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The Tendaguru Formation (Late Jurassic to Early Cretaceous, southern Tanzania): definition, palaeoenvironments, and sequence stratigraphy

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Abstract

The well-known Late Jurassic to Early Cretaceous Tendaguru Beds of southern Tanzania have yielded fossil plant remains, invertebrates and vertebrates, notably dinosaurs, of exceptional scientific importance. Based on data of the German-Tanzanian Tendaguru Expedition 2000 and previous studies, and in accordance with the international stratigraphic guide, we raise the Tendaguru Beds to formational rank and recognise six members (from bottom to top): Lower Dinosaur Member, *Nerinella* Member, Middle Dinosaur Member, *Indotrigonia africana* Member, Upper Dinosaur Member, and *Rutitrigonia bornhardti-schwarzi* Member. We characterise and discuss each member in detail in terms of derivation of name, definition of a type section, distribution, thickness, lithofacies, boundaries, palaeontology, and age. The age of the whole formation apparently ranges at least from the middle Oxfordian to the Valanginian through Hauterivian or possibly Aptian. The Tendaguru Formation constitutes a cyclic sedimentary succession, consisting of three marginal marine, sandstone-dominated depositional units and three predominantly coastal to tidal plain, fine-grained depositional units with dinosaur remains. It represents four third-order sequences, which are composed of transgressive and highstand systems tracts. Sequence boundaries are represented by transgressive ravinement surfaces and maximum flooding surfaces. In a more simple way, the depositional sequences can be subdivided into transgressive and regressive sequences/systems tracts. Whereas the transgressive systems tracts are mainly represented by shallow marine shoreface, tidal channel and sand bar sandstones, the regressive systems tracts predominantly consist of shallow tidal channel, tidal flat, and marginal lagoonal to supratidal deposits.

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Introduction

The Tendaguru area is located in the Lindi hinterland in the southern coastal region of Tanzania, East Africa (Fig. 1), the earth history of which has attracted the attention of geologists and palaeontologists since the end of the 19th century. A number of workers have studied various aspects of the geology and palaeontology of this region that is widely characterised by Mesozoic and Cenozoic deposits (e.g. Bornhardt 1900; Müller 1900; Weissermel 1900; Fraas 1908; Dacqué & Krenkel 1909; Krenkel 1911; Hennig 1914a, 1937a; Janensch 1914a; Staff 1914; Parkinson 1930a; Quennell et al. 1956; Aitken 1961; Kent et al. 1971; Mpanda 1997).

The Tendaguru area first received worldwide notice in scientific circles through the efforts of the famous German Tendaguru Expedition of 1909 to 1913 (GTE) that is regarded as one of the largest and most significant palaeontological expeditions ever to have taken place (Hennig 1912a; Janensch 1912, 1914b; Maier 2003). The GTE focused primarily on the recovery of dinosaur bones, but field work also concentrated on the

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surface geology, geomorphology, and the collection of invertebrate fossils. A series of monographs on the geology (e.g. Hennig 1914a), geomorphology (Staff 1914), invertebrates (e.g. Dietrich 1914, 1933a; Lange 1914; Zwierzycki 1914), and vertebrates, notably dinosaurs (e.g. Hennig 1925; Janensch 1929a, 1935, 1955, 1961a), published by the members of the GTE and their collaborators still remains the basis for the work of geologists and palaeontologists in the Tendaguru region. One of the main scientific results obtained was a detailed account of the sequence of Mesozoic and Cenozoic strata exposed in the hinterland of Lindi and Kilwa (Hennig 1914a; Janensch 1914a). Based on extended geological and palaeontological observations the "Tendaguruschichten" (= Tendaguru Beds) were established by Hennig (1914a) and Janensch (1914a) to define a sequence of Late Jurassic to Early Cretaceous strata which contain dinosaur remains of exceptional scientific interest that continue to play a key role in palaeontological research.

The GTE was followed by the British Tendaguru Expedition (BTE) from 1924 through 1931 that likewise concentrated on the recovery of dinosaur bones but also continued the study of the Tendaguru Beds (Migeod 1927, 1930, 1931; Parkinson 1930a, 1930b). Important geological research was undertaken by W. G. Aitken in the 1950s. His extensive exploration of the Mesozoic rocks in the Mandawa-Mahokondo and Makangaga (south)-Ruawa regions (Aitken 1954, 1956a, 1956b, 1957, 1958; Quennell et al. 1956) resulted in a fundamental summary account of the geology and palaeontology of the Jurassic and Cretaceous deposits of southern Tanzania (Aitken 1961) that significantly contributed to the knowledge of the Tendaguru Beds.

Great progress towards a more detailed understanding of the Tendaguru Beds has been made by the German-Tanzanian Tendaguru Expedition (GTTE) that conducted geological and palaeontological field work in the surroundings of Tendaguru Hill in September 2000 (Heinrich et al. 2001; Aberhan et al. 2002; Maier 2003). The exploration resulted in a standard section for the Tendaguru Beds (R. Bussert in Heinrich et al. 2001 and Aberhan et al. 2002). New fossil material, notably microfossils, sedimentological and stratigraphical data were collected that have substantially extended our knowledge of the Mesozoic strata in the Tendaguru area (e.g. Aberhan et al. 2002; Arratia et al. 2002; Bussert & Aberhan 2004; Schrank 2005; Süss & Schultka 2006; Msaky 2007; Sames 2005, 2008) and provided, together with previously published records, a sufficient base for a reappraisal of the Tendaguru Beds.

Nevertheless, there have been gaps in our understanding of the Tendaguru Beds. The data obtained by the GTTE have shown that the term "Tendaguruschichten", which was widely used in the literature for about hundred years, is not in accordance with the guidelines of the International Commission on Stratigraphy (Murphy & Salvador 1999), as previously suggested by Schudack (1999). Moreover, the link of eustatic sea level changes to the various sedimentary divisions of the Tendaguru Beds has scarcely received the attention it merits. The present study reviews the available evidence and attempts to remedy some of these deficiencies.

Here we provide a reinterpretation of the Tendaguru Beds. Our principal goals are (1) to describe the Tendaguru Beds and to raise them to the rank of a formation; (2) to describe the lithostratigraphic subdivisions of the Tendaguru Beds and to elevate them to the rank of members; (3) to characterise the depositional environments of the formation in its type area; and (4) to provide a sequence stratigraphic interpretation of the Tendaguru Formation.

The present paper is dedicated to the German Tendaguru Expedition that celebrates its centenary in 2009.

Previous work

The first report of the geology and palaeontology of the Tendaguru area, which is named after Tendaguru Hill located approximately 10 km south of Mtapaia in the Lindi district, southeast Tanzania (Fig. 1), was made by the German geographer Wilhelm Bornhardt who explored much of the hinterland of Lindi and Kilwa in 1896 and 1897 (Bornhardt 1900). He collected fossils at several sites such as Ntandi located approximately 15 km southeast of Tendaguru Hill and dated them as Neocomian (Müller 1900; Weissermel 1900). It is worth noting that as early as 1897, Bornhardt collected a bone fragment of a supposed dinosaur in a stream section near Nambango village, situated about 15 km southeast of Tendaguru Hill. The poorly preserved specimen was first tentatively identified as a plesiosaur (Müller 1900; Hennig 1914a). Bornhardt never visited Tendaguru Hill, and erroneously mapped it as a small gneiss monadnock in the early stage of research (Bornhardt 1900: geological map VI).

The first palaeontologist to explore the Jurassic and Cretaceous rocks exposed in the surroundings of Tendaguru Hill was Eberhard Fraas in 1907 (Wild 1991). He concentrated on the recovery of dinosaur bones, but also collected fossil invertebrates, e.g. from Ntandi, Tendaguru Hill, Matapua, Niongala, and Mikadi, which were regarded as Early Cretaceous (Krenkel 1910). Niongala, though, was tentatively assigned to the Cenomanian by Fraas (1908). Along with a description of the dinosaur remains, he gave an account of the stratigraphy of the Mesozoic deposits exposed in the Tendaguru area and assigned the whole succession to the Cretaceous, including his Late Cretaceous dinosaur-bearing bed that was described as light-coloured, sandy marl with intercalated friable, coarse-grained sandstone (Fraas 1908).

During the field work of the GTE, interest in the geology and palaeontology of the Tendaguru area received a new impetus. Large-scale excavations were successfully undertaken to recover dinosaur bones that

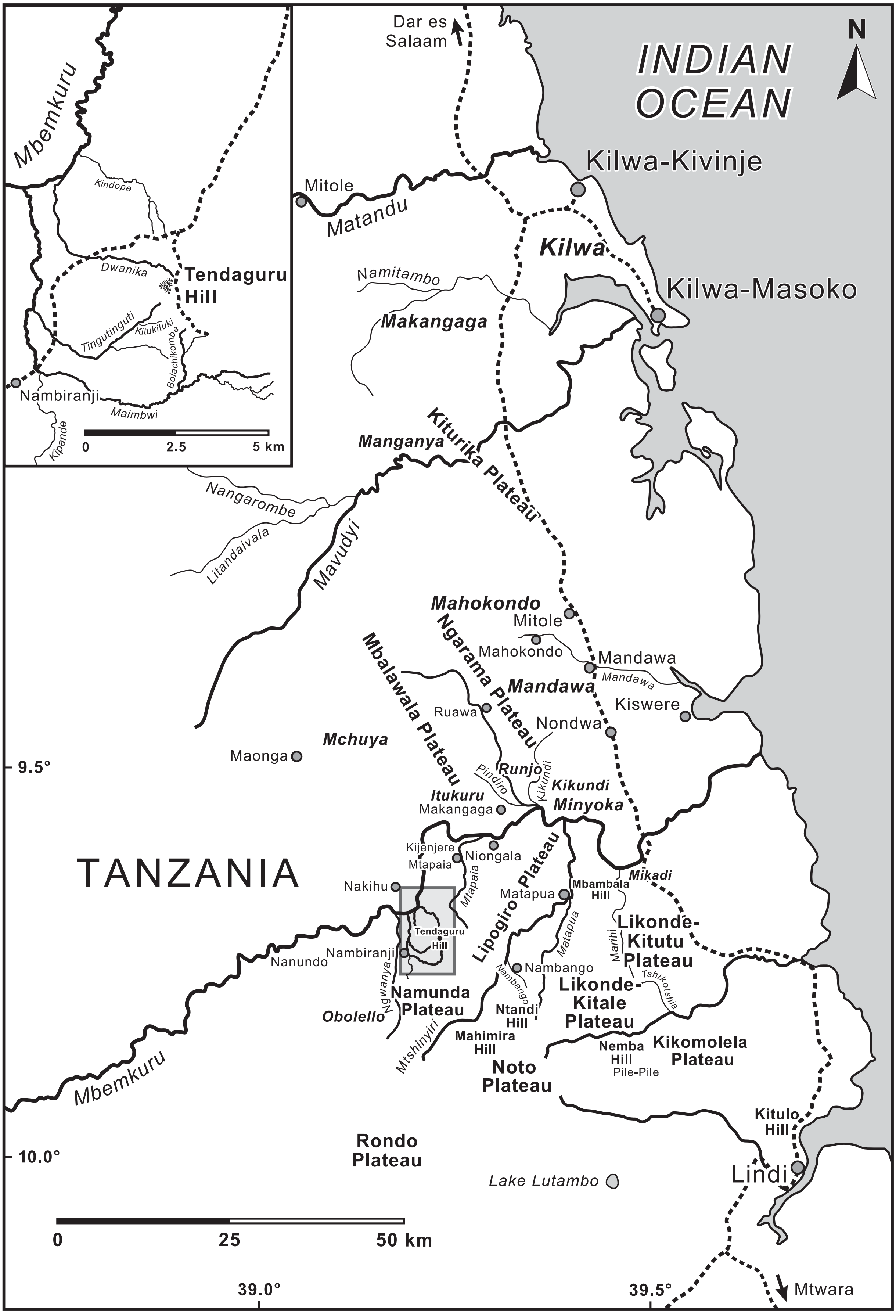


Figure 1. Geographic map of the coastal region of southern Tanzania, East Africa, indicating localities and geographic features mentioned in the text. Insert shows geographic details of the type area of the Tendaguru Formation.

Table 1. Stratigraphic terms for the Tendaguru Formation as used in previous studies.

Proposed name	Previous names	Literature
Tendaguru Formation	Tendaguru-Schichten	Hennig (1912c, 1924, 1927, 1937a); Zwierzycki (1914); Krenkel (1925, 1957); Kapilima (1984); Heinrich (2003)
	Tendaguru-Serie	Hennig (1912, 1937b); Hölder (1964)
	Tendaguruschichten	Hennig (1914a); Janensch (1914c); Janensch & Hennig (1914); Dietrich (1914, 1933a, 1933b); Lange (1914); Sames (2005)
	Tendaguru Series	Schuchert (1918); Spath (1928–1933); Parkinson (1930b); Wade (1937); Aitken (1956b, 1961); Cox (1965); Zils et al. (1995); Mpanda (1997)
	Gigantosaurus Beds	Gregory (1921)
	Tendaguru Beds	Simpson (1926); Teale (1934); Haughton (1938); Arkell (1956); Quennell et al. (1956); Heinrich (1999a); Bonaparte et al. (2000); Heinrich et al. (2001); Aberhan et al. (2002); Bussert & Aberhan (2004); Schrank (2004, 2005); Remes (2007)
	Tendaguru reptile beds	Furon (1963)
	Tendaguru Formation	Raath & MacIntosh (1987); Schudack (1999); Schudack & Schudack (2002); Süss & Schultka (2006); Msaky (2007)
	Tendaguru Group	Schlüter (1997)
	Tendaguru formation	Sames (2008)

chiefly occurred in three discrete horizons (Janensch 1914b; Maier 2003), the uppermost of which is, in fact, equivalent to the dinosaur horizon described by Fraas (1908). In addition, fossil invertebrates and plants were collected. The dinosaur-bearing Tendaguru Beds (Hennig 1914a; Janensch 1914a; Table 1) are well exposed in the immediate surroundings of Tendaguru Hill such as in the Tingutinguti, Maimbwi, and Dwanika stream sections. These exposures are of exceptional interest as they allow a subdivison of the Tendaguru Beds and the observation of the vertical distribution of the fauna and flora they contain, especially the dinosaur assemblages.

Lithological and palaeontological studies of the succession formed the basis for the subdivision of the Tendaguru Beds into six units, all of them representing discrete depositional settings (Janensch 1914a) (Table 2). Most subsequent workers used this subdivision that still holds. However, different opinions have also been advanced regarding the succession and age of strata at Tendaguru Hill (e.g. Kitchin 1929; Parkinson 1929, 1930a; Spath 1928–1933). Parkinson (1929, 1930b), for instance, erroneously doubted the existence of the Lower Saurian Bed and considered the Middle and Upper Saurian Bed as one stratum of continental deposits that interrupted the continuous deposition of marine sediments in the former Tendaguru area. Moreover, Parkinson (1929, 1930b) considered the *Nerinea* Bed as a lower and local interval of the *Trigonia smeei* Bed.

Dietrich (1933a, 1933b) subdivided the *Nerinea* Bed into two units, with the Sandstone with *Trigonia dietrichi* at the base and the Littoral with *Cyrena* and *Mytilus* at the top. Gregory (1921) used the term *Gigantosaurus* Beds for the dinosaur-bearing deposits at Tendaguru Hill. In addition, Gregory (1921), followed by Parkinson (1930b) and Wade (1937), applied the names Upper, Middle, and Lower Reptile Bed for the dinosaur-bearing deposits of the Tendaguru Beds.

The three dinosaur-bearing beds were described as sandy, partly greenish-grey, partly reddish marl; the remaining three units as sandstone-dominated deposits containing marine invertebrate assemblages (Janensch 1914a; Behrend 1918). In the immediate surroundings of Tendaguru Hill, the thickness of the Tendaguru Beds was estimated at approximately 125 m (Janensch 1914a).

Hennig (1914a) suggested that the dinosaur-bearing beds are linked by brackish transitional beds to the intercalated marine strata. Dietrich (1933a) described these transitional strata as littoral deposits with '*Cyrena*' [= *Eomiodon*] and '*Mytilus*' [= *Falcimytilus*] among others. The nomenclature of some eponymous macroinvertebrates has changed since that time. Therefore, some workers applied the terms *Rutitrigonia schwarzi* Bed instead of *Trigonia schwarzi* Bed and *Indotrigonia africana* Bed instead of *Trigonia smeei* Bed (e.g. Raath & McIntosh 1987), following the taxonomical revisions by Aitken (1961).

Bedding planes within the succession are broadly parallel. Therefore, the whole succession of sediments was originally regarded as a continuous, fairly flat-lying and undisturbed series of strata (Hennig 1914a, 1937a; Janensch 1914a). Later, an unconformity that coincides with a considerable break in the faunal succession between the Upper Saurian Bed and the *Trigonia schwarzi* Bed was recognised (Schuchert 1918, 1934; Parkinson 1930b; Dietrich 1933a, 1933b; Spath 1928–1933; Quennell et al. 1956; Aitken 1961). Moreover, an unconformity located at the top of the *Nerinea* Bed was also taken into consideration (Schuchert 1918).

Interpretation of the depositional environments of the Tendaguru Beds has differed considerably. Janensch (1914a) regarded the three dinosaur-bearing deposits as

Table 2. Stratigraphic terms for the subdivisions of the Tendaguru Formation as used in previous studies and the new nomenclature as defined in this study.

Proposed names		Previous names	Literature
Tendaguru Formation	*Rutitrigonia bornhardti-schwarzi* Member	*Trigonia-bornhardti* und *schwarzi*-Schicht	Hennig (1914a)
		Trigonia schwarzi-Schichten	Dietrich (1914, 1927a); Heinrich (2003); Sames (2005)
		Trigonia schwarzi-Schicht	Lange (1914); Zwierzycki (1914); Behrend (1918); Dietrich (1926)
		Schwarzi-Schicht	Dietrich (1914, 1925b); Hennig (1914c); Janensch & Hennig (1914)
		Obere Sandsteinzone mit *Trigonia schwarzi*	Janensch (1914a)
		Trigonia schwarzi zone	Lull (1915); Simpson (1926)
		Trigonia-*schwarzi*-Horizont	Behrend (1918)
		Upper sandstones with *Trigonia schwarzi*	Schuchert (1918)
		Schwarzi-Stufe	Hennig (1924); Dietrich (1933a, 1933b)
		Trigonia schwarzi Beds	Parkinson (1930b); Wade (1937); Haughton (1938)
		Trigonia schwarzi Bed	Parkinson (1930b); Aitken (1956b, 1961); Quennell et al. (1956); Heinrich (1999a); Bonaparte et al. (2000); Heinrich et al. (2001); Aberhan (2002); Schrank (2004, 2005); Msaky (2007)
		Schwarzi Beds	Teale (1934)
		Schwarzi-*Bornhardti*-Zone	Hennig (1937a)
		Bornhardti-*Schwarzi*-Zone	Hennig (1937b); Krenkel (1957)
		Trigonia schwarzi Sandstone	Arkell (1956)
		Marine transgressive beds with *Trigonia schwarzi* and *Hoplites neocomiensis*	Furon (1963)
		Schichten mit *Trigonia schwarzi*	Hölder (1964)
		Rutitrigonia schwarzi Bed	Raath & McIntosh (1987)
		Bornhardti-*Schwarzi* Complex	Zils et al. (1995)
		Trigonia Schwarzi Member	Schlüter (1997)
		Trigonia Schwarzi member	Sames (2008)
		Schwarzi Member	Schudack (1999); Schudack & Schudack (2002)
	Upper Dinosaur Member	Dinosaurierhorizont	Fraas (1908)
		Oberster Saurier-Horizont	Hennig (1914a); Zwierzycki (1914); Behrend (1918)
		Oberste (dritte) Saurierzone	Janensch (1914c)
		Obere Sauriermergel	Janensch (1914c); Krenkel (1957)
		Obere Saurierschicht	Dietrich (1914); Hennig (1914b, 1914c)
		Upper dinosaur horizon	Lull (1915)
		Upper or third dinosaur zone	Schuchert (1918).
		Upper Reptile Bed	Gregory (1921); Parkinson (1930b); Wade (1937)
		Obere Saurier-Schicht	Hennig (1924, 1937a, 1937b); Dietrich (1927a)
		Oberer Saurier-Horizont	Krenkel (1925)
		Upper dinosaur beds	Simpson (1926)
		Upper Dinosaur Bed	Parkinson (1930b); Msaky (2007)
		Oberer Sauriermergel	Dietrich (1933a, 1933b)
		Upper Saurian Horizon	Teale (1934)

Table 2. continued

Proposed names		Previous names	Literature
Tendaguru Formation	Upper Dinosaur Member	Upper Saurian Bed	Taele (1934); Wade (1937); Haughton (1938); Arkell (1956); Quennell et al. (1956); Aitken (1956b, 1961); Russell et al. (1980); Raath & McIntosh (1987); Heinrich (1999a); Bonaparte et al. (2000); Heinrich et al. (2001); Aberhan et al. (2002); Schrank (2004, 2005)
		Oberer Dinosaurier-Mergel	Hennig (1937a)
		Upper Reptile Horizon	Furon (1963)
		Oberes Saurier-Lager	Hölder (1964)
		Upper Saurian Beds	Zils et al. (1995)
		Upper Saurian Member	Schlüter (1997)
		Upper Dinosaur Member	Schudack (1999); Schudack & Schudack (2002)
		Obere Saurierschichten	Heinrich (2003); Sames (2005)
		Upper Saurian member	Sames (2008)
	Indotrigonia africana Member	Trigonienschichten	Fraas (1908); Quennell et al. (1956)
		Trigonia Smeei-(*Beyschlagi*)-Schicht	Hennig (1914a)
		Mittlere Sandsteinzone mit *Trigonia smeei*	Janensch (1914c)
		Trigonia smeei-Schicht	Lange (1914); Zwierzycki (1914); Dietrich (1926, 1927a)
		Trigonia smeei zone	Lull (1915); Simpson (1926)
		Trigonia-smeei (*-beyschlagi*)-Horizont	Behrend (1918)
		Middle marine sandstones with *Trigonia smeei*	Schuchert (1918)
		Smeei-Stufe	Hennig (1924)
		Smeei-Schicht	Dietrich (1925a); Hennig (1927)
		Trigonia smeei-Horizont	Krenkel (1925)
		Trigonia smeei Bed	Parkinson (1930b); Wade (1937); Haughton (1938); Quennell et al. (1956); Aitken (1956b, 1961); Cox (1965); Heinrich (1999a); Bonaparte et al. (2000); Heinrich et al. (2001); Aberhan et al. (2002); Bussert & Aberhan (2004); Schrank (2004, 2005); Msaky (2007)
		Smeei Bed	Teale (1934); Arkell (1956)
		Trigonia smeei Beds	Teale (1934); Furon (1963)
		Smeei-Zone	Hennig (1937a)
		Trigonia smeei-Zone	Krenkel (1957)
		Schichten mit *Trigonia mandavae* (*smeei* auct.)	Hölder (1964)
		Indotrigonia africana Bed	Raath & McIntosh (1987)
		Smeei Beds	Zils et al. (1995)
		Trigonia smeei Member	Schlüter (1997)
		Smeei Member	Schudack (1999); Schudack & Schudack (2002)
		Trigonia smeei-Schichten	Heinrich (2003); Sames (2005)
		Trigonia smeei member	Sames (2008)
	Middle Dinosaur Member	Mittlerer Saurier-Horizont	Hennig (1914a); Zwierzycki (1914); Behrend (1918); Krenkel (1925)
		Mittlere (zweite) Saurierzone	Janensch (1914c)
		Mittlere Saurierschicht	Dietrich (1914, 1925a); Hennig (1914b, 1914c)
		Mittlere Sauriermergel	Janensch (1914c)
		Middle dinosaur horizon	Lull (1915)

Table 2. continued

Proposed names		Previous names	Literature
Tendaguru Formation	Middle Dinosaur Member	Middle or second dinosaur zone	Schuchert (1918)
		Saurier-Horizont II	Behrend (1918)
		Middle Reptile Bed	Gregory (1921); Parkinson (1930b); Wade (1937).
		Mittlere Saurier-Schicht	Hennig (1924, 1937a, 1937b); Dietrich (1927a)
		Middle dinosaur beds	Simpson (1926)
		Middle Saurian Bed	Parkinson (1930b); Teale (1934); Wade (1937); Haughton (1938); Arkell (1956); Quennell et al. (1956); Aitken (1961); Russell et al. (1980); Raath & McIntosh (1987); Heinrich (1999a); Bonaparte et al. (2000); Heinrich et al. (2001); Aberhan et al. (2002); Schrank (2004, 2005)
		Mittlerer Sauriermergel	Dietrich (1933a, 1933b); Krenkel (1957)
		Middle Saurian Horizon	Teale (1934)
		Mittlerer Dinosaurier-Mergel	Hennig (1937a)
		Middle Reptile Horizon	Furon (1963)
		Mittleres Saurier-Lager	Hölder (1964)
		Middle Saurian Beds	Zils et al. (1995)
		Middle Saurian Member	Schlüter (1997)
		Middle Dinosaur Member	Schudack (1999); Schudack & Schudack (2002)
		Mittlere Saurier-Schichten	Heinrich (2003)
		Mittlere Saurierschichten	Sames (2005)
		Middle Dinosaur Bed	Msaky (2007)
		Middle Saurian member	Sames (2008)
	Nerinella Member	Nerineen-Schicht	Hennig (1914a); Dietrich (1914, 1927a); Krenkel (1925)
		Untere Sandsteinzone, Nerineenzone	Janensch (1914c)
		Nerineenschicht	Zwierzycki (1914); Janensch & Hennig (1914); Behrend (1918); Dietrich (1925a)
		Nerinea zone	Lull (1915); Simpson (1926)
		Nerineen-Schichten	Behrend (1918)
		Lower or *Nerinea* sandstones	Schuchert (1918)
		Nerineen-Stufe	Hennig (1924)
		Unterer Saurier-Horizont	Krenkel (1925)
		Nerinea Bed	Parkinson (1930b); Teale (1934); Wade (1937); Haughton (1938); Quennell et al. (1956); Aitken (1961); Raath & McIntosh (1987); Heinrich (1999a); Bonaparte et al. (2000); Heinrich et al. (2001); Aberhan et al. (2002); Schrank (2004, 2005); Msaky (2007)
		Nerinean Horizon	Teale (1934)
		Nerinellen-Zone	Hennig (1937a, 1937b); Krenkel (1957)
		Nerinella bed: sandstone with *Trigonia dietrichi*	Arkell (1956)
		Nerinea Beds	Furon (1963); Zils et al. (1995)
		Nerinellen-Bänke	Hölder (1964)
		Nerinella Bed	Cox (1965)
		Nerinea Member	Schlüter (1997); Schudack (1999); Schudack & Schudack (2002)
		Nerineenschichten	Heinrich (2003); Sames (2005)
		Nerinea member	Sames (2008)

Table 2. continued

Proposed names		Previous names	Literature
Tendaguru Formation	Lower Dinosaur Member	Unterster Saurier-Horizont	Hennig (1914a); Zwierzycki (1914)
		Untere Saurier-Schicht	Dietrich (1914, 1925a, 1927a); Hennig (1924, 1937a)
		Untere (erste) Saurierzone	Janensch (1914c)
		Untere Sauriermergel	Janensch (1914c); Krenkel (1957)
		Lower dinosaur horizon	Lull (1915)
		Unterer Saurierhorizont	Behrend (1918)
		Lower or first dinosaur sandy marl	Schuchert (1918)
		Lower Reptile Bed	Gregory (1921); Parkinson (1930b); Wade (1937)
		Unterer Saurier-Horizont	Krenkel (1925)
		Lower dinosaur beds	Simpson (1926)
		Lower Saurian Bed	Parkinson (1930b); Teale (1934); Wade (1937); Haughton (1938); Arkell (1956); Quennell et al. (1956); Aitken (1961); Raath & MacIntosh (1987); Heinrich (1999a); Bonaparte et al. (2000); Heinrich et al. (2001); Aberhan et al. (2002); Schrank (2004, 2005)
		Lower Saurian Horizon	Teale (1934)
		Unterer Dinosaurier-Mergel	Hennig (1937a)
		Lower Reptile Horizon	Furon (1963)
		Unteres Saurier-Lager	Hölder (1964)
		Lower Saurian Beds	Zils et al. (1995)
		Lower Saurian Member	Schlüter (1997); Russell et al. (1980)
		Lower Dinosaur Member	Schudack (1997); Schudack & Schudack (2002)
		Untere Saurierschichten	Heinrich (2003); Sames (2005)
		Lower Dinosaur Bed	Msaky (2007)
		Lower Saurian member	Sames (2008)

lagoonal, the *Nerinea* Bed, *Trigonia smeei* Bed, and *Trigonia schwarzi* Bed as marginal marine in origin (see also Hennig 1912b). Dietrich (1933a) considered the dinosaur beds as lagoonal-estuarine strata. Reck (1925) argued that the dinosaur-bearing beds were deposited in saline marshes. Parkinson (1930a) interpreted the palaeo-environment of the Tendaguru Beds below the *Trigonia schwarzi* Bed as an estuary.

Throughout its range, the Tendaguru Beds have yielded abundant fossils including vertebrates, invertebrates, and plants from deposits of alternating marginal marine and continental environments. The three dinosaur-bearing deposits are of particular importance because they have produced rich assemblages of dinosaurs referable to Sauropoda, Ornithopoda and Theropoda (e.g. Janensch 1914c, 1925a, 1929a, 1955, 1961a; Hennig 1925; for details see below). Invertebrates are mainly reported from the three marine divisions and include, for example, corals, bivalves, gastropods, cephalopods, arthropods, and brachiopods (e.g. Dietrich 1914, 1933a; Lange 1914; Zwierzycki 1914; Quennell et al. 1956; Aitken 1961; Cox 1965; for details see below). In the three dinosaur-bearing beds, invertebrate fossils are far less common (Hennig 1914b). Fossil plant remains were also described (e.g. Gothan 1927; Kahlert et al. 1999; Stockey 1978; Schrank 1999, 2005; Süss & Schultka 2006).

The age of the Tendaguru Beds has been a subject of much debate for many years and opinions vary considerably (e.g. Fraas 1908; Janensch 1914a; Dietrich 1925a, 1933a; Kitchin 1929; Hennig 1924, 1927, 1937a, 1937b; Simpson 1926; Arkell 1956; Quennell et al. 1956; Aitken 1961; Kent et al. 1971). For the purposes of the present report it is not necessary to discuss all these views in detail, because many of them are now obsolete. A review of the dating of the Tendaguru Beds in the early stages of research was given by Hennig (1937a), Quennell et al. (1956), Aitken (1961: tab. 2), and Sames (2008: tab. 1).

The Tendaguru Beds consist of a Late Jurassic part, comprising the Lower Saurian Bed, *Nerinea* Bed, Middle Saurian Bed, *Trigonia smeei* Bed, and the Upper Saurian Bed, and an Early Cretaceous part, the *Trigonia schwarzi* Bed (e.g. Dietrich 1927a, 1933a, 1933b; Spath 1928–1933; Aitken 1961; Heinrich et al. 2001; Aberhan et al. 2002). In contrast, some authors included the whole Upper Saurian Bed (e.g. Hennig 1914a; Janensch 1914a; Lange 1914; Zwierzycki 1914; Sames 2008) or parts of it (e.g. Hennig 1937a) into the Early Cretaceous (Neocomian).

Originally, published ages for the marine stratigraphic units were primarily based on ammonites and bivalves (*Trigonia*). Later, palynomorphs and ostracods yielded new insights into the age of some of these units (Schrank 2004, 2005; Msaky 2007; Sames 2008). The age determination of the dinosaur-bearing deposits mainly relied on the interfingering relationships with the marine strata of the Tendaguru Beds. More recently, palynomorphs, charophytes, and ostracods have yielded useful biostratigraphical criteria (Schudack 1999; Schudack & Schudack 2002; Schrank 2004, 2005; Sames 2008).

On biostratigraphical grounds, Dietrich (1933a, 1933b) subdivided the Tendaguru Beds into (1) the Late Jurassic "Smeeistufe" (*smeei* Stage), comprising strata from the *Trigonia dietrichi* Sandstone (basal part of the *Nerinea* Bed) up to the Upper Saurian Bed, regarded as Sequanian (late Oxfordian) to early Portlandian (early Tithonian) in age; and (2) the Early Cretaceous "Schwarzistufe" (*schwarzi* Stage) represented by the *Trigonia schwarzi* and *Trigonia bornhardti* sandstone. The *schwarzi* Stage was considered to be late Valanginian to early Aptian in age (Dietrich 1933a, 1933b). A more sophisticated biostratigraphic subdivision of the Tendaguru Beds ("Vor-*smeei*-Lager", "Mittleres Dinosaurier-Lager", "Haupt-*smeei*-Lager", "Oberes Dinosaurier-Lager", "Spät-*smeei*-Lager", "*Trigonia bornhardti*-Schicht", "*Trigonia schwarzi*-Schicht") was provided by Hennig (1937a). A detailed account of age ranges is given below in the characterisation of the various members of the Tendaguru Formation.

In the hinterland of Lindi, the Tendaguru Beds are overlain by the Makonde Beds (Janensch 1914a), a term which was first applied by Bornhardt (1900) for a sequence of strata in southern Tanzania that mainly consists of conglomerate, sandstone and intercalated siltstone, silty sand and clay as well as red sandy beds of possibly Aptian (e.g. Hennig 1914a; Janensch 1914a; Behrend 1918; Krenkel 1925), possibly late Aptian (e.g. Aitken 1961) or middle Aptian to middle Albian age (Veeken & Titov 1996). The transition from the *Trigonia schwarzi* Bed into both the late Aptian marine Kiturika Beds and the predominantly continental Makonde Beds was described by Hennig (1914a, 1937a) from several localities in the hinterland of Lindi and Kilwa. Aitken (1961), however, also recorded sites without this upward sequence (see also Kent et al. 1971). Parkinson (1930b), who had compared the Tendaguru Beds and the Makonde Beds on the basis of their heavy mineral contents, concluded that the Makonde Beds from the Noto Plateau are "in reality much younger than hitherto supposed". More recent investigations in the Rovuma Basin (northern Mozambique) suggest a late Aptian-early Albian age for the Makonde Formation (Hancox et al. 2002). Janensch (1914a) referred the Tendaguru Beds along with the "Makondeschichten" (Makonde Beds) to the "Lindiformation" (Lindi Formation), a stratigraphic term, which was introduced by Dacqué & Krenkel (1909), but now is regarded as having been superseded (Quennell et al. 1956).

Geological setting

The Tendaguru area is situated in the southwestern part of the Mandawa Basin that forms an embayment of the Somali Basin (Kent et al. 1971; Scrutton et al. 1981; Veeken & Titov 1996; Mpanda 1997). The Mandawa Basin is underlain by Neoproterozoic gneiss (Hennig 1914a; Veeken & Titov 1996). The basin evolution is closely related to plate tectonic processes and the gradual break-up of Gondwana that commenced in the latest Carboniferous/Early Permian with the formation of the East African continental Karroo rift system (Schandelmeier et al. 2004; Nicholas et al. 2007). The oldest sediments belong to the Karroo Supergroup. They mainly consist of fluvial and lacustrine deposits with occasional local marine incursions, the age of which ranges from the Permo-Carboniferous to the Early Jurassic (Kreuser et al. 1990; Wopfner 1992; Balduzzi et al. 1992; Hankel 1994).

Local, restricted marine or coastal to marine conditions in the subsiding Mandawa Basin resulted in the deposition of evaporites (e.g. gypsum, halite, anhydrite) with silty shales from the Triassic to the Early Jurassic (e.g. Upper Pindiro Evaporites: Kagya 1996; Nondwa Evaporite: Veeken & Titov 1996). During the Jurassic, Madagascar and other parts of East Gondwana rifted gradually away from the region of what is now Tanzania, Kenya and Somalia (Kent et al. 1971; Reeves et al. 2002; Geiger et al. 2004; Schandelmeier et al. 2004; Rabinowitz & Woods 2006; Nicholas et al. 2007). This continental break-up is assumed to have commenced in the Middle Jurassic (e.g. Hankel 1994; Salman & Abdula 1995; Veeken & Titov 1996). There is some evidence, however, that Madagascar possibly already separated during the late Early Jurassic (Toarcian) (Geiger et al. 2004; Geiger & Schweigert 2006).

As a result, the Tethys Ocean spread into the rift zone between Gondwana and Madagascar from the north (Scrutton et al. 1981; Hankel 1994; Luger et al. 1994; Mpanda 1997) and flooded the Somali Basin and the Mandawa sub-basin during the Bajocian, which saw two major episodes of eustatic sea level rise (Hallam 2001). With the onset of sea floor spreading, the Somali Basin developed into the passive Tanzanian continental margin (Mpanda 1997).

A regression during the early Bathonian was followed by the main Jurassic transgression in the late Bathonian which extended widely over East Africa and continued at least until the Kimmeridgian-Tithonian (Luger et al. 1994). Marine shales with intercalated evaporites of Callovian age are reported from the Mandawa Basin (e.g. Mandawa-7 well; Mpanda 1997). The cyclic depositional character of the Upper Jurassic and Lower Cretaceous sediments of the Mandawa Basin such as the Tendaguru Beds suggests control by eustatic sea-level changes (Aberhan et al. 2002).

In the early Early Cretaceous, an unconformity developed in the Mandawa Basin owing to uplift and widespread drop of the sea level (Aitken 1961; Mpanda 1997; Aberhan et al. 2002). This basin-wide regression occurred apparently in the Valanginian to middle Aptian (Mpanda 1997) or during the Aptian (Veeken & Titov 1996) but did not likely affect the Mandawa area (Mpanda 1997). During the late Early Cretaceous the sediments of the Makonde Formation were predominantly deposited in fluvial to marginal marine environments.

The time span from the Late Cretaceous (Santonian) to Early Oligocene, which was characterised by exceptional tectonic stability of the Tanzanian coastal region (Kent et al. 1971), led to the deposition of the Kilwa Group (Nicholas et al. 2006). The end of the Kilwa Group deposition occurred in the Oligocene and corresponds with the top of the Pande Formation (Nicholas et al. 2007), and it indicates the termination of the Tanzanian continental passive margin. It was followed by the reactivation of older Mesozoic faults and the creation of new faults during the Neogene (Nicholas et al. 2007).

Methods

This study is based on all available information from the Tendaguru Beds. In particular, this comprises data of the GTE (including unpublished original field notes, the so-called field catalogue of Janensch which is housed at the Museum für Naturkunde Berlin) and data of the GTTE (see Aberhan et al. 2002 for the methods applied). In establishing a formal lithostratigraphy of the Tendaguru Beds we follow the guidelines of the International Subcommission on Stratigraphic Classification (Murphy & Salvador 1999), one exception being the naming of the members. While the guidelines recommend the usage of an appropriate geographic name in naming lithostratigraphic units, we refer to the original names for the various subunits of the Tendaguru Beds. This has two reasons: (1) several members are defined in the Tingutinguti stream section and no geographic

Table 3. Geographic coordinates [GPS data, UTM system, datum: New (1960) Arc] of samples of the Tendaguru Formation mentioned in the text. For stratigraphic position of samples see Figure 3 and Aberhan et al. (2002: fig. 2).

Sample number	Stratigraphy and locality	Easting (UTM)	Northing (UTM)
Dwa 8	Upper Dinosaur Member, Dwanika stream bed	37 L 0524 703	8927 488
Dwa 7	Upper Dinosaur Member, Dwanika stream bed	37 L 0524 678	8927 524
Dwa 6	Upper Dinosaur Member, Dwanika stream bed	37 L 0524 651	8927 573
Dwa 5	Upper Dinosaur Member, Dwanika stream bed	37 L 0524 649	8927 573
Dwa 3	Upper Dinosaur Member, Dwanika stream bed	37 L 0524 593	8927 611
Dwa 2	Upper Dinosaur Member, Dwanika stream bed	37 L 0524 579	8927 632
Dwa 1	Upper Dinosaur Member, Dwanika stream bed	37 L 0524 516	8927 655
Dwa A	Upper Dinosaur Member, Dwanika stream bed	37 L 0524 417	8927 788
Tin 11b	Upper Dinosaur Member, Tendaguru Hill	37 L 0524 625	8927 092
Tin 11a	Upper Dinosaur Member, Tendaguru Hill	37 L 0524 606	8927 066
Tin 10f	Upper Dinosaur Member, Tingutinguti stream bed	37 L 0524 606	8927 024
Tin 10e	Upper Dinosaur Member, Tingutinguti stream bed	37 L 0524 635	8926 922
Tin 10d	Upper Dinosaur Member, Tingutinguti stream bed	37 L 0524 574	8926 830
Tin 9w	*Indotrigonia africana* Member, Tingutinguti stream bed	37 L 0524 479	8926 730
Tin 9u	*Indotrigonia africana* Member, Tingutinguti stream bed	37 L 0524 422	8926 736
Tin 9r	*Indotrigonia africana* Member, Tingutinguti stream bed	37 L 0524 323	8926 772
Tin 9p	*Indotrigonia africana* Member, Tingutinguti stream bed	37 L 0524 316	8926 766
Tin 7l	Middle Dinosaur Member, Tingutinguti stream bed	37 L 0524 174	8926 630
Tin 7k	Middle Dinosaur Member, Tingutinguti stream bed	37 L 0524 150	8926 614
Tin 7h	Middle Dinosaur Member, Tingutinguti stream bed	37 L 0524 024	8926 508
Tin 7f	Middle Dinosaur Member, Tingutinguti stream bed	37 L 0524 050	8926 468
Tin 7e	Middle Dinosaur Member, Tingutinguti stream bed	37 L 0524 034	8926 472
Tin 7d	Middle Dinosaur Member, Tingutinguti stream bed	37 L 0524 034	8926 347
Tin 6a	Middle Dinosaur Member, Tingutinguti stream bed	37 L 0524 025	8926 340
Tin 4h	*Nerinella* Member, Tingutinguti stream bed	37 L 0523 938	8926 260
Tin 3a	*Nerinella* Member, Tingutinguti stream bed	37 L 0523 846	8926 220
Tin 2	*Nerinella* Member, Tingutinguti stream bed	37 L 0523 846	8926 230
Tin 1	Lower Dinosaur Member, Tingutinguti stream bed	37 L 0523 681	8926 216
Tin 0a	Lower Dinosaur Member, Tingutinguti stream bed	37 L 0523 827	8926 078

names are available to distinguish between the type localities; and (2) the original terms are firmly anchored in the literature. In such a case, section B.3.g of the International Stratigraphic Guide (Murphy & Salvador 1999) allows for the preservation of traditional or well-established names provided that they are well defined.

The definition of type sections presented herein rests on a detailed sedimentological survey of the Tingutinguti (Tin, Kit) and Dwanika (Dwa) stream sections at Tendaguru (Fig. 1) by the GTTE. Recorded parameters include lithology, grain-size, texture, sedimentary structures, geometry of the strata, trace fossils and bioturbation intensity. The smallest stratigraphic unit recognised are individual beds. They are labelled according to the acronym of the stream section and are numbered consecutively (see Table 3). Occasionally, such a numbered unit may cover up to a few meters in thickness and comprises several successional beds of uniform lithology.

When citing other authors' age assignments of a stratigraphical unit, we used the age as provided in the original paper. We are well aware of the fact that the stratigraphical nomenclature for the Late Jurassic was not used consistently over the past 100 years of research on the Tendaguru Beds. By keeping the original ages, however, the corresponding discussion remains reproducible. Note, for instance, that the middle Kimmeridgian is abandoned and is now included in the late Kimmeridgian and that the Portlandian can be equated with the Tithonian.

In the context of palaeoenvironmental interpretations we draw on palaeoecological data as far as they are directly relevant. A more detailed palaeoecological interpretation, including the palaeobiology of the Tendaguru dinosaurs, was given in Aberhan et al. (2002) and is not repeated here.

Description of lithostratigraphic units

Tendaguru Formation

Figure 2, Table 1

Based on previous and current data (e.g. Hennig 1914a; Janensch 1914a; Aberhan et al. 2002; Bussert & Aberhan 2004), the Tendaguru Formation is subdivided into six members, which are renamed here as follows (from bottom to top): Lower Dinosaur Member [formerly "Untere (erste) Saurierzone", Lower Saurian Bed], *Nerinella* Member [formerly "Untere Sandsteinzone (Nerineenzone)", *Nerinea* Bed], Middle Dinosaur Member [formerly "Mittlere (zweite) Saurierzone", Middle Saurian Bed], *Indotrigonia africana* Member [formerly "Mittlere Sandsteinzone mit *Trigonia smeei*", *Trigonia smeei* Bed], Upper Dinosaur Member [formerly "Oberste (dritte) Saurierzone", Upper Saurian Bed], and *Rutitrigonia bornhardti-schwarzi* Member [formerly "Obere Sandsteinzone mit *Trigonia schwarzi*", *Trigonia schwarzi* Bed].

Name. The name of the formation was derived from Tendaguru, which means steep hill in the language of the Wamwera tribe. The series of strata that now makes up the Tendaguru Formation was previously named "Tendaguruschichten" (Hennig 1914a; Janensch 1914c). Here, we formally raise the succession of strata to formation rank and change this name and other, previously applied terms to Tendaguru Formation (Table 1). Note that the term Tendaguru Formation was previously suggested by Schudack (1999) but the author failed to describe and define the formation. Terms such as Tendaguru Series (e.g. Schuchert 1918; Wade 1937; Aitken 1961; Mpanda 1997) or Tendaguru Group (Schlüter 1997) are also abandoned here (Table 1).

Type section. Tendaguru Hill located in the Mbemkuru Valley in the southern coastal area of Tanzania is regarded as type locality (Quennell et al. 1956). However, neither the GTE nor the BTE designated a type section for the Tendaguru Beds now named Tendaguru Formation. Here, the Tendaguru Formation is formally typified along the Tingutinguti and Dwanika stream sections (Fig. 1). Owing to the lack of complete and extended sections through the formation from bottom to top, a composite type section for the Tendaguru Formation is established and defined from the following beds: Tin 1 to Tin 10e, Dwa 1 to Dwa 7, Tin 11a to Tin 11d, and Kit 6 to Kit 8 (Fig. 3, Table 3).

Distribution. The sediments of the Tendaguru Formation are located in an approximately north-south trending belt of predominantly Jurassic to Cretaceous rocks in the southern coastal area of Tanzania. The Tendaguru Formation is best exposed in the surroundings of Tendaguru Hill (Figs 1, 4A). Confirmed or supposed equivalents occupy larger parts of (1) the Mbemkuru river valley and adjacent regions (Tendaguru area); (2) the Mandawa-Mahokondo area; and (3) the Makangaga (south)-Ruawa area, covering approximately 2000 km^2 (Hennig 1914a, 1937a). Altogether, outcrops of the Tendaguru Formation are found from Matandu river in the north to Lake Lutambo in the south. Mapping by the GTE resulted in a geological map (scale: 1 : 300,000) showing the generalised distribution of the Tendaguru Formation in these areas (Hennig 1914a).

Subsequent exploration has confirmed most of the mapping performed by the GTE but also challenged some conclusions relating the distribution and correlation of the members of the Tendaguru Formation (Quennell et al. 1956; Aitken 1961).

Considering these limitations, the southernmost occurrences of the Tendaguru Formation, mapped as Upper Dinosaur Member, are located east and northeast of Lake Lutambo approximately 25 km west of the seaport of Lindi (Fig. 1) (Hennig 1914a: geological map). The northernmost outcrops of the Tendaguru Formation, also mapped as Upper Dinosaur Member, are found near Mitole at the Matandu river roughly 36 km west of Kilwa-Kinvinje (Fig. 1) (Hennig 1914a: geological map). The Tendaguru Formation has been traced southwestward as far as the Mavudyi river region (mapped as *Rutitrigonia bornhardti-schwarzi* Member) and Likoniengwale river regions (mapped as Upper Dinosaur Member but not shown in Figure 1 due to position of inlay), and its easternmost occurrence is an outlier located at the western slope of Kitulo Hill near Lindi where Lower Cretaceous deposits with *Rutitrigonia schwarzi* are exposed (Hennig 1937a). Generally, scattered outcrops of the Tendaguru Formation far north of the Mbemkuru river, such as in the Makangaga (south)-Ruawa region, are difficult to correlate with the

Epoch	Stage	Formation	Member	Lithology
Early Cretaceous	Aptian to early Albian	Makonde Formation		Fine- to medium-grained sandstones, red to purple, intercalated conglomerates, siltstones, silty sandstones and claystones. **~ 200 m**
Early Cretaceous	Valanginian to Hauterivian	Tendaguru Formation	***Rutitrigonia bornhardti-schwarzi* Member**	Fine- to medium-grained sandstones with molluscs, echinoderms and variable amounts of calcite. At the base a conglomerate bed consisting of quartz pebbles and sedimentary lithoclasts. **5 m to 70 m**
unconformity		Tendaguru Formation	**unconformity**	
Late Jurassic	Tithonian	Tendaguru Formation	**Upper Dinosaur Member**	Mainly ripple cross-bedded, fine-grained, calcareous sandstones and siltstones with intercalated claystone beds and isolated micritic carbonates, partly dolomites. Dinosaur bones. **~ 32 m**
Late Jurassic	late Kimmeridgian to Tithonian	Tendaguru Formation	***Indotrigonia africana* Member**	Brown to grey, calcite-cemented, bioclast- and feldspar-rich sandstones. Conglomerate beds, thin clay- and siltstone layers and sandy limestones. Sandstones interfinger with oolithic limestones in upper part of the succession (e.g., NE of Tendaguru Hill). **20 m to 50 m**
Late Jurassic	late Kimmeridgian	Tendaguru Formation	**Middle Dinosaur Member**	Mainly light grey, ripple cross-bedded, fine-grained, calcareous sandstones and siltstones and massive to crudely bedded silt- and claystones. Dinosaur bones. **13 m to 30 m**
Late Jurassic	Oxfordian to Kimmeridgian	Tendaguru Formation	***Nerinella* Member**	Trough cross-bedded or massive sandstones, partly fossiliferous. Well sorted, planar to low-angle cross-bedded as well as isolated swaley cross-bedded sandstones. **5 m to 45 m**
Late Jurassic	? Callovian to middle Oxfordian	Tendaguru Formation	**Lower Dinosaur Member**	Upper part: Grey to green, ripple cross-bedded, fine-grained, calcareous sandstones and siltstones, both rich in feldspar. Interbedded clay-rich siltstones. Dinosaur remains. **> 20 m**
unconformity				
Neoproterozoic				gneiss

Figure 2. Stratigraphic succession and subdivision of the Tendaguru Formation in its type area.

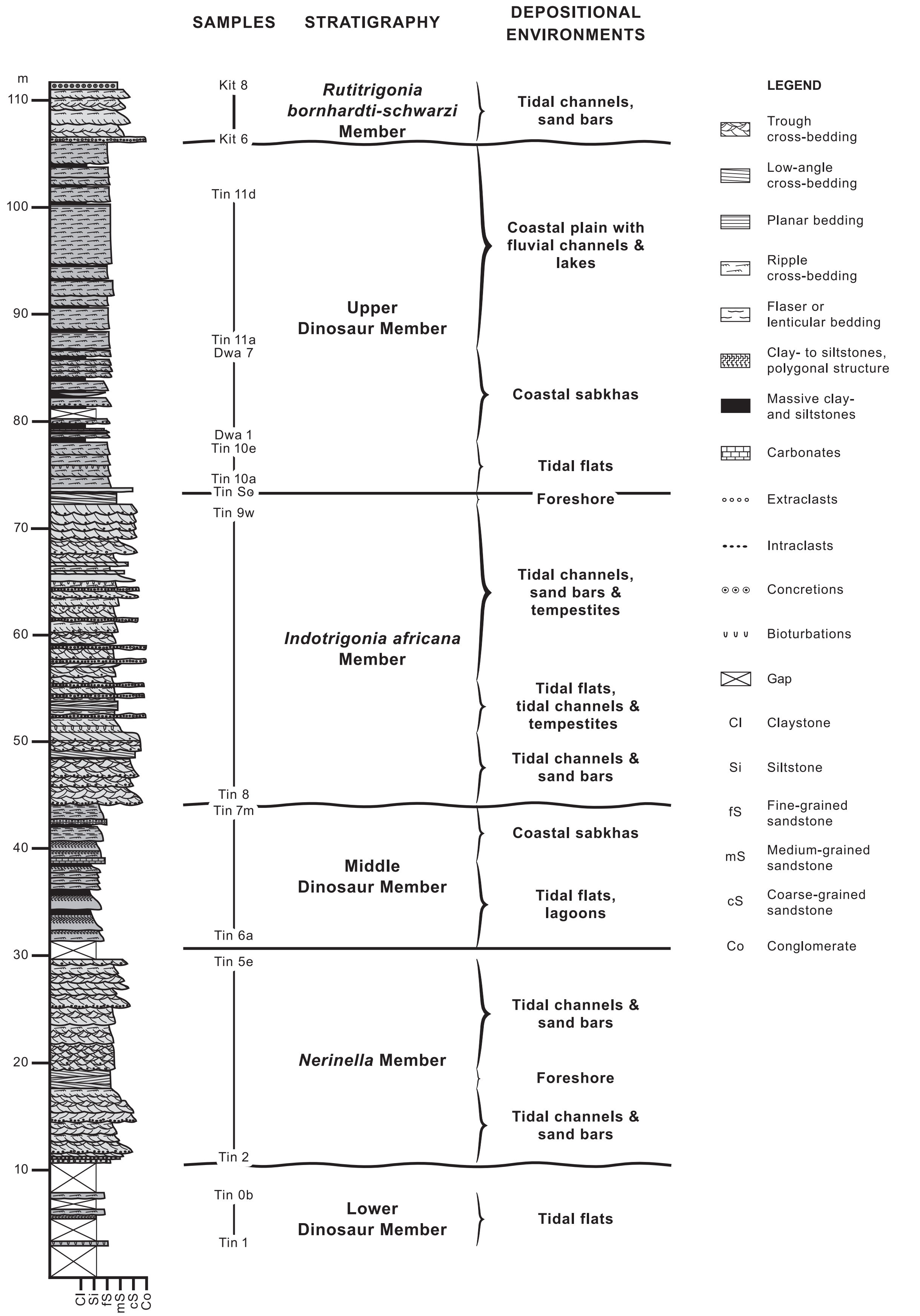


Figure 3. Composite section of the Tendaguru Formation in the type area. Sample numbers refer to samples of the German-Tanzanian Tendaguru Expedition 2000 (GTTE). Stratigraphic terms are defined in this study. For interpretation of depositional environments see text. For a complete depiction of the stratigraphic position of samples see Aberhan et al. (2002).

standard sequence of strata in the Tendaguru area, because of the lack of adequate exposures and lithofacies deviations in the intervening areas. A detailed report of strata in the Mandawa-Mahokondo and Makangaga (south)-Ruawa areas which were referred to the Tendaguru Formation was given by Aitken (1961).

Thickness. The Tendaguru Formation shows remarkable variations in thickness due to the uneven surface on which it was deposited. In the surroundings of Tendaguru Hill the formation was measured by the GTTE at several localities in the Tingutinguti and Dwanika stream sections where its thickness exceeds 110 m (Aberhan et al. 2002). This approaches the thickness of approximately 125 m reported by Janensch (1914a) for the type area. These data contrast markedly with a total thickness of approximately 970 m given by Aitken (1961: tab. 4) for the equivalents of the Tendaguru Formation in the area of Mandawa-Mahokondo. Schlüter (1997) reported erroneously an estimated formation thickness of about 315 m in the type area. Overall, the thickness of the sandstone-dominated marine members of the Tendaguru Formation increases distinctly towards the east, whereas that of the continental to marginal marine dinosaur-bearing members decreases in the same direction (Hennig 1937a).

Lithofacies. The fine-grained dinosaur-bearing members are dominated by ripple cross-bedded to massive siltstone as well as small-scale cross-bedded, fine-grained sandstone with some claystone and carbonate layers. The sandstone is rich in feldspars and the matrix consists chiefly of calcite. The clay mineral fraction is dominated by smectite and illite (Aberhan et al. 2002). In contrast, the marine members consist mainly of siliciclastic, bioclast-rich, well-stratified and trough cross-bedded sandstone, but low-angle and ripple cross-bedded sandstone as well as flaser bedded heterolithic beds also occur (Aberhan et al. 2002).

Boundaries. The Tendaguru Formation is bounded at the base by an unconformity. The GTTE was unable to locate the basal contact owing to the lack of exposures, but Hennig (1914a) and Janensch (1914a) described the base of the Lower Dinosaur Member as unconformable on Neoproterozoic basement gneisses. Exposures showing this contact are rare. Basement gneisses at Ngwanya creek, located approximately 9 km south-southwest of Tendaguru Hill (Fig. 1), are reported to be overlain unconformably by deposits of the Lower Dinosaur Member (Hennig 1914a) but a detailed description of the basal unconformity was not given.

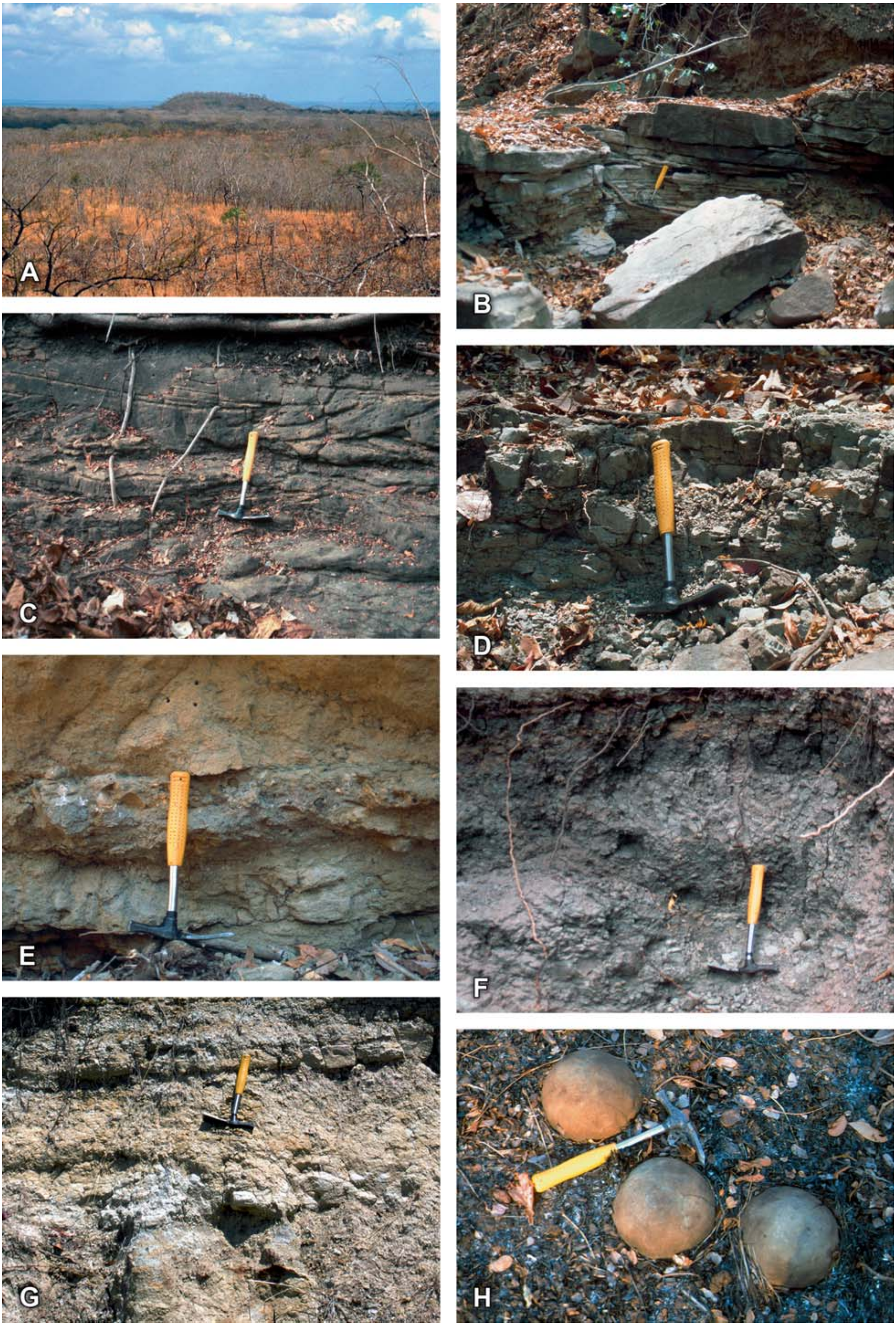
The Tendaguru Formation is unconformably overlain by the Makonde Formation that forms the top of several plateaus, for instance, the Namunda, Rondo, Noto, and Likonde-Kitale plateaus. However, at Tendaguru Hill and in its immediate surrounding erosion has removed any contacts that most probably previously existed between both formations. At the top of Tendaguru Hill, the *Rutitrigonia bornhardti-schwarzi* Member is capped by brownish fluvial sands and gravels which were tentatively identified as Mikindani Beds (now Mikindani Formation; Schlüter 1997) by Janensch (1914a), the age of which seems to be Pliocene or early Pleistocene (Schlüter 1997).

The time range of the hiatus between the Upper Dinosaur Member and the *Rutitrigonia bornhardti-schwarzi* Member is still a matter of discussion (e.g. Schrank 2005; Sames 2008) and is probably not great. Following Aitken (1961) we therefore include all six sequences as members in one lithostratigraphic unit, the Tendaguru Formation, rather than treating the *Rutitrigonia bornhardti-schwarzi* Member as a separate formation as suggested by Arkell (1956).

Palaeontolgy. The Tendaguru Formation has yielded a variety of exceptional fossils. The land vertebrates are dominated by dinosaurs, notably *Brachiosaurus* (Janensch 1914c, 1929b, 1935, 1950a, 1950b, 1961a), *Dicraeosaurus* (Janensch 1914c, 1925a, 1929b), *Kentrosaurus* (Hennig 1915, 1916, 1925; Galton 1982a), *Dysalotosaurus* (Janensch 1955, 1961b; Galton 1977, 1981), and *Elaphrosaurus* (Janensch 1925a, 1929c; Galton 1982b) among others. Fishes (Hennig 1914c; Arratia et al. 2002), as yet unidentified sphenodontians (Heinrich 2003), a paramacellododid lizard (Broschinski 1999), crocodiles (Janensch 1914c; Heinrich et al. 2001), pterosaurs (Reck 1931; Unwin & Heinrich 1999), and mammals (e.g. Dietrich 1927b; Simpson 1928; Heinrich 1998, 1999b) also occur. The recovered invertebrate assemblages include foraminifera (e.g. Fahrion 1937; Zils et al. 1995; Aberhan et al. 2002), corals (Weissermel 1900; Dietrich 1926), bivalves (e.g. Hennig 1914b; Lange 1914; Dietrich 1933a; Quennell et al. 1956; Aitken 1961; Cox 1965; Aberhan et al. 2002), gastropods (e.g. Hennig 1914b; Dietrich 1914, 1933a; Cox 1965; Aberhan et al. 2002), cephalopods (e.g. Zwierzycki 1914; Dietrich 1925a, 1933a; Spath 1928–1933; Aberhan et al. 2002), brachiopods (Lange 1914), arthropods (e.g. Beurlen 1933; Janensch 1933; Aberhan et al. 2002; Schudack & Schudack 2002; Sames 2005,

▶

Figure 4. Exposures of the Tendaguru Formation in its type area. **A.** Tendaguru Hill, view from the southeast; **B.** Low-angle cross-bedded foreshore sandstone; *Nerinella* Member, Tingutinguti stream section (GTTE site Tin 4b–Tin 4d); **C.** Trough cross-bedded tidal channel sandstone; *Nerinella* Member, Tingutinguti stream section (Tin 4j); **D.** Fine-grained sandstone and siltstone of a tidal flat environment; Middle Dinosaur Member; Tingutinguti stream section (Tin 7f); **E.** Bioclast-rich coarse-grained tempestites; *Indotrigonia africana* Member; Tingutinguti stream section (Tin 9s); **F.** Fluvial and lacustrine/sabkha fine-grained sandstone, siltstone, and claystone; Upper Dinosaur Member; Dwanika stream section (Dwa 5); **G.** Trough and ripple cross-bedded tidal channel and bar sandstone; *Rutitrigonia bornhardti-schwarzi* Member, Tendaguru Hill (Kit 7); **H.** Ball-shaped sandstone concretions ("Kugelsandstein"), *Rutitrigonia bornhardti-schwarzi* Member, top of Tendaguru Hill (Kit 8). This figure is available in colour online at museum-fossilrecord.wiley-vch.de.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2008), crinoids (Sieverts-Doreck 1939; Aberhan et al. 2002), and annelids (Lange 1914). Fossil macroplant remains include a poorly preserved silicified conifer cone (Gothan 1927; Stockey 1978, 1982), silicified wood remains and fusain (e.g. Kahlert et al. 1999; Süss & Schultka 2001, 2006; Philippe et al. 2004), driftwood bored by teredinids (Dietrich 1933a), and cuticles (Kahlert et al. 1999; Schultka in Heinrich et al. 2001). Palynomorphs (e.g. Jarzen 1981; Schrank 1999, 2005) and charophytes (Schudack 1999; Sames 2005, 2008) are also reported.

Age. Based on the existing biostratigraphical evidence, the age of the Tendaguru Formation ranges in the type area from the middle Oxfordian through the Tithonian (Lower to Upper Dinosaur Member) and from the Valanginian through Hauterivian or possibly Aptian (*Rutitrigonia bornhardti-schwarzi* Member) (e.g. Heinrich et al. 2001; Aberhan et al. 2002; Sames 2008).

Members of the Tendaguru Formation

Lower Dinosaur Member

Figures 2, 3, Table 2

Name. The name "Untere (erste) Saurierzone" (Lower Saurian Bed) was coined by Janensch (1914a) for the lowermost of the three dinosaur-bearing horizons of the Tendaguru Beds. Here, we formally emend this name, and other terms applied previously to this unit, to Lower Dinosaur Member (Table 2). Note that the term Lower Dinosaur Member was previously suggested by Schudack (1999) but the author failed to describe and define this member. The term refers to sauropod and theropod bones which were recovered from this unit.

Type section. Tendaguru Hill is regarded as the type locality of the Lower Dinosaur Member (Quennell et al. 1956). However, neither the GTE nor the BTE designated a type section for the Lower Saurian Bed. The GTTE has studied the Lower Dinosaur Member in the Tingutinguti stream section, at localities approximately 1.2 km southwest of Tendaguru Hill (Fig. 1; Tin 1, Tin 0a, and Tin 0b). These beds cover only the upper part of the Lower Dinosaur Member. For this reason, we refrain from defining a type section of the Lower Dinosaur Member and the formal establishment of a complete type section has to await the discovery of more extended exposures.

Distribution. Exposures of the Lower Dinosaur Member are confined to the surroundings of Tendaguru Hill (Janensch 1914a). Outcrops are found along the western escarpment of the Tendaguru Plateau, where small tributaries of the Mbemkuru river have incised minor valleys such as the Kipande, Maimbwi, Tingutinguti, Dwanika, and Kindope creeks. Unfortunately, these exposures are largely overlain by Mbemkuru floodplain deposits and material derived from erosion of the stream section slopes. The generalised distribution of the Lower Dinosaur Member in the surroundings of Tendaguru Hill is illustrated by Hennig (1914a: geological map), Janensch (1914b: p. 45; 1925b: XVIII), and Aberhan et al. (2002: fig. 1).

Thickness. The thickness is difficult to determine owing to the lack of extended exposures. Janensch (1914a) reported more than 20 m, Hennig (1937a) 15 m to 50 m for the entire thickness of the Lower Dinosaur Member in the Tendaguru area. The uneven underlying gneiss surface probably explains the variations in local thickness that are difficult to assess.

Lithofacies. Janensch (1914a) described the member as consisting of grey and reddish sandy marl exposed in the Tingutinguti and Dwanika stream sections. GTTE data from the Tingutinguti stream section showed that the upper portion of the Lower Dinosaur Member consists predominantly of light grey to green coloured, ripple cross-bedded, fine-grained sandstone and siltstone, with interbedded massive, clay-rich siltstone (Aberhan et al. 2002). Beds of massive, in part bioturbated, fine-grained sandstone are intercalated, containing fragments of bivalves and fusain. The sediments are rich in feldspar and contain calcite; the clay mineralogy is dominated by smectite, with minor amounts of illite.

Boundaries. In the Tendaguru area, the Lower Dinosaur Member rests directly on Neoproterozoic gneiss (Janensch 1914a). According to Hennig (1914a), the contact with basement gneiss was observed at GTE site Ngwanya, located at the northwestern foot of the Namunda Plateau approximately 9 km southwest of Tendaguru Hill (for the geographic position of the site see Janensch 1914b: p. 50), but a detailed description of the contact was not given. Although the direct contact was not observed by the GTTE, the Lower Dinosaur Member is likely to be unconformably overlain by shallow marine deposits consisting of trough cross-bedded or massive, poorly sorted, medium- to coarse-grained sandstone of the *Nerinella* Member (Aberhan et al. 2002). Here, we define the boundary with the *Nerinella* Member by the first appearance of moderately to poorly sorted, medium- to coarse-grained sandstone.

Palaeontolgy. Mollusc assemblages from the upper part of the Lower Dinosaur Member (Tin 0a, Tin 1) are dominated by bivalves, notably juveniles of *Meleagrinella radiata*, *Liostrea dubiensis*, *Nanogyra nana*, and *Eomiodon cutleri*. Gastropods include *Pseudomelania dietrichi*, *Cryptaulax* sp., and *Promathildia* sp. (Aberhan et al. 2002). Serpulid worm tubes, benthic foraminifera, and fragments of echinoids and crinoids have also been found. Moreover, the ostracods *Pirileberis madoensis* and *Cytherura* sp. were identified (Sames 2008).

Poorly preserved fish remains recovered from Tin 0a do not permit precise taxonomic determinations (Arratia et al. 2002). The land vertebrate fauna is also poorly known due to the lack of outcrops. A few skeletal remains were assigned to *Brachiosaurus brancai*. Several isolated teeth of carnivorous dinosaurs were tentatively referred to '*Megalosaurus* (?) *ingens*', '*Ceratosaurus* (?) *roechlingi*' [= basal ceratosaur; Rauhut 2005], and '*Allosaurus* (?) *tendagurensis*' [= basal tetanuran; Rauhut 2005] (Janensch 1925a, 1961a).

An impoverished palynoflora obtained from Tin 1 and Tin 0a contains chiefly conifer pollen grains of the Cheirolepidiaceae. Possible representatives of the Podocarpaceae and Araucariaceae have also been found along with pteridophytic spores (Aberhan et al. 2002). The mesoflora is dominated by cuticles of cheirolepidiaceans, while those of the Araucariaceae and ginkgoales are less common (Aberhan et al. 2002).

Age. The precise age of the Lower Dinosaur Member has not been established so far owing to the lack of adequate fossils. The occurrence of *Pirileberis madoensis* in Tin 0a, together with ostracods recovered from the overlying *Nerinella* Member is supposed to indicate a middle Oxfordian or older age for the upper portion of the Lower Dinosaur Member (Sames 2008). Previous opinions had tentatively suggested an Oxfordian (Zwierzycki 1914; Krenkel 1925; Hennig 1937a) or even a Callovian age (Dietrich 1927a). In contrast, Quennell et al. (1956) and Aitken (1961) believed that the Lower Dinosaur Member is probably not older than middle or late Kimmeridgian.

Nerinella Member

Figures 2, 3, 4B–C, Table 2

Name. The strata here referred to as the *Nerinella* Member were originally described as "Untere Sandsteinzone (Nerineenzone)" (*Nerinea* Bed) by Janensch (1914a). They were provisionally named after the occurrence of nerineid gastropods (Janensch 1914a), which are common elements of the marine macroinvertebrate assemblages of the Tendaguru Formation. Cox (1965) referred to this unit as *Nerinella* Bed. He erected the new species *Nerinella cutleri* (Figs 5A–B), which is common in the *Nerinella* Bed at several localities in the Tendaguru area. However, *N. cutleri* is not an index fossil of this unit and also occurs in younger strata of the *Indotrigonia africana* Member. Here, we formally emend all terms applied previously to this unit to *Nerinella* Member (Table 2).

Type section. Tendaguru Hill is regarded as the type locality (Quennell et al. 1956), but neither the GTE nor the BTE designated a type section for the *Nerinea* Bed. Here, we formally establish a type section of the *Nerinella* Member defined from Tin 2 to Tin 5e in the Tingutinguti stream section (Fig. 3).

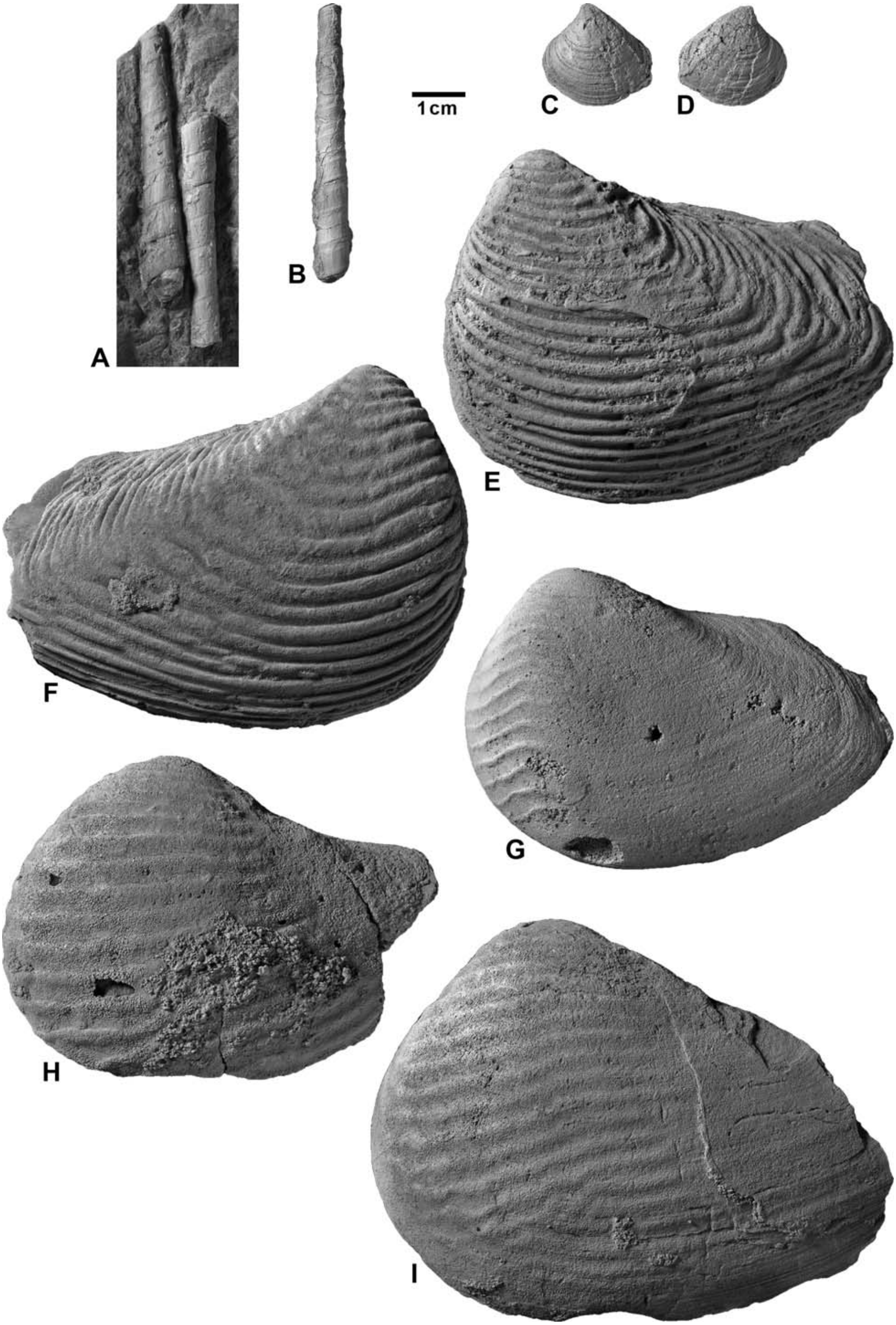
Distribution. Exposures of the *Nerinella* Member are confined to the surroundings of Tendaguru Hill and have not been definitely identified outside the Tendaguru region (Quennell et al. 1956; Aitken 1961). The generalised distribution of the *Nerinella* Member in the Tendaguru area is illustrated, for instance, by Hennig (1914a: geological map) and Aberhan et al. (2002: fig. 1). Mapping by Hennig (1914a) showed that it stretches along the western escarpment of the Tendaguru Plateau, mainly between the Kindope stream section to the north and the Kipande stream section to the south. Outcrops are reported from the Kindope and Tingutinguti stream sections (Janensch & Hennig 1914) as well as from the Bolachikombe stream section south of Tendaguru Hill (see inlay of Fig. 1; Dietrich 1933a). Continuous exposures of the *Nerinella* Member can be observed in the Tingutinguti stream section south of Tendaguru Hill (Aberhan et al. 2002).

Thickness. Janensch (1914a) reported a thickness of 25 m for the *Nerinella* Member in the Tendaguru area. Hennig (1937a) gave the following thickness measurements: ca. 45 m (Kipande path), 15–20 m (Tingutinguti stream section), ca. 25 m (Nambiranj path), 30–35 m (Dwanika stream section), and 15–20 m (Kindope stream section). Based on data mainly obtained in the Tingutinguti stream section, Aberhan et al. (2002) reported a thickness of approximately 20 m for the *Nerinella* Member at the type section.

Lithofacies. Originally, the *Nerinella* Member was described as consisting of friable, fine- to medium-grained, limey, yellowish sandstone (ca. 6–7 m) which is overlain by fine- to medium-grained, limey, grey sandstone (11–13 m), followed by friable, fine-grained, yellowish sandstone (6–7 m) (Janensch 1914a). This description was rendered more precisely by the GTTE. According to Aberhan et al. (2002), the member is mainly characterised by (1) trough cross-bedded or massive, poorly sorted, medium- to coarse-grained sandstone; (2) massive to indistinctly cross-bedded, fine- to medium-grained sandstone containing occasionally rich assemblages of marine invertebrates; (3) stacked sequences of chiefly trough cross-bedded, fine- to medium-grained sandstone; and (4) well sorted, horizontally bedded to low-angle cross-bedded sandstone and isolated swaley cross-bedded sandstone. The sandstone is generally rich in feldspar, but variable in respect of the content of fossils, calcite cement, heavy minerals and micas, as well as in sorting and sedimentary structures.

The basal part of the *Nerinella* Member is built up mainly by trough cross-bedded to massive, moderately to poorly sorted, medium- to coarse-grained, in part pebbly, grey to yellow coloured, calcite-cemented, siliciclastic sandstone. The sandstone is rich in bioclasts, predominantly bivalves, foraminifera, and echinoderms, but also in lithoclasts. It forms crude fining-upward sequences. Dip directions of cross-bedding foresets indicate a variably directed sediment transport.

The basal sandstone is overlain by horizontally bedded to low-angle cross-bedded, in part ripple cross-bedded, mostly well sorted, fine- to medium-grained, grey to brown coloured, calcite-containing, siliciclastic sandstone. In comparison to the basal part of the *Neri-*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nella Member, these beds contain less bioclasts, but are richer in mica. Several layers with heavy mineral concentrations are also present.

The basal part is overlain by mostly trough cross-bedded, fine- to coarse-grained, moderately to well sorted, yellow to brown coloured sandstone. Some of these sandstone layers contain abundant bioclasts, mainly echinoderms, bivalves, and some foraminifera as well as coalified woody plant fragments, whereas others contain only few bioclasts, but increased amounts of mica and heavy minerals. The calcite content is generally low. Transport directions are highly variable, with NE, E, and W directions being most prominent.

The uppermost part of the *Nerinella* Member is formed by dominantly trough cross-bedded, in part bioturbated, poorly to well sorted, coarse- to fine-grained, yellow to brown coloured, calcite-containing, siliciclastic sandstone. Bioclasts are limited to scattered bivalve remains, whereas in some beds heavy mineral-rich layers are present. The sandstone forms thin fining-upward sequences that start with an erosive boundary, overlain by coarse-grained pebbly sandstone grading upward into trough cross-bedded and finally into ripple cross-bedded fine-grained sandstone. Sediment transport directions are again variable, and mainly oriented to the NE, E, and SW.

Boundaries. The *Nerinella* Member is underlain by the Lower Dinosaur Member and overlain conformably by the Middle Dinosaur Member. The lower boundary is defined by a clear break in grain-size of the sediments and the first appearance of moderately to poorly sorted, medium- to coarse-grained sandstone. We define the upper boundary to the Middle Dinosaur Member with the last appearance of some decimeter thick, fine- to medium-grained, cross-bedded sandstone.

Palaeontolgy. Common macroinvertebrates of the basal parts of the *Nerinella* Member (e.g. Tin 2, Tin 3/base, Tin 3b) are the bivalves *Protocardia schencki* and *Grammatodon irritans* that are associated with limids and pectinids (Aberhan et al. 2002), while gastropods are generally less common. However, Hennig (1937a) reported a local mass accumulation of gastropods ("Schneckennest") of the *Nerinea* Bed associated with '*Perisphinctes sparsiplicatus*' [= *Pachyplanulites*? sp.; G. Schweigert, personal communication 2008] from a small stream section located between the Tingutinguti and Maimbwi stream section. Janensch & Hennig (1914) mentioned only three localities that have produced invertebrates from the *Nerinea* Bed: Kindope (approximately 5 km north-northwest of Tendaguru Hill) and GTE invertebrate sites 3 (about 3 km northwest of Tendaguru Hill, path to Nanundo) and 14 and 14a (Tingutinguti stream section). Dietrich's (1914, 1925a, 1933a) and Cox' (1965) descriptions of the gastropods and bivalves of the *Nerinea* Bed include, for instance, '*Nerinella credneri*' [= *Nerinella cutleri*], '*Patella*' [= *Scurriopsis (Dietrichiella)*] *kindopensis*, *Lissochilus stremmei*, *Stegoconcha gmuelleri*, *Arcomytilus subpectinatus*, '*Astarte*' [= *Herzogina*] *recki*, *Rutitrigonia dietrichi*, and many others. Cephalopods are rare elements (e.g. *Nautilus sattleri*, *Haploceras* [= *Metahaploceras* sp.; G. Schweigert, personal communication 2008], '*Perisphinctes sparsiplicatus*' [= *Pachyplanulites*? sp.; G. Schweigert, personal communication 2008], *Perisphinctes staffi*; Zwierzycki 1914; Dietrich 1925a; Spath 1928–1933; Arkell 1956; *Torquatisphinctes* cf. *torquatus*, *Taramelliceras* sp. ex gr. *kiderleni*; Heinrich et al. 2001). The calcareous microfauna from Tin 2a includes ostracods (e.g. *Majungaella oxfordiana*, *Cytherella disjuncta*, *Cytherella umbilica*, *Fastigatocythere* sp.; Sames 2008), and undetermined benthic foraminifera (Aberhan et al. 2002).

Calcareous concretions obtained from bioturbated sandstone deposits in the lower part of the *Nerinella* Member (Tin 3d) have yielded a rich macroinvertebrate assemblage dominated by bivalves (see Aberhan et al. 2002: fig. 3). Ostracods (e.g. *Cytherella disjuncta*, *Cytherella umbilica*?, *Galliaecytheridea manyuliensis*, *Mandelstamia* sp. 2, *Bairdia* sp. and *Majungaella* sp. 1; Sames 2008) and benthic foraminifera have also been recovered from the lower part of the *Nerinella* Member. Moreover, it has produced a *Rigaudella aemula-Chlamydophorella wallala* assemblage of palynomorphs (Schrank 2005). GTTE bed Tin 3d has also produced conifer woods (as fusain) which were identified as *Primopodocarpoxylon podocarpoides* (Süss & Schultka 2006).

Age. Based on dinoflagellate cysts, the *Nerinella* Member exposed in the Tingutinguti stream section (Tin 2–Tin 4h) ranges from Oxfordian to Kimmeridgian in age (Schrank 2005). Similarly, Sames (2008) suggested an age range from at least the middle Oxfordian to the

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Figure 5. Characteristic Late Jurassic and Early Cretaceous invertebrates of the Tendaguru Formation; **A–B.** *Nerinella cutleri* Cox; *Nerinella* Member, Tendaguru, Tingutinguti streambed, GTE site 14; **A.** MB.Ga.3847.1; **B.** MB.Ga.1104; **C–D.** *Eomiodon cutleri* Cox; Upper Dinosaur Member, Tendaguru, GTE site G; MB.M.1645.4; **C.** Left valve view; **D.** Right valve view; **E–F.** *Indotrigonia africana* Aitken; *Indotrigonia africana* Member, Tendaguru, Tingutinguti streambed, GTE site 1; **E.** Left valve view; MB.M.1620; **F.** Right valve view; MB.M.1636; **G.** *Rutitrigonia schwarzi* (Müller), left valve view; *Rutitrigonia bornhardti-schwarzi* Member, Likonde-Kitale; MB.M.1779; **H–I.** *Rutitrigonia bornhardti* (Müller), left valve view; *Rutitrigonia bornhardti-schwarzi* Member; **H.** West of Ngomanji between Niongala and Mtapaia; MB.M.1783.2; **I.** Ntandi; MB.M.5912.1. All specimens are figured in natural size. They have been coated with ammonium chloride and are housed at the Museum für Naturkunde Berlin (inventory numbers with the prefix MB).

Kimmeridgian for ostracod assemblages recovered from the lower portion of the *Nerinella* Member (Tin 2a, Tin 3b, Tin 3d). On the basis of ammonoids, previous studies assigned an Oxfordian (Zwierzycki 1914; see also Hennig 1937a), Sequanian (late Oxfordian) (Dietrich 1933b), Oxfordian (?)-late Kimmeridgian (Aberhan et al. 2002), early to middle Kimmeridgian (Dietrich 1925a), and late Kimmeridgian age (Arkell 1956; Heinrich et al. 2001). A definite age determination, however, is not possible with the available ammonoids, although a late early Kimmeridgian (Divisum Zone) age appears most likely (G. Schweigert, personal communication 2008). Therefore, we retain a relatively wide age range herein and tentatively suggest an Oxfordian to Kimmeridgian age range for the *Nerinella* Member.

Middle Dinosaur Member

Figures 2, 3, 4D, Table 2

Name. The name "Mittlere (zweite) Saurierzone" (Middle Saurian Bed) was coined by Janensch (1914a) for the middle of the three dinosaur-bearing units of the Tendaguru Beds. Here, we formally emend this name and other terms, applied previously to this unit, to Middle Dinosaur Member (Table 2). Note that the term Middle Dinosaur Member was previously suggested by Schudack (1999) but the author did not describe and define this member. The name refers to the rich assemblages of well preserved sauropod, ornithopod, and theropod bones.

Type section. Tendaguru Hill is regarded as the type locality (Quennell et al. 1956). Neither the GTE nor the BTE designated a type section for the Middle Saurian Bed. Here, we formally establish the type section of the Middle Dinosaur Member in the Tingutinguti stream section, defined from Tin 6a to Tin 7m (Fig. 3).

Distribution. Deposits of the Middle Dinosaur Member have been recognised over large parts of the hinterland of the towns of Kilwa and Lindi. Its generalised distribution in the surroundings of Tendaguru Hill and adjacent areas was illustrated in a geological map (scale 1 : 300.000) by Hennig (1914a). Based on further data of the GTE (Janensch 1914b) and new data of the GTTE, the distribution of the member in the immediate surroundings of Tendaguru Hill was presented in a map by Aberhan et al. (2002: fig. 1). Accordingly, the member is mainly known from outcrops along the western escarpment of the Tendaguru Plateau and, for instance, from exposures at Mtapaia (GTE sites Aa, XX) about 10 km north of Tendaguru Hill. Farther to the west, deposits are restricted to an isolated outlier between Nakihu and Maonga approximately 11 to 12 km northwest of Tendaguru Hill (fig. 1) (Hennig 1914a). More extensive outcrops of the Middle Dinosaur Member are also present in the valley of the Mtshinyiri river, a tributary of Mbemkuru river, and southeast of Minyoka where it crops out extensively in two belts along the slopes of the Mbemkuru stream valley (fig. 1) (Hennig 1914a). The westernmost outcrop of the member is probably GTE site Oa at Obolello, located approximately 15 km southwest of Tendaguru Hill. At this locality two dinosaur beds were exposed in superposition, of which one is likely identical with the Middle Dinosaur Member (Janensch 1914b). The member is also present at GTE site S in the Kitukituki stream section, about 1.0 km south-southwest of Tendaguru Hill, that has produced two skeletons of *Brachiosaurus brancai*, among them the famous Berlin specimen (Janensch 1950b).

Thickness. Janensch (1914a) reported a thickness of approximately 15 m for the Middle Dinosaur Member in the type area. Thickness data by Hennig (1937a) are as follows: ca. 15–20 m (Kipande path), 10 m (Tingutinguti stream section), ca. 10 m (Nambiranji path), 15–20 m (Dwanika stream section), and 30 m (Kindope stream section). The GTTE measured a thickness of 13 m for the Middle Dinosaur Member in the Tingutinguti stream section (Aberhan et al. 2002).

Lithofacies. Janensch (1914a) defined the Middle Saurian Bed as alternating layers of grey and red, sandy marl with dinosaur bones and an argillaceous bed at the base (12 m), overlain by red sandy marl (3 m). Field work of the GTTE has shown that the lower part of the Middle Dinosaur Member is mainly built up by ripple cross-bedded, fine-grained siliciclastic sandstone and siltstone, and massive to crudely bedded silt- and claystone (Aberhan et al. 2002). The sandstone and siltstone is mainly light grey coloured, whereas the clay-rich deposits are dark grey or reddish-brown. The sediments contain very variable amounts of calcite as well as sporadic dolomite. The clay mineralogy is dominated by smectite and illite, containing traces of kaolinite as well. Fossils such as bivalves and gastropods are most abundant in the basal part of the member.

The basal part consists of fining-upward sequences that are some decimetres thick. They are composed of ripple cross-bedded to ripple cross-laminated, fine-grained sand- and siltstone that grades upward into massive clayey siltstone with abundant bivalve and gastropod remains. The calcite content is highly variable; dolomite-rich beds are missing, in contrast to the upper part of the member. Ripple cross-bedded sandstone beds occasionally contain heavy mineral layers. In the upper part of the fining-upward sequences, some sandy to silty micritic limestone beds occur.

In the upper part of the Middle Dinosaur Member, sandy to silty and partly peloidal micrite horizons are intercalated into the prevalent siltstone and fine-grained sandstone. Lithoclasts consisting of sandy to silty micrite are also present in adjacent sandstone beds. The calcite content is variable and, in several beds, dolomite is present. Two bone beds at GTE site Ig (WJ) represent channel lag deposits containing dinosaur bones, mud clasts, and reworked caliche nodules.

Boundaries. The lower boundary of the Middle Dinosaur Member to the *Nerinella* Member is defined as the first occurrence of ripple cross-laminated, fine-grained sandstone and siltstone on top of cross-bedded, fine- to medium-grained sandstone. It is very likely a conformable, gradual contact without a major shift in facies, and reflects a more or less continuous change from upper shoreface to shallow lagoonal sediments. In contrast, the upper boundary is unconformable to the *Indotrigonia africana* Member. It is marked by a conspicuous break in grain-size that corresponds to a considerable environmental change, with ripple cross-laminated siltstone and fine-grained sandstone erosively overlain by trough cross-bedded, coarse-grained pebbly sandstone.

Palaeontolgy. Vertebrates of particular significance include fishes (e.g. *Lepidotes* sp., unidentified selachians and teleosts; Arratia et al. 2002; Hennig 1914b), as yet unidentified amphibians [Lissamphibia (Salientia?) indet.; Aberhan et al. 2002; Heinrich 2003], a paramacellododid lizard (Broschinski 1999), pterosaurs (e.g. *Tendaguripterus recki*; Unwin & Heinrich 1999), crocodiles (e.g. *Bernissartia* sp.; Heinrich et al. 2001; Aberhan et al. 2002), dinosaurs (e.g. *Elaphrosaurus bambergi*, 'Coelurosaurier B and C' [= abelisauroid; Rauhut 2005], '*Allosaurus* (?) *tendagurensis*' [= basal tetanuran; Rauhut 2005], '*Ceratosaurus* (?) *roechlingi*' [= basal ceratosaur; Rauhut 2005], '*Labrosaurus* (?) *stechowi*', '*Megalosaurus* (?) *ingens*', *Dicraeosaurus hansemanni*, *Brachiosaurus brancai*, *Kentrosaurus aethiopicus*, *Dysalotosaurus lettowvorbecki* (e.g. Janensch 1914c, 1920, 1925a, 1929a, 1929b, 1955, 1961a; Hennig 1925; Galton 1981; Rauhut 2003, 2005), and mammals (*Allostaffia aenigmatica*, *Tendagurodon janenschi*, *Tendagurutherium dietrichi*, and as yet unidentified symmetrodonts; Heinrich 1998, 1999b, 2001, 2003).

Invertebrate fossils have been found throughout large parts of the Middle Dinosaur Member. At its base, as identified at GTE site 19 within the Bolachikombe stream section approximately 3 km south of Tendaguru Hill (Fig. 1) (Hennig 1914b), massive, limey sandstone deposits were found just below skeletal remains of *Brachiosaurus brancai*, among them a bone which was overgrown with oysters (Janensch, GTE field catalogue: p. 76). These sandstone beds yielded '*Cyrena*' [= *Eomiodon*], '*Mytilus*' [= *Falcimytilus*], *Pseudomelania*, '*Nerita*', and other invertebrates (Hennig 1914b; Dietrich 1933a). Similarly, at the Tingutinguti stream section, the basal part of the Middle Dinosaur Member (Tin 6, Tin 7b) yielded a macrobenthic mollusc assemblage that is strongly dominated by the bivalve *Eomiodon cutleri* (Aberhan et al. 2002). Mytilid bivalves and gastropods (e.g. *Promathildia* sp., *Pseudomelania dietrichi*) are far less common. About 300 m west of Tendaguru Hill, the lowermost beds of the Middle Dinosaur Member and the contact with the underlying *Nerinella* Member were exposed at GTE site p that has produced an articulated series of *Brachiosaurus brancai* caudal vertebrae (Janensch, GTE field catalogue: p. 56), again associated with '*Cyrena*' [= *Eomiodon*], and pseudomelanid gastropods together with '*Trigonia*' and crinoids (Hennig 1914b).

In the remaining part of the type section, from Tin 7c to Tin 7l, macroinvertebrates are rare, and in addition to the previously mentioned mollusc taxa small specimens of the eurytopic oysters *Liostrea* and *Nanogyra* occur (Aberhan et al. 2002). The uppermost strata of the Middle Dinosaur Member were exposed at GTE site Aa near Mtapaia (Hennig 1914a). They consist of poorly lithified, sandy marl (Dietrich 1933a) that have yielded skeletal remains of *Brachiosaurus brancai*, among them a humerus overgrown by oysters (Janensch GTE field catalogue: p. 140), and invertebrates such as *Thracia incerta*, *Pleuromya tellina*, '*Cyrena*' sp. [= *Eomiodon*], *Protocardia schencki*, '*Trigonia*' [= *Indotrigonia*] *dietrichi*, '*Modiola*' [= *Inoperna*] *perplicata*, '*Pseudomonotis tendagurensis*' [= *Meleagrinella radiata*], and *Perisphinctes* sp. (Hennig 1914b).

Ostracods from GTE site Aa are referred to *Trapezoidella* sp. and *Paracypris* sp. (Schudack & Schudack 2002). Dietrich (1933a) considered these deposits as brackish transitional beds that connected the Middle Dinosaur Member with the overlying *Indotrigonia africana* Member. Owing to their fine-grained nature, we include these transitional beds in the Middle Dinosaur Member. Ostracods have also been recovered recently from the lower part the type section (Tin 7a, Tin 7b, Tin 7d), notably *Bythocypris* sp., *Cytheropteron* sp., *Cetacella* sp., *Darwinula* sp., *Trapezoidella* sp., and *Cypridea* sp. 1 (Sames 2008). Higher up (Tin 7g, Tin 7i), *Darwinula*? sp., *Cypridea* sp. 2 and sp. 3, and *Mantelliana* sp. were recognised (Sames 2008). Moreover, the bone bed WJ at GTE site Ig (= GTE site dy; Janensch 1955) has yielded the ostracods *Mandelstamia* sp. and *Cetacella* sp. (Schudack & Schudack 2002). In addition, *Trapeziodella* sp. B, *Mandelstamia* sp., *Cypridea* sp., *Rhinocypris* sp., and *Darwinula* sp. and others were reported from the Middle Dinosaur Member of the Kitukituki stream section by Schudack & Schudack (2002).

Only a few flagellate dinocysts have been recovered from the Middle Dinosaur Member, chiefly from the lower (Tin 6a, Tin 7b) and middle part of the succession (Tin 7f/1, Tin 7f/2) (Schrank 2005). They are representatives of the *Endoscrinium attadalense*-*Ctenidodinium sellwoodi* group assemblage (Schrank 2005). Charophytes are known from GTE site Ig (WJ) (*Mesochara canellata*, *Mesochara harrisi*, *Aclistochara* cf. *bransoni*), from the *Cyrena* Marls (*Mesochara harrisi*), from deposits exposed in the Kitukituki stream section (*Mesochara harrisi*, *Mesochara canellata*, *Aclistochara* cf. *minor*) (Schudack 1999) and from Tin 7d (*Mesochara* sp.; Sames 2008). Freshwater algae (*Ovoidites*) have also been found in Tin 6 and Tin 7f (Aberhan et al. 2002).

Age. The age of the Middle Dinosaur Member was tentatively identified as late Kimmeridgian or Tithonian by Quennell et al. (1956). Recent work on dinoflagellate cysts suggests that the *Endoscrinium attadalense*-

Ctenidodinium sellwoodi group assemblage from the Middle Dinosaur Member is likely late Kimmeridgian (Schrank 2005). This dating is consistent with the palaeontological age assessments of Schudack & Schudack (2002). This led us to tentatively assign a late Kimmeridgian age to the Middle Dinosaur Member.

Indotrigonia africana Member

Figures 2, 3, 4E, Table 2

Name. This member is named after the bivalve species *Indotrigonia africana* (Figs 5E–F). Lange (1914), Dietrich (1933a), and Cox (1952) accepted that *Trigonia smeei* from the Upper Jurassic of the Tendaguru area and adjacent regions was taxonomically identical to *Trigonia smeei* from the Argovian of Kachchh, western India. However, data subsequently published by Aitken (1961) indicated that the Tendaguru specimens referred to *Trigonia smeei* differ from the Indian *smeei*. They belong to a distinct species which was described as *Trigonia* (*Indotrigonia*) *africana* by Aitken (1961). We therefore change the name "Mittlere Sandsteinzone mit *Trigonia smeei*" (Janensch 1914a) (*Trigonia smeei* Bed) and other terms applied previously to this unit to *Indotrigonia africana* Member (Table 2). The term *Trigonia smeei* Bed was coined for the middle of the three marine horizons of the Tendaguru Beds (Hennig 1914a; Janensch 1914a) and applied for strata considered to be equivalent to those deposits which were previously described by Fraas (1908) as "Trigonienschichten mit *Trigonia beyschlagi*" (Hennig 1914a).

Type section. Tendaguru Hill is regarded as the type locality (Quennell et al. 1956). Janensch's (1914a) description of the *Trigonia smeei* Bed is based on exposures in the Tingutinguti stream section. Neither the GTE nor the BTE designated a type section. Here, we formally establish a type section for the *Indotrigonia africana* Member in the Tingutinguti stream section, defined from beds Tin 8 to Tin 9w (Fig. 3).

Distribution. The generalised distribution of the *Indotrigonia africana* Member in the surroundings of Tendaguru Hill and adjacent areas was illustrated in a geological map (scale 1 : 300,000) by Hennig (1914a). The distribution of the member in the immediate surroundings of Tendaguru Hill is shown by Aberhan et al. (2002: fig. 1). The member is mainly exposed in stream sections of the tributaries of the Mbemkuru river, such as the Mtapaia, Mtshinyiri and Marihi creeks, in the Mbemkuru stream valley southeast of Minyoka, and in the Kikundi stream section (Hennig 1914a, 1937a). Farther to the north, Hennig (1914a) had mapped strata with *Trigonia smeei* in the Mahokondo area. However, Quennell et al. (1956) and Aitken (1961) have shown that *Trigonia smeei* recovered from the lower part of the so-called *smeei*-Oolite and the "Haupt-*smeei*-Zone" of the Mandawa-Mahokondo area is distinct from that of the *Indotrigonia africana* Member in the Tendaguru area. It was described as *Indotrigonia mandawae* (Aitken 1961). Consequently, the correlation is lapsed (Aitken 1961). The *Indotrigonia africana* Member is well-developed along the western escarpment of the Tendaguru Plateau as well as south of Tendaguru Hill in the Tingutinguti and Maimbwi stream sections.

Thickness. At Tendaguru Hill the *Indotrigonia africana* Member is about 20 m thick (Janensch 1914a), with gradual thickening to the northeast to about 30 m in the Mtapaia stream section and a more marked thickening towards the northeast to about 50 m in the Mtshinyiri stream section at Matapua (Hennig 1937a). In addition, Hennig (1937a) gave the following thickness measurements: ca. 20 m (Kipande path), ca. 30 m (Tingutinguti stream section), ca. 17 m (Nambiranji path), 20–25 m (Dwanika stream section), and 30 m (Kindope stream section) (Fig. 1). Based on data mainly obtained in the Tingutinguti stream section, Aberhan et al. (2002) reported a thickness of approximately 20 m for the *Indotrigonia africana* Member.

Lithofacies. The deposits of the *Indotrigonia africana* Member were described as friable, soft, yellow and grey sandstone with intercalations of massive calcareous, fine- to coarse-grained, sometimes conglomeratic sandstone horizons (Janensch 1914a). Data of the GTTE have shown that the deposits in the Tendaguru area mainly consist of brown to grey, calcite-cemented, bioclast-rich sandstone, several conglomerate beds as well as of some thin clay- and siltstone layers and sandy limestone (Aberhan et al. 2002; Bussert & Aberhan 2004). In the upper part of the succession the sandstone interfingers with oolitic limestone northeast of Tendaguru Hill (Aberhan et al. 2002). Similar to the *Nerinella* Member, the sandstone of the *Indotrigonia africana* Member is uniformly rich in feldspars, whereas its calcite content is highly variable.

The *Indotrigonia africana* Member can be subdivided into three parts. The basal part consists of stacked sequences of trough cross-bedded, partly low angle or tabular cross-bedded, moderately to poorly sorted, coarse- to medium-grained, pebbly sandstone. This sandstone frequently forms thin fining-upward sequences which start with a basal erosion surface. Palaeocurrent directions, derived from dip directions of the cross-bedding foresets, are variable. Bioclasts are represented mostly by fragments of bivalves, and by some echinoderms. In several layers, concentrations of heavy minerals occur.

The middle part is mainly built up by cross-bedded, fine- to medium-grained sandstone, and by ripple cross-bedded, in part flaser, lenticular or parallel bedded, fine-grained sandstone, siltstone, and minor claystone. At several levels, beds of coarse-grained pebbly sandstone or conglomerates, mostly 10–25 cm thick, are intercalated. These beds start with a basal erosion surface and display wave ripple as well as swaley and hummocky cross-bedding structures. They contain abundant bioclasts, predominantly bivalves, as well as concentrations of heavy minerals and lithoclasts.

The upper part of the member consists mostly of trough cross-bedded, moderately to poorly sorted, coarse- to medium-grained, pebbly sandstone, some of which form fining-upward sequences. Although bioclasts such as bivalves are present, they are rarer when compared to the middle part of the member.

Fossils such as bivalves, gastropods, corals, echinoderms, and foraminifera are present in all parts of the member, but are most abundant in the middle part.

Boundaries. An unconformable, sharp and erosive contact, marked by an abrupt increase in grain-size from siltstone and fine-grained sandstone of the Middle Dinosaur Member to trough-cross-bedded, coarse-grained sandstone and the occurrence of heavy-mineral concentrations represent the lower boundary of the *Indotrigonia africana* Member. The lower boundary clearly reflects substantial erosion as well as a major environmental change. The upper boundary to the Upper Dinosaur Member is defined by the topmost appearance of medium- to fine-grained, cross-bedded sandstone beds, which are conformably overlain by cross-laminated fine-grained sandstone of the Upper Dinosaur Member. The lower boundary is best exposed in the Dwanika and the upper boundary in the Tingutinguti stream section.

Palaeontolgy. The *Indotrigonia africana* Member contains a diverse marine assemblage of macroinvertebrates, including corals (e.g. *Astrocoenia bernensis* and '*Latimaeandraraea*' [= *Meandrophyllia*] *oolitotithonica*; Dietrich 1926), bivalves (e.g. '*Epihippopodium*' [= *Hippopodium*] *quenstedti*, '*Astarte*' [= *Herzogina*] *recki*, '*Astarte*' [= *Seebachia*] *krenkeli*, '*Cardium* (*Tendagurium*)' [= *Integricardium*] *propebanneianum*, *Lithophaga subobionga*, *Chlamys curvivarians*, *Protocardia schencki*, *Pseudomonotis tendagurensis* [= *Meleagrinella radiata*], *Indotrigonia dietrichi*, *Indotrigonia africana*, and many others (Dietrich 1933a; Quennell et al. 1956; Aitken 1961; Cox 1965), gastropods (e.g. '*Nerinea*' [= *Cossmannea*] *hennigi*, *Nerinella credneri* [= *N. cutleri*], *Pleurotomaria* aff. *jurensis*, and *Pseudomelania dietrichi*; Dietrich 1914, 1933a; Cox 1965), cephalopods (e.g. *Subdichotomoceras* cf. *sparsiplicatum*, *Hildoglochiceras kobelli*, *Holcophylloceras mesolcum*, *Haploceras elimatum*, '*Craspedites*' [= *Procraspedites*] *africanus*, *Nautilus dorsatus* var. *sattleri*, *Belemnites* aff. *tanganensis*; Zwierzycki 1914; Dietrich 1933a; Arkell 1956; Quennell et al. 1956), brachiopods (*Terebratula carteroniana*, *Terebratula matapuana*, *Rhynchonella expressa*; Lange 1914; Hennig 1937a; Quennell et al. 1956), echinoderms (e.g. *Cidaris glandifera*, *Apiocrinus* sp.; Dietrich 1933a; Hennig 1937a; Sieverts-Doreck 1939), and arthropods (*Protaxius* sp.; Beurlen 1933). More recently recovered macroinvertebrate assemblages of the *Indotrigonia africana* Member are summarised by Aberhan et al. (2002).

The microfauna includes textulariid, lenticuline, and nodosariid foraminifera and ostracods (Zils et al. 1995). More recently, GTTE beds Tin 9j, Tin 9 p/3, Tin 9p/5, Tin 9qb, and Tin 9r have yielded ostracod assemblages, covering the middle part of the member. The following taxonomical identifications have been made (Sames 2008): *Cytherella* cf. *obscura*?, *Bythocypris* sp.?, *Majungaella* sp. 2, *Pirileberis* sp. 1, sp. 2 and sp. 3, *Cypridea* sp. 4, *Pleurocythere* sp., *Ilyocypris* sp., *Procytherura* sp., *Mandawacythere striata*?, and *Cytherella* sp. 2.

Charophyta (Clavatoroidea indet.) are reported from Tin 9p/5 (Sames 2008). Schrank (2005) recorded a *Dingodinium jurassicum-Kilwacysta* assemblage, consisting of about 50 short- and long-ranging dinocyst species. They include *Microdinium avocetianum* (Tin 9f2), *Pareodina robusta* (Tin 9f2, Tin 9l2), *Kilwacysta semiseptata* (Tin 9g to Tin 9l2), *Kilwacysta multiramosa* (Tin 9j2, Tin 9p2), and *Tubotuberella apatela* (Tin 9j1 to Tin 9o1). Some of the dinoflagellate cyst taxa are associated with acritarchs and freshwater algae (Schrank 2005). Msaky (2007) reported the dinoflagellates *Wanaea tendagurensis*, *Dingodinium swanense*, *Prolixosphaeridium mixtispinosum*, *Pareodinia antennata*, and *Komewuia glabra*.

GTTE bed Tin 9h, located in the lower portion of the *Indotrigonia africana* Member, has yielded the richest and most diverse conifer assemblage of the Tendaguru Formation (Süss & Schultka 2006), including *Primopodocarpoxylon circoporoides*, *Semipodocarpoxylon compactum*, *Glyptostroboxylon janenschii*, *Tetraclinoxylon antiquum*, and *Paratetraclinoxylon tendagurense*. Higher up in the section, specimens of *Taxodioxylon compressum* (Tin 9p) and *Podocarpoxylon jurassicum*, *Podocarpoxylon microtracheidale*, and *Widdringtonioxylon tanzaniense* (all Tin 9q) were found (Süss & Schultka 2006).

Age. Previously, the *Indotrigonia africana* Member was dated as middle to late Kimmeridgian (Hennig 1937a, 1937b), late Kimmeridgian to early Tithonian (Dietrich 1925a, 1926), late Kimmeridgian to Tithonian (Zwierzycki 1914; Lull 1915; Behrendt 1918; Aitken 1961), Kimmeridgian to Tithonian (Schrank 1999), and Tithonian (Lange 1914; Schrank 2005). In contrast, Spath (1928–1933) assigned it, along with the *Nerinella* Member and the two upper dinosaur-bearing members, to the Portlandian (see also Hennig 1937a; Aitken 1961: tab. 2).

More recently, evaluation of the stratigraphical ranges of dinocyst taxa strongly suggests "a Tithonian, probably Late Tithonian age for the *Trigonia smeei* Bed, at least up to level Tin 9o4" (Schrank 2005: p. 78). Higher up, *Barbatacysta creberbarbata*, *Barbatacysta capitata*, and *Dingodinium jurassicum* (all known from Tin 9p2) "suggest a Late Jurassic, rather than an Early Cretaceous age" (Schrank 2005: p. 78). The short-ranging dinoflagellate *Wanaea tendagurensis*, reported from the *Indotrigonia africana* Member together with *Dingodinium swanense*, *Prolixosphaeridinium mixtispinosum,* and *Pareodinia antennata*, is assumed to be an index fossil for the Kimmeridgian of Tanzania (Msaky 2007). Another dinocyst taxon, *Komewuia glabra,* is known from the late Kimmeridgian to Tithonian of Madagascar (Chen 1982) and the Kimmeridgian to Tithonian of Kenya (Jiang et al. 1992). Consequently, the co-occurrence of *Wanaea tendagurensis* and *Komewuia glabra* could indicate a Kimmeridgian age for the *Indotrigonia africana* Member. However, a Tithonian age appears more likely, because the underlying Middle Dinosaur Member is probably late Kimmeridgian in age. This view is corroborated by the presence of the ammonoids *Procraspedites africanus* and several species of *Hildoglochiceras*, which indicate an early Tithonian age (G. Schweigert, personal communication 2008). Overall, the existing microfloral record suggests a Late Jurassic rather than an Early Cretaceous age, as suggested previously (e.g. Dietrich 1925a, 1926, 1933a; Hennig 1937a; Quennell et al. 1956). In contrast, Sames (2008) tentatively placed the Jurassic-Cretaceous boundary a short distance below the strata exposed at Tin 9p/5 into the *Indotrigonia africana* Member.

Upper Dinosaur Member

Figures 2, 3, 4F, Table 2

Name. The name "Oberste (dritte) Saurierzone" (Upper Saurian Bed) was coined by Janensch (1914a) for the uppermost of the three dinosaur-bearing horizons of the Tendaguru Beds. Here, we formally emend the name and other terms applied previously to this unit to Upper Dinosaur Member (Table 2). Note that the term Upper Dinosaur Member was previously suggested by Schudack (1999) but the author failed to describe and define this member. The name refers to the assemblages of sauropod, ornithopod, and theropod bones.

Type section. Tendaguru Hill is regarded as the type locality (Quennell et al. 1956). Neither the GTE nor the BTE designated a type section. Here, we formally establish a type section of the Upper Dinosaur Member defined from subsections Tin S0, Tin 10a to Tin 10e, Dwa 1 to Dwa 7, Tin 11a to Tin 11d (Fig. 3; Table 3).

Distribution. The Upper Dinosaur Member is the most widespread member of the Tendaguru Formation. According to the geological map of Hennig (1914a), scattered outcrops extend from the eastern shore of Lake Lutambo, about 30 km west of the town of Lindi, for ca. 145 km in a northwestern direction to the banks of Matandu river at Mitole, approximately 36 km west of Kilwa-Kivinje (Fig. 1). The best studied area with exposures of the Upper Dinosaur Member is the Tendaguru region.

Hennig (1914a, 1937a) suggested that the Upper Dinosaur Member of the Tendaguru area passes eastwards into marine calcareous ooid-bearing strata. Oolitic limestone (*smeei* Oolite), developed in the northern part of the Mandawa-Mahokondo area, was in part considered to be a temporal equivalent of the Upper Dinosaur Member of the Tendaguru area (Hennig 1937a). However, this correlation was questioned by Quennell et al. (1956) and Aitken (1956b, 1961).

Thickness. The GTTE estimated a thickness of 32 m for the Upper Dinosaur Member in the immediate surroundings of Tendaguru Hill (Aberhan et al. 2002). This measurement differs from the thickness of about 40 m reported by Janensch (1914a). Hennig (1933a) gave the following thickness data for the Upper Dinosaur Member: ca. 30 m (Tingutinguti stream section), ca. 35 m (Nambiranji path), 35 m (Dwanika stream section), and 20–25 m (Kindope stream section).

Lithofacies. Janensch (1914a) characterised the Upper Dinosaur Member as a succession of grey or reddish sandy marl alternating with friable, yellowish sandstone. According to the investigations of the GTTE, the member is mainly built up by ripple cross-bedded, fine-grained sandstone and siltstone with intercalated claystone layers and isolated micritic carbonate, in part dolomite layers (Aberhan et al. 2002).

At the base, thinning-upward sequences composed of small-scale trough and ripple cross-bedded, fine-grained sandstone occur, some of which contain heavy mineral concentrations. The middle and upper part is formed mainly of ripple cross-bedded and occasionally small-scale cross-bedded, fine-grained sandstone and siltstone with minor claystone layers and some dolomite beds.

Boundaries. The lower boundary is marked by the first appearance of monotonous, ripple cross-laminated, fine-grained sandstone and siltstone on top of cross-bedded, medium- to fine-grained sandstone of the *Indotrigonia africana* Member. The change in grain-size reflects a gradual environmental shift rather than an abrupt change and thus is a largely undisturbed, conformable contact. In contrast, the upper contact to the *Rutitrigonia bornhardti-schwarzi* Member is distinctly unconformable, with a sharp change in grain-size and indicators of substantial erosion and reworking of sediments of the Upper Dinosaur Member.

Palaeontolgy. Significant vertebrate fossils recorded from the Upper Dinosaur Member include fishes (e.g. *Hybodus* sp., *Lonchidion* sp., *Sphenodus* sp., *Engaibatis schultzei*, and *Lepidotes tendaguruensis*; Hennig 1914c; Arratia & Schultze 1999; Arratia et al. 2002), as yet unidentified sphenodontians (Aberhan et al. 2002; Heinrich 2003), crocodiles (*Bernissartia* sp.; Heinrich et al. 2001; Aberhan et al. 2002; Heinrich 2003), pterosaurs (Dsungaripteroidea indet., Rhamphorhynchoidea indet.; Reck 1931; Unwin & Heinrich 1999; Heinrich 2003), and dinosaurs (e.g. *Elaphrosaurus bambergi*, '*Ceratosaurus* (?) *roechlingi*' [= basal ceratosaur; Rauhut 2005], '*Labrosaurus* (?) *stechowi*' [= in part apparently a spinosaurid theropod; Buffetaut 2008], '*Megalosaurus* (?) *ingens*', '*Barosaurus*' *africanus*' [= *Torneria africana*; Remes 2006], *Dicraeosaurus sattleri*, *Australodocus bohetii*, *Brachiosaurus brancai*, *Janenschia robusta*, *Tendaguria tanzaniensis*, and *Kentrosaurus aethiopicus* (e.g. Janensch 1914c, 1925a, 1929a, 1935, 1950b, 1955, 1961a; Hennig 1925; Galton 1981, 1982a, 1982b, 1983; Bonaparte et al. 2000; Rauhut 2005; Remes 2006, 2007), and a mammal (*Brancatherulum tendagurense*; Dietrich 1927b; Simpson 1928).

The principal macroinvertebrates recorded from the Upper Dinosaur Member include bivalves (e.g. *Eomiodon cutleri* (Figs 5C–D), '*Mytilus* cf. *gallinnei*' [= *Falcimytilus dietrichi*]; Dietrich 1914; Hennig 1914b; Quennell et al. 1956; Aberhan et al. 2002), gastropods (e.g. *Physa tendagurensis*; Hennig 1914b), and arthropods (*Estheria tendagurensis*; Janensch 1933; *Cypridea* sp. 5; Sames 2008).

Conifer remains recovered from the Upper Dinosaur Member (Kit 1) were identified as *Semicircoporoxylon fruticulosum* (Süss & Schultka 2006). *Conites araucarioides* was previously described by Gothan (1927).

Age. Most workers placed the Jurassic/Cretaceous boundary at the base of the *Rutitrigonia bornbardti-schwarzi* Member and considered the Upper Dinosaur Member as Late Jurassic (e.g. Schuchert 1918, 1934; Parkinson 1930a, 1930b; Dietrich 1933a, 1933b; Spath 1928–1933; Quennell et al. 1956; Aitken 1961). This contrasts with other views that positioned the boundary at the base of (e.g. Hennig 1914a; Janensch 1914a; Lange 1914; Behrendt 1918) or within the Upper Dinosaur Member (Hennig 1937a) or even within the underlying *Indotrigonia africana* Member (Sames 2008). This latter assignment, however, requires further study. U-Pb dating of a pelvic bone from *Brachiosaurus brancai* of the Upper Dinosaur Member provided an age range from ca. 140 to 150 Ma (Romer 2001) that falls approximately into the Tithonian (150.8 ± 4.0 Ma to 145.5 ± 4.0 Ma; Gradstein et al. 2004) and the Berriasian (145.5 ± 4.0 Ma to 140.2 ± 3.0 Ma; Gradstein et al. 2004). Schrank (2005) noted the absence of *Cicatricosisporites* in the Upper Dinosaur Member (Dwa 6/0) and the underlying *Indotrigonia africana* Member that could indicate a Tithonian age of these units. More work is needed to decide unambiguously whether the Upper Dinosaur Member is wholly Late Jurassic or, in part, Early Cretaceous.

Rutitrigonia bornhardti-schwarzi Member

Figures 2, 3, 4G–H, Table 2

Name. The uppermost of the three marine units of the Tendaguru Formation was originally named "Obere Sandsteinzone mit *Trigonia schwarzi*" (Janensch 1914a) (*Trigonia schwarzi* Bed). Later the term "*Trigonia bornhardti-schwarzi* Zone" (or "Stage") (e.g. Hennig 1937a) or "Schwarzistufe" (Dietrich 1933a) was applied (Table 2). According to Hennig (1914a), the member includes strata which were formerly described by Fraas (1908) from several localities in the Tendaguru area under the names "Kalksandsteine mit *Trigonia schwarzi*" [Tshikotshia (Majembe) stream section, eastern face of the Likonde-Kitale Plateau, and Pile-Pile], "Ntandischichten" (with *Trigonia bornhardti*, Ntandi Hill west of Likonde-Kitale Plateau), and Niongala Beds (with *Trigonia bornhardti*, Niongala north of Tendaguru Hill) (Fig. 1). Janensch (1914a) applied the term "Obere Sandsteinzone mit *Trigonia schwarzi*" for strata exposed at the top of Tendaguru Hill.

The stratigraphic ranges of both *Rutitrigonia bornhardti* (Figs 5H–I) and *Rutitrigonia schwarzi* (Fig. 5G) are not sufficiently known. They are said to be mutually exclusive (Aitken 1961) but the order of superposition is disputed. Dietrich (1933a) considered *Trigonia schwarzi* to be stratigraphically older than *Trigonia bornhardti*, whereas, conversely, Hennig (1937a) believed that the latter species preceded the former one. Aitken (1961) did not rule out that *Rutitrigonia bornhardti* occurs only at horizons below those with the "group of *Rutitrigonia schwarzi*", but emphasised that the definite subdivision requires further study of the temporal distribution of *Rutitrigonia*. Nevertheless, from the existing evidence it can be concluded that apparently neither *Rutitrigonia schwarzi* nor *Rutitrigonia bornhardti* occurs throughout the whole member. Therefore, the broader term *Rutitrigonia bornhardti-schwarzi* Member is adopted here to designate the uppermost of the three marine units of the Tendaguru Formation.

Type section. Quennell et al. (1956) argued that Tendaguru Hill should be regarded as type locality. However, neither the GTE nor the BTE designated a type section for the *Rutitrigonia bornhardti-schwarzi* Member. Here, we refrain from defining a type section of the *Rutitrigonia bornhardti-schwarzi* Member because of its strongly reduced thickness at Tendaguru Hill. The formal establishment of a type section has to await the detailed investigation of more extended exposures in the hinterland of Lindi, e.g. at the Kikomolela Plateau (see below).

Distribution. Strata of the *Rutitrigonia bornhardti-schwarzi* Member are represented in much of the hinterland of Lindi and Kilwa. The general distribution of the member is shown in outline on the geological map (1 : 300,000) by Hennig (1914a). It extends along the western face of the Lipogiro Plateau and is exposed in the flanks of the Kikomolela Plateau, Nemba Hill, Mahimira Hill, Namunda, Likonde-Kitale, and Likonde-Kitutu plateaus at some distance southeast and east of Tendaguru Hill (Fig. 1). North of Tendaguru Hill, outcrops occur along the sides of the Mbemkuru river valley north of Kijenjere and in Itukuru. Yet farther to the north, the member crops out along the slopes of the eastern and northern part of the Kiturika Plateau, and it also occurs in a larger area through which the Nangarombe and Litandaivala rivers flow, southwest of Manganya (Fig. 1). In addition to these principal regions, there are several outliers of small areal extent such as at the top of Tendaguru Hill, where only a small part of the member is exposed due to erosion, at Runjo, Mchuya, and in the surroundings of Makangaga in the far north. The easternmost outlier of the *Rutitrigonia bornhardti-schwarzi* Member was reported from the western face of Kitulo Hill near Lindi (Hennig 1937a).

Several significant fossiliferous outcrops that are considered to be equivalents of the *Rutitrigonia bornhardti-schwarzi* Member have been described by Aitken (1961). They are located in the Namitambo stream valley (with *Eulytoceras* cf. *kikadiense*); the Kikundi stream section, where calcareous, pebbly grit just below the unconformity with the overlying Albian marl produced *Rutitrigonia bornhardti*; the Nloweka stream section, where calcareous grit is exposed below the limestone of the Nloweka cliffs; near Mirumba village; in the Lihimaliao stream section; and the Runjo stream section, with an exposure of massive, grey, medium- to coarse-grained, sometimes pebbly, calcareous grit.

A notable section of the *Rutitrigonia bornhardti-schwarzi* Member was described from the north-western face of the Kikomolela Plateau, located approximately 30 km northwest of Lindi (Hennig 1937a). It rests on marls identified as Upper Dinosaur Member. Interbedded in the succession of marine strata is a dinosaur-bearing bed ("Sauriermergel") that has produced a huge sauropod caudal vertebra identified tentatively as titanosaurid dinosaur (Hennig 1937a). If properly identified, the Kikomolela section contains a fourth dinosaur member in the Tanzanian coastal region deposited during the Early Cretaceous (Hennig 1937a). This is an important point that should be considered in future work on the stratigraphical subdivision of the Tendaguru Formation.

Thickness. Janensch (1914a) and Aberhan et al. (2002) estimated a thickness of approximately 5 m at the top of Tendaguru Hill, but the *Rutitrigonia bornhardti-schwarzi* Member has been shown to reach a thickness of up to about 70 m at the Ngarama Plateau and 40 m at the Kikomolela Plateau (Hennig 1937a).

Lithofacies. Janensch (1914a) described the sequence of strata as consisting of fossiliferous, yellow-brown, massive calcareous sandstone with nodular concretions ("Kugelsandstein") that is overlain by whitish, calcareous coarse-grained sandstone containing quartz, feldspar, granitic pebbles, and bivalves and corals. In the Tendaguru area, the GTTE recognised a basal conglomerate overlain conformably by trough cross-bedded or ripple-bedded, medium- to fine-grained sandstone that forms fining-upward sequences and is followed by siltstone and claystone (Aberhan et al. 2002). At Tendaguru summit, a basal conglomerate consisting mainly of quartz pebbles with numerous sedimentary lithoclasts is overlain by fine- to medium-grained sandstone with variable amounts of calcite cement, which contains fragments of bivalves and echinoderms. In the Namunda Plateau, the basal conglomerate is overlain by fine-grained, trough cross-bedded sandstone, by ripple cross-bedded siltstone and by horizontally laminated claystone, which is in part bioturbated. Here, the basal conglomerate contains abundant, moderately rounded basement (gneiss) clasts and numerous sedimentary lithoclasts. When compared to the sandstone of the *Nerinella* and *Indotrigonia africana* members, this sandstone exhibits higher potassium/plagioclase feldspar-ratios.

Boundaries. A basal conglomerate which consists of quartz pebbles and clasts of reworked mudstone of the Upper Dinosaur Member and overlies an erosive contact, signals the lower boundary of the *Rutitrigonia bornhardti-schwarzi* Member. It implies a substantial break in sedimentation and extensive erosion of underlying sediments of the Upper Dinosaur Member during the initial deposition of the *Rutitrigonia bornhardti-schwarzi* Member. In the Tendaguru area, the lower boundary is only exposed at Tendaguru Hill. The upper boundary to the Makonde Formation is present in the Namunda Plateau south of Tendaguru Hill, but exposure is poor. In areas east and northeast of Tendaguru, the *Rutitrigonia bornhardti-schwarzi* Member is overlain by Urgonian-type limestone (Hennig 1937a), most probably with conformable contact, reflecting a gradual change from a mixed siliciclastic-carbonate to a predominantly carbonate depositional environment.

Palaeontolgy. The sediments of the *Rutitrigonia bornhardti-schwarzi* Member have yielded abundant invertebrate fossils in many places. These include annelids (e.g. *Serpula concava, Serpula triangulata*; Lange 1914), corals (e.g. *Astrocoenia colliculosa*, *A. subornata*, *Thamnastrea tendagurensis*, *Pleurosmilia hennigi*; Weissermel 1900; Dietrich 1926), bivalves (e.g. *Arctostrea rectangularis*, '*Astarte*' [= *Seebachia*] *krenkeli*, '*Cardium* (*Tendagurium*)' [= *Integricardium*] *rothpeltzi, Exogyra couloni*, '*Gervilleia*' [= *Gervillaria*] *alaeformis*, *Megacucullaea kraussi*, *Plagiostoma euplocum*, *Pholadomya gigantea*, *Prohinnites fraasi*, *Protocardia schencki*, *Tancredia tellina*, *Rutitrigonia bornhardti*, *Rutitrigonia schwarzi*, *Sphaera corrugata*; Müller 1900; Krenkel 1910; Dietrich 1914, 1933a; Lange 1914; Quennell et al. 1956; Aitken 1961); gastropods (*Chenopus eurypterus*, *Chrysostoma staffi*, *Natica crassitesta*, *Pleurotomaria janenschi*, *Trochus brancai*; Dietrich 1914; Quennell et al. 1956), cephalopods (e.g. *Nautilus dietrichi*, *Phylloceras deplanatum*, *Lytoceras hennigi*, *Holcostephanus crassus*, *Holodiscus inflatus*, *Hoplites* cf. *neocomiensis*, *Crioceras* sp., *Parahoplites martini*, *Hamulina* cf. *quenstedti*, *Belemnites pistilliformis*, *Duvalia elegantissima*; Zwierzycki 1914; Hennig 1937a; Quennell et al. 1956), brachiopods (e.g. *Kingena transiens*, *Rhynchonella rauffi*, *Zeilleria dubiosa*; Lange 1914), echinoderms (*Pygurus* sp.; Krenkel 1910), and arthropods (e.g. *Glyphea hennigi*; Beurlen 1933).

Plant microfossils are poorly known and include land-derived sporomorphs such as *Classopollis* (Aberhan et al. 2002). In addition, a marine *Muderongia-Oligosphaeridium* dinoflagellate cyst assemblage with *Muderongia tetracantha*, *Oligosphaeridium complex*, *Oligosphaeridium pulcherrimum* etc., recovered from GTTE site Nam 1b at the Namunda Platea, probably also belongs to the *Rutitrigonia bornhardti-schwarzi* Member (Schrank 2005).

Age. The *Rutitrigonia bornhardti-schwarzi* Member contains a variety of molluscs attributable to the Valanginian to Hauterivian (Krenkel 1910), Neocomian (Behrend 1918), lower-middle Neocomian (Lull 1915), late Valanginian to early Aptian (Dietrich 1933a) or Hauterivian to Aptian (Spath 1928–1933).

Palaeoenvironmental interpretation of the Tendaguru Formation at its type locality

The interpretation of depositional environments represented in the Tendaguru Formation is based on the association of ten distinct and recurring lithofacies types (see Aberhan et al. 2002: table 1) and the ecological requirements of the fossils. The upper portion of the Lower Dinosaur Member is tentatively assigned to a tidal flat environment with salinity variations and relatively long exposure times exerting a certain degree of environmental stress (Aberhan et al. 2002). Ostracods recovered from Tin 0a suggest a mesohaline to euhyaline aquatic environment (Sames 2008). This is in accordance with earlier interpretations by Janensch (1914a) who regarded the dinosaur-bearing beds as mud deposits of shallow-water lagoons, although this lagoon should have been of an open type with extensive tidal flats and tidal channels.

The composition of benthic molluscs and foraminifera, euhaline to mesohaline ostracods, and dinoflagellate assemblages indicate marine, shallow water conditions for the *Nerinella* Member, in particular for the lower part (Aberhan et al. 2002; Schrank 2005; Sames 2008). Sedimentation occurred as tidal channel fills, subtidal and tidal sand bars, minor storm layers (tempestites), and beach deposits. Overall, the *Nerinella* Member represents a variety of shallow subtidal to lower intertidal environments influenced by tides and storms (Aberhan et al. 2002).

The sedimentological characteristics of the basal part of the Middle Dinosaur Member suggest deposition on tidal flats and in small tidal channels of a lagoonal palaeoenvironment (Aberhan et al. 2002). The ostracod *Bythocypris* sp. from Tin 7a indicates polyhaline to euhaline conditions (Sames 2008). Slightly higher up (Tin 7b), a faunal sample dominated by the bivalve *Eomiodon* and an ostracod assemblage composed of brackish to freshwater taxa (Sames 2008) is indicative of a brackish water palaeoenvironment with distinct influx of freshwater as revealed by the nonmarine ostracod genus *Cypridea,* charophytes, and other freshwater algae in Tin 7d. Sames (2008) has shown that the palaeoenvironment of the ostracod assemblages of the Middle Dinosaur Member changed upsection from a marine setting in the basal parts (Tin 7a) through alternating marine-brackish conditions (Tin 7b) to freshwater conditions in the higher parts of this member (Tin 7d to Tin 7i). This conclusion agrees well with previous interpretations by Aberhan et al. (2002), according to which sabkha-like coastal plains with ephemeral brackish lakes and ponds are recorded in the upper part of the Middle Dinosaur Member. This part also contains pedogenic calcretes indicating subaerial exposure and the onset of soil formation.

The coarse-grained sandstone of the lower part of the *Indotrigonia africana* Member that shows highly variable transport directions is interpreted as deposits of large tidal channels (Aberhan et al. 2002). Grain-size, large-scale sedimentary structures, and the lack of both trace fossils and epifaunal and infaunal body fossils suggest high water energy and frequent reworking. This basal succession passes upward in cross-bedded sandstone and minor siltstone and claystone with flaser or lenticular bedding that are interpreted as tidal flat and tidal channel deposits. Horizontal to low-angle cross-bedded, fine-grained sandstone with intercalated bivalve pavements indicates tidal currents that operated in small flood and ebb tidal deltas and along the coast (Aberhan et al. 2002). Stacked successions of trough cross-bedded, medium- to coarse-grained sandstone of the upper part of the *Indotrigonia africana* Member are interpreted as tidal channel and sand bar deposits. At some places in the surroundings of Tendaguru Hill, these sediments interfinger with oolitic limestone layers that represent high-energy ooid shoals (Aberhan et al. 2002).

In the Tingutinguti stream section, the *Indotrigonia africana* Member exhibits several up to 20 cm thick, poorly sorted, conglomeratic sandstone beds. They contain mud clasts, reworked concretions and/or accumulations of thick-shelled bivalves (mainly *Indotrigonia africana* and *Seebachia janenschi*), and exhibit megaripple surfaces (Bussert & Aberhan 2004). These conglomeratic sandstone layers are interpreted as storm deposits by Bussert & Aberhan (2004). In the Dwanika and Bolachikombe stream sections, and in a small tributary of the Bolachikombe creek, a discrete, up to 70 cm thick conglomerate in the lower portion of the *Indotrigonia africana* Member displays evidence of a tsunami deposit (Bussert & Aberhan 2004). All in all, lithofacies and the diverse macroinvertebrate and microfossil assemblages of the *Indotrigonia africana* Member suggest a shallow marine environment. Based on the diverse mesoflora and the abundance of *Classopollis*, a nearby vegetated hinterland is postulated that was dominated by xerophytic conifers (Aberhan et al. 2002).

The small-scale trough and ripple cross-bedded fine-grained sandstone at the base of the Upper Dinosaur Member is interpreted as tidal flat deposits (Aberhan et al. 2002). Unfossiliferous sandstone in the upper part was most likely deposited in small fluvial channels in a coastal plain environment, whereas argillaceous deposits were laid down in still water bodies such as small lakes and ponds (Aberhan et al. 2002). Rare occurrences of the ostracod *Cypridea* in Dwa 5b/1 (Sames 2008) and charophytes signal the influence of freshwater, whereas the sporadic occurrence of marine invertebrates suggests a depositional environment close to the sea (Aberhan et al. 2002).

Fining upward sequences of the basal part of the *Rutitrigonia bornhardti-schwarzi* Member are interpreted as tidal channel fills, the overlying fine-grained sandstone, silt- and claystone as tidal flat deposits (Aberhan et al. 2002). From the immediate surroundings of Tendaguru Hill, invertebrates and vertebrates are poorly known and limit the palaeoenvironmental interpretation of this member. The composition of the land-derived sporomorph assemblage suggests a terrestrial vegetation which was dominated by cheirolepidiacean conifers in association with ferns (Aberhan et al. 2002).

In summary, the sedimentary rocks and fossils record a repeated shift from shallow marine to tidal flat environments indicating that the strata of the Tendaguru Formation were deposited near an oscillating strandline which was controlled by sea level changes. The three dinosaur-bearing members are continental to marginal marine and the three sandstone-dominated members are marginal marine in origin.

Sequence stratigraphy

The Tendaguru Formation comprises four major depositional sequences, each bounded by unconformities at the base and at the top. These surfaces are thought to represent sequence boundaries because they are of regional extent. They mark a clear facies shift from under- to overlying sediments and partly document a significant amount of reworking of underlying sediments. Considering the presumed duration of the deposition of the Tendaguru Formation, the four sequences probably have formed as third-order sequences with an estimated duration ranging from less than one to up to a few million years (e.g. Vail et al. 1977; Haq et al. 1988; Emery & Myers 1996). Such sequences were either forced by global sea-level change or by regional tectonism, or by an interplay of both mechanisms. The lack of detailed investigation of this stratigraphic interval in other regions of the Mandawa Basin or in neighbouring basins makes it difficult to decide which of these potential trigger mechanisms was crucial.

The lower boundary of the Lower Dinosaur Member with the basement gneiss has not yet been described in any detail. In the area west of Tendaguru, Hennig (1914a) and Janensch (1914a) envisaged a morphologically structured coastal plain with isolated gneiss hills, which was partly flooded during transgression by a very shallow sea. It is not yet clear, what kind of sediments directly overlay the gneiss. Likewise it is a matter of speculation, whether the surface was mainly shaped by subaerial exposure and erosion before the sea invaded the area or if it represents a transgressive surface sculptured at least in part by wave and/or tidal processes. In any case, it represents a nonconformity of regional extent, thus a sequence boundary which was exposed to an unkown magnitude of subaerial weathering and erosion before the sea reached the area. The Lower Dinosaur Member must therefore be considered, at least in its basal part, as forming part of a transgressive systems tract. Whether the maximum flooding surface, which marks the upper boundary of the transgressive systems tract, and overlying sediments of the highstand systems tract or of other systems tracts are documented in the Lower Dinosaur Member, is difficult to tell, mainly because of the poor outcrop situation. The occurrence of a marine fauna and of sediments characteristic of a tidal flat environment near the boundary of the *Nerinella* Member nevertheless leads to the conclusion that the upper part of the Lower Dinosaur Member consists of regressive sediments belonging to a highstand systems tract. This is quite similar to the situation in the Middle and Upper Dinosaur members (see below).

The lower boundaries of the *Nerinella* Member, the *Indotrigonia africana* Member, and the *Rutitrigonia bornhardti-schwarzi* Member to the Lower, Middle, and Upper Dinosaur Member, respectively, are of erosive nature and represent sequence boundaries. An in-depth discussion of these boundaries is limited by their generally poor exposure. Under- and overlying sediments nevertheless give conclusive evidence for the sharp and erosive character of these contacts.

Lithostratigraphically, the base of the *Nerinella* Member can be defined as the first appearance of poorly sorted, medium- to coarse-grained sandstone that overlies fine-grained sandstone and siltstone of the Lower Dinosaur Member. The basal sediments, trough cross-bedded or massive, medium- to coarse-grained sandstone which contains abundant bioclasts indicating normal marine conditions, are thought to represent mainly deposits of lower intertidal or shallow subtidal channels. The lowermost exposed sandstone beds, however, are massive, fine- to medium-grained, moderately to well sorted, and contain, besides marine bivalves, abundant calcrete and mudstone clasts. Lithologically, they can be assigned to the Lower Dinosaur Member, but genetically they are interpreted to represent foreshore sediments related to the landward shift of the coastline during transgression. The basal surface below these sandstone beds resulted most probably from wave erosion in the upper shoreface and represents a transgressive or wave ravinement surface (e.g. Nummedal & Swift 1987). The intraclasts formed as a transgressive lag from the reworking of formerly underlying palaeosols and supratidal sediments, likely indicating a relatively high amount of scouring at the base of the transgressive sediments. These intraclasts attest the former presence of non-marine or supratidal deposits, whereas the overlying sediments most probably represent very shallow subtidal to tidal channel and sand bar deposits of a normal marine environment. The basal erosion surface thus separates very shallow marine tidal sediments of the Lower Dinosaur Member from normal marine sediments of the basal part of the *Nerinella* Member. It is the surface of initial transgression, or wave ravinement, and forms the lower sequence boundary.

The fining-upward sequences of the basal *Nerinella* Member probably represent the filling of tidal channels and the migration of subtidal sand bars. It is not clear, if these sequences represent true parasequences or if they are the result of autocyclic processes such as local shifts and abandonments of tidal channels. Whereas the basal part of the *Nerinella* Member contains fauna of normal marine habitats, the upper part of the *Nerinella* Member – cross-bedded sandstone with only few marine bioclasts – might partly represent deposits of more shallow and stressed environments such as very shallow tidal channels and tidal sand bars. This implies that the maximum flooding surface is located below these deposits, possibly at the top of the fining-upward sequences of the basal *Nerinella* Member, but a condensed section is either missing or was not discovered during field work. Carter et al. (1998) addressed the problem of identifying the position of the maximum flooding surface in outcrops and suggested that this boundary be allowed to remain unspecified or unknowable. In any case, the upper part of the *Nerinella* Member was deposited during the late stage of base-level rise, when littoral sediments were starting to aggrade and to prograde into the basin. Thus it constitutes part of the highstand systems tract. Forming a rather thick and monotonous succession, these sediments imply a relatively high rate of aggradation due to continuous base-level rise.

The contact to the Middle Dinosaur Member, although not well exposed, most probably is conformable and gradual, suggesting that sedimentation had slowly outpaced base-level rise. The overlying Middle Dinosaur Member was deposited in a tidally influenced shallow lagoonal environment and contains facies indicative of subaerial exposure and soil development in its upper part. Yet, no strong subaerial unconformity and therefore no major sequence-bounding surface exists, because the paleosols are overlain by sediments that are lithologically and genetically very similar to the underlying deposits, contradicting an abrupt shift in facies. The upper part of the *Nerinella* Member and the Middle Dinosaur Member jointly form a more or less continuous sequence of aggrading and prograding shallow marine and littoral sediments above a maximum flooding surface and can therefore be considered to represent a highstand systems tract. It remains speculative if deposits of a lowstand systems tract, e.g. fluvial sediments, were once present at the top of the Middle Dinosaur Member, but were subsequently eroded by wave and/or tidal activity during the following transgression.

The lower boundary of the *Indotrigonia africana* Member is clearly erosive, and the result, at least partly, of tidal channel scouring during shoreline transgression, thus representing a transgressive and/or tidal ravinement surface. Tidal channel sandstones in the basal part of the *Indotrigonia africana* Member contain heavy mineral concentrations which are comparable to transgressive lag deposits. Heavy mineral concentrations resulted from wave and tidal reworking in near-shoreface environments and their accumulation in tidal channels. Heterolithic sediments likely represent mixed sand-mud tidal flat and tidal channel deposits. Overlying shoreface sandstones which are punctuated by tempestites might enclose the maximum flooding surface or they alternatively can be considered as the "condensed section systems tract" (Carter et al. 1998). Up to these beds, the basal part of the *Indotrigonia africana* Member belongs to the transgressive systems tract. These sediments are overlain by tidal channel and tidal sand bar deposits that likely record the progradation of tidal deposits onto shoreface sediments and therefore already form part of the highstand systems tract. The regressive trend within the upper *Indotrigonia africana* Member continues without a significant break in sedimentation or an abrupt facies change to the tidal flat and lagoonal sediments of the Upper Dinosaur Member. Similar to the Middle Dinosaur Member, this member contains micritic carbonate layers of supratidal origin and in addition sandstone lenses which were deposited in small fluvial channels. A major break in sedimentation nevertheless does not seem to have occurred.

The *Rutitrigonia bornhardti-schwarzi* Member overlies the Upper Dinosaur Member with a basal conglomerate above an erosional contact. The overlying cross-bedded sandstone that forms fining-upward sequences and contains trigonid bivalves, is interpreted as tidal channel fills. The basal boundary to the lagoonal and tidal flat sediments of the Upper Dinosaur Member is therefore interpreted as a transgressive ravinement surface and the overlying shallow marine sediments of the *Rutitrigonia bornhardti-schwarzi* Member as the basal part of a transgressive systems tract. The incomplete preservation of the *Rutitrigonia bornhardti-schwarzi* Member in the Tendaguru area prevents any further sequence stratigraphic interpretation.

The Tendaguru Formation contains four third-order sequences that consist basically of transgressive and highstand systems tracts. Sequence boundaries are formed by transgressive ravinement surfaces and by maximum flooding surfaces, albeit the latter are difficult to identify. For the *Rutitrigonia bornhardti-schwarzi* Member, the existence of a highstand systems tract is likely, but, because of its fragmentary preservation, cannot be proven in the Tendaguru area. It is also questionable, whether deposits of lowstand systems tracts are preserved at the top of the Middle and Upper Dinosaur members.

Considering the difficulties in identifying the maximum flooding surface and in differentiating the highstand normal regressive from the lowstand normal regressive sediments, the four major depositional sequences of the Tendaguru Formation might be subdivided in a simple way into transgressive-regressive sequences thus into transgressive and regressive systems tracts (Embry & Johannessen 1992).

The transgressive systems tracts consist mainly of shallow marine shoreface, tidal channel, and sand bar sandstone, the highstand systems tracts (or regressive systems tracts) predominantly of shallow tidal channel, tidal flat, and marginal lagoonal to supratidal deposits. The sedimentation and preservation of fine-grained lagoonal and tidal sediments is likely related to a low-gradient ('shelf') setting, a flat topography at the shoreline and a moderate mixed tide-wave environment in the shelf sea. The general decrease of the grain-size of the sediments towards the shoreline as well as the almost complete lack of fluvial deposits in the highstand systems tract indicates that the majority of sand was not supplied by rivers of the direct hinterland but was introduced from entry points farther away by longshore currents.

Conclusions

Utilising all available sedimentological and palaeontological data, including those obtained by the recent German-Tanzanian Tendaguru Expedition, we are in the position to formally define the Tendaguru Formation and its six constituent members. These are, from bottom to top, the Lower Dinosaur Member, *Nerinella* Member, Middle Dinosaur Member, *Indotrigonia africana* Member, Upper Dinosaur Member, and *Rutitrigonia bornhardti-schwarzi* Member. In the Tendaguru area, outcrops of the Lower Dinosaur Member are limited and the establishment of a type section for this member has to await the discovery of more extended exposures. Due to the greatly reduced thickness of the *Rutitrigonia bornhardti-schwarzi* Member at Tendaguru Hill, the designation of its type section requires the investigation of more extended exposures outside the Tendaguru area.

In its type area, the Tendaguru Formation was deposited in a marginal marine to continental setting. The various palaeoenvironments comprise tide-influenced, shallow subtidal, marine environments above fair weather wave base, extended tidal flats with tidal channels, brackish lakes and ponds, and low relief coastal plains, dissected by small fluvial channels and with pools in the intervening areas.

In terms of sequence stratigraphy, the Tendaguru Formation comprises four third-order sequences which are composed of transgressive and highstand systems tracts. Sequence boundaries are represented by transgressive ravinement surfaces and maximum flooding surfaces. The latter are difficult to identify and, therefore, a subdivision of the depositional sequences into transgressive and regressive systems tracts is more straightforward.

The age of the Tendaguru Formation ranges at least from the middle Oxfordian to the Hauterivian or possibly Aptian, but the exact chronostratigraphy of its members still needs to be established. The placement of the Jurassic/Cretaceous boundary within the Tendaguru Formation is as yet uncertain.

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