Pacific and Tethys, it is part of a West Pacific/East African realm.

The Miocene assemblage is typical of that period with abundant lepidocyclinids and miogypsinids. Highly rounded *Nephrolepidina* similar to Indo-Pacific species are common and potential range of *Nephrolepidina* into the Upper Miocene suggests a possible Indo-Pacific affinity, however much more detailed identification is needed to confirm this. *Cycloclypeus* is notably absent and is not known from elsewhere in East Africa, again suggesting it is part of a West Pacific/East African realm with certain characteristics unique to this region.

The results of the Tanzania EOT study were compared to two other sites; the Melinau Limestone of Sarawak and the Fuente Caldera section of Spain. The Melinau Limestone is thought to be one of the most complete shallow carbonate EOT sites, however it lacks independent dating. Therefore although detailed studies of LBF biostratigraphy were carried out by Adams (1965) the exact boundary level was not possible to determine. In Chapter 5 bulk isotope studies were carried out on the samples studied by Adams (1965), which allowed the onset of the EOGM to be identified. The LBF extinction, as documented by Adams (1965) occurred below this level, indicating that the extinction occurs before the global sea-level fall. This therefore supports that the extinction pattern seen in Tanzania and indicates it is likely to be a global phenomenon. The well-known Fuente Caldera site was also examined, due to reports of orthophragmines ranging into the Oligocene. However, when examined closely large amounts of reworking of Middle Eocene material was evident from the Oligocene sediments. It is likely that the orthophragmine extinction at this site also occurs during the EOT and that higher occurrences are due to reworking.

6.1.5 Improve LBF stratigraphic correlation.

This thesis has provided a large amount of new data on the LBF present in the southern coastal region of Tanzania. One of the major findings of this work was the extinction level of LBF at the EOB. This creates an important tie point in LBF stratigraphy between regional zonal schemes. A generic level overview of LBF through the Paleogene of the region has also been carried out. Little data on the LBF of Tanzania and also East Africa are currently available. Therefore this study provides an important resource and basis for future work, contributing towards an East African LBF biostratigraphy and an overall improved understanding of LBF migrations, biostratigraphy and evolution.

6.2 Future work

As the EOT is an important interval in the evolution of Earth’s climate and the LBF of the Tanzanian region is poorly studied, there are many potential ways to continue this research. Notably, though Chapter 3 contains an overview of LBF from the Eocene to Miocene of Tanzania, this has been carried out at a generic level. There is a large diversity of LBF in Tanzania, which it was not possible to study in detail within this PhD. In order to accurately compare the LBF to other regions and to build up a detailed biostratigraphy species level identifications are needed. Chapter 3 is therefore useful to identify potential target areas for sampling by future workers with specific interests.

One area of interest is the Kiswere section. This area shows an apparently complete carbonate succession through the Lutetian to Priabonian and into the Oligocene (although there may be a possible hiatus). This therefore should include the interval absent from the TDP records which contains the upper Middle Eocene extinction event. This section could therefore shed further light on the LBF extinction before the EOT and potentially lead to a greater understanding of the mechanisms behind both events. The successful results of the bulk isotope study of the Melinau Limestone also suggest it may be possible to constrain the age of the Kiswere section using the same technique.

Further EOT sites should be studied to confirm the extinction pattern is truly global, although potential sites for such work are extremely rare. The extinction mechanism itself still remains ambiguous, culturing experiments using living LBF could be used to assess the effects of global cooling and ascertain whether this is likely to have been a major contributing factor to their extinction. There is therefore a high potential for future studies in this region, particularly relating to biostratigraphy, evolution and mechanisms of extinction.

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