

Reappraisal of foraminiferal assemblages of the Santonian-Campanian Mzamba Formation type section, and their correlation with the stratigraphic succession of the KwaZulu Basin

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(with 2 figures)

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Recent processing of additional samples, re-processing of the M. Makrides samples and re-evaluation of benthic and planktic foraminifera assemblages previously described from Mzamba Cliff, has led to the finding of several rare species that support previous ammonite datings of the succession. These include numbers of the planktic species *Dicarinella asymetrica* (Sigal) and *Sigalia* sp., which are limited to the Middle to Late Santonian, and to the Middle Santonian, respectively. *Sigalia* sp. appears to be a different species from the widely distributed *Sigalia deflaensis* (Sigal), as it is distinguished by depressed sutures throughout. Alternatively *Sigalia* sp. may be a variant limited to shallow or temperate waters; or it may be a juvenile form of *Sigalia deflaensis*. In addition, rare tests of the Santonian larger benthic foraminifera *Pseudosiderolites* sp. have been found, the first such larger foraminifera from the Late Cretaceous succession of southern Africa. Comments on the possible stratigraphic value of a species of *Cyclammina* occurring through the Campanian interval at Mzamba Cliff are also included. A palaeoecological review is presented, as well as an updated attempt at a foraminiferal bed-by-bed stratigraphy of the Mzamba outcrop succession.

Key words: Cretaceous, Santonian, Campanian, benthic, planktic, foraminifera, mudbelt.

CONTENTS

Abstract	25	boundary	29	Summary	31
Introduction	25	Campanian beds	30	Acknowledgements	32
Additions to Mzamba foraminiferal assemblages	26	Santonian and Campanian depositional environments	30	References	32
Santonian beds	29	Planktic foraminiferal biostratigraphy	31	Appendix: Bed-by-bed Foraminifera listings	33
The Santonian-Campanian					

INTRODUCTION

Klinger & Kennedy (1980) examined the ammonites and the stratigraphic succession of Mzamba Cliff and adjacent outcrops, the type section of the Mzamba Formation, which is exposed intermittently along the south-east coastline of South Africa. The type section lies about 150 km south of Durban. They concluded that the ammonites indicated the presence of ammonite assemblages Santonian II and Santonian III (Middle to Late Santonian), as well as Campanian I and Campanian II (Early Campanian). Dingle (1969, 1985) examined the ostracods of the Mzamba exposures. Initial studies of Mzamba foraminifera were by Chapman (1904, 1923); more recently Late Cretaceous foraminifera of the KwaZulu Basin and other coastal outcrops have been detailed by Smutter (1955, 1957*a,b*), De Gasparis (1968), Lambert (1971, 1973), Stapleton (1975) and Wright (1998). Makrides (1979) comprehensively

examined the benthic and planktic foraminifera of the Mzamba succession, and on the basis of differences in the foraminiferal assemblages was able to divide the succession into Santonian and Campanian portions, but did not subdivide the succession in such great detail as the ammonite zonation achieved by Klinger & Kennedy (1980). Cooper & Greyling (1996) listed benthic and planktic foraminifera assemblages identified by H. Petrie and V.H. Valicenti from the Mzamba Formation temporary exposure of the Campanian succession in excavations for a new car-park at the Wild Coast Casino. Mzamba Cliff foraminiferal assemblages compare closely with those of the proximal portion of the Santonian-Campanian interval of the KwaZulu Basin succession, which is the southernmost portion of the Mozambique Basin, mostly located in south-central Mozambique (Abdula & Salman 1995; Salman & Abdula 1996). Mzamba biostratigraphy is detailed by Kennedy &

Klinger (1975), Klinger & Kennedy (1977, 1980), Dingle (1980), Greyling (1992) and Cooper & Greyling (1996). Cretaceous palaeoenvironments at Mzamba are discussed by Krassilov *et al.* (1996).

ADDITIONS TO MZAMBA FORAMINIFERAL ASSEMBLAGES

The following comments are presented in the light of much previous analysis of the benthic and planktic foraminifera assemblages of 10 deep oil exploration boreholes (Fig. 1) drilled in the KwaZulu Basin during the period 1963 to 1977 by the companies Anglo-Vaal, Soekor and Aquitaine, a summary of which was included by McMillan (2003). However, McMillan (2003) contributed little to an overall reappraisal of the foraminifera assemblages of the Mzamba Formation. He considered there to be only one Santonian unit on the Indian Margin of southern Africa, determined as Early Santonian age on the basis of the planktic foraminifera, but this interpretation is incorrect, as detailed below. McMillan noted that the essentially inner neritic setting at Mzamba led to low-diversity planktic assemblages mostly lacking more oceanic, age-diagnostic species. This, and the rather southerly, non-tropical setting, means that a few Santonian and Campanian planktic markers with unusually short time-ranges, most diverse in the Tethyan realm, are either absent, or extremely rare. These rarities, some present in the KwaZulu Basin, include: (i) diagnostic Santonian planktic species such as *Dicarinella concavata* (Brotzen), *Dicarinella asymetrica* (Sigal), *Sigalia deflaensis* (Sigal) and other *Sigalia* species; (ii) diagnostic Santonian-Campanian boundary species *Ventilabrella eggeri* Cushman, found in both the latest part of the Santonian and the earliest part of the Campanian successions; and (iii) diagnostic Campanian *Globotruncanita* species, basal Campanian marker species *Rugoglobigerina rugosa* (Plummer) and *Gublerina ornatisima* (Cushman & Church), as well as *Heterohelix* and other biserial genera and their species. This lack is a particularly acute problem with the Early Campanian part of the Mzamba succession, which consists of distinctly more terrestrially-influenced siliciclastic sediments, usually with lower diversity and lower abundance, mainly benthic foraminifera assemblages, than does the Santonian part. *Globotruncanita elevata* (Brotzen) occurs widely but irregularly in the Early to Late Campanian succession in boreholes in the KwaZulu Basin, but it has not yet been found in the contemporary beds at Mzamba. By contrast, *Radotruncana calcarata* (Cushman), globally restricted to the Late Campanian, and with a unique, spinose test periphery, is known only in the tropical Late Campanian of Tanzania (Singano & Karega 2000; Nicholas *et al.* 2006), and has not yet been found in the more temperate KwaZulu Basin and Thekwini Basin successions on the Indian continental margin of South Africa (Fig. 1). Consequently, what survives into the Late Cretaceous Mzamba inner neritic zone (the innermost mud-belt) are those planktic species that inhabit more temperate oceanic regions, and those that can survive more turbid and slightly hyposaline or hypersaline coastal conditions, but these often tend to be long-ranging, conservative species. Turbidity and its restriction on light penetration into the water column has always been a significant limiting factor for most planktic foraminifera, since they

cultivate algae within their shells, with which they live in symbiotic relationship, not viable in water without sunlight.

Robust bicarinate planktic species such as *Globotruncana linneiana* (D'Orbigny), *Globotruncana tricarinata* (Quereau) and *Contusotruncana fornicata* (Plummer), well-represented through most of the Mzamba succession (see Makrides 1979), apparently have little stratigraphic value for dating or subdividing the Mzamba Formation since most range from about Late Coniacian to Early Maastrichtian (Caron 1985). Of the planktic species detailed by Makrides (1979), only *Marginotruncana coronata* (Bolli) is limited to the Santonian time period. The benthic species are also of biostratigraphic value, are usually easily recognizable, often present in some numbers, and they are often characterized by short stratigraphic ranges. However, they display marked endemism to southern Africa, and consequently compare poorly with assemblages from anywhere else other than the KwaZulu Basin and Wanderfeld IV outcrop, and more generally with the southern African Cretaceous basins. Thus without intensive biostratigraphic study the benthics initially constitute poor chronostratigraphic markers.

Recent examination of additional foraminiferal assemblages shows that they provide a much more complex picture of the Mzamba sedimentary succession than previously understood. It seems that what is now needed for the soft claystones at this outcrop is a specific micropalaeontological resampling of accessible portions of the cliff section, collecting large, preferably shell-poor or shell-free claystone samples of 1 kg, that are least likely to be affected by calcite cementing or dissolution. By carefully washing the entire bulk down through a 63-micron sieve, it should be possible to obtain the smallest possible washed residue, hopefully consisting only of foraminifera tests, with the intention of looking for ultra-rare benthics and planktics. The difficulty of singling out ultra-rare species which provide a robust dating, or correlation with elsewhere, may take much foraminifera picking time to discover. In addition, the thin cemented beds, ignored by all previous foraminiferal researchers because of sample processing difficulties, evidently contain a very different biostratigraphy from that discovered in the soft sandy claystones that constitute the bulk of the succession. The cemented beds also need to be incorporated into the foraminiferal biostratigraphy. The present article attempts to provide viable directions for future study.

Examination of the foraminifera from six additional samples from the Mzamba beds, obtained through the courtesy of Dr H. Klinger (Iziko South African Museum) and Dr David Broad (Petroleum Agency of South Africa), and reprocessing and restudy of the microfaunal residues of the nine samples studied by M. Makrides, leads to the following conclusions. It is clear that these extra samples, as well as those originally studied by Makrides, have each yielded microfossil assemblages that are essentially similar, but also subtly different from each other. The bed-by-bed analysis of foraminifera assemblages, as it expands as more samples are studied, is a valid future programme to follow, and those species from the studied horizons are listed in the appendix below. Illustrated specimens of the diagnostic species *Dicarinella asymetrica* and *Sigalia* sp., together with other notable species from Mzamba Cliff are shown in Fig. 2.

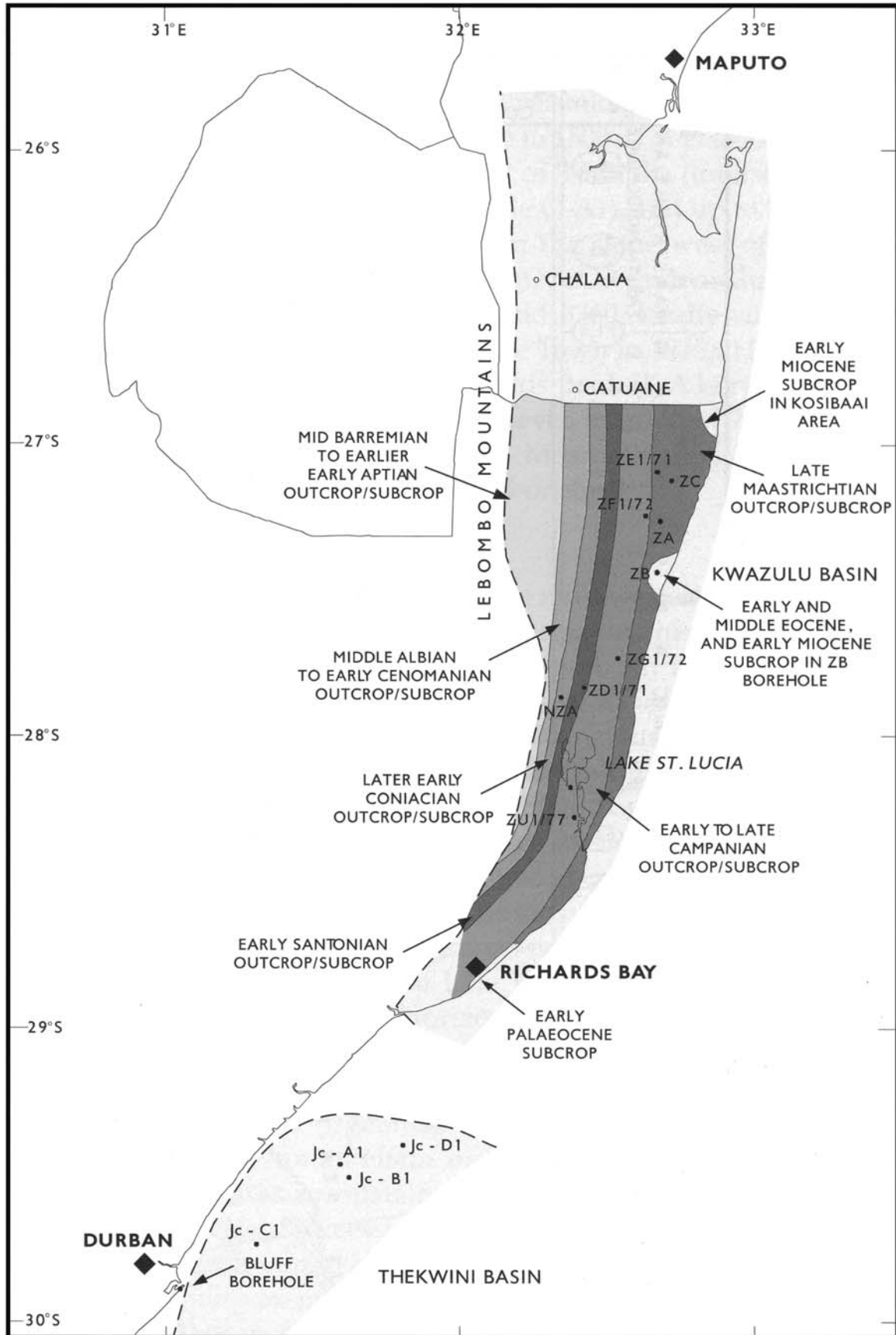


Fig. 1. The Mzamba locality is situated 150 km south of Durban. Relative to boreholes drilled in the onshore part of the KwaZulu Basin (southernmost South Mozambique Basin).

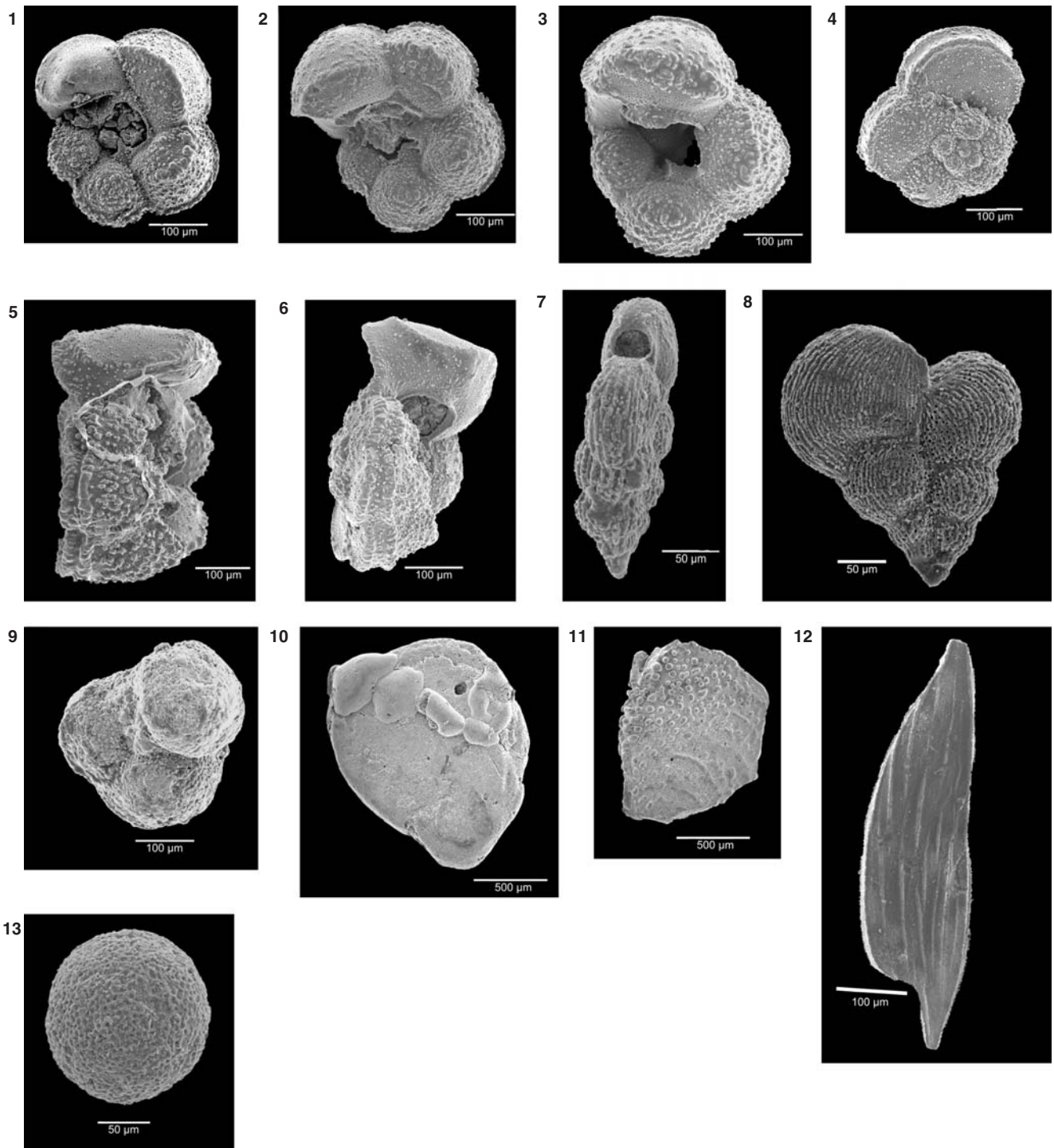


Fig. 2. 1–6: *Dicarinella asymmetrica* (Sigal). 1, Umbilical view, specimen no. SAM-PQ-MF-2121, Mzamba Formation type locality at Mzamba cliff, bed A7, sample KK-1, Middle to Late Santonian. 2, Umbilical view, specimen no. SAM-PQ-MF-2122, same sample. 3, Umbilical view, specimen no. SAM-PQ-MF-2123, same sample. 4, Spiral view, specimen no. SAM-PQ-2124, same sample. 5, Apertural view, specimen no. SAM-PQ-MF-2125, same sample. 6, Apertural view, specimen no. SAM-PQ-MF-2126, same sample. 7–8: *Sigalia* sp. 7, Edge view, specimen no. SAM-PQ-MF-2127, Mzamba Formation type locality at Mzamba cliff, bed A7, sample KK-1, Middle Santonian. 8, Side view, specimen no. SAM-PQ-MF-2128, same sample. 9: *Dicarinella concavata* (Dalbiez), specimen no. SAM-PQ-MF-2129, sample no. 2 or 'lower sample' of Klinger (1977), also designated Soekor sample 8587, subsurface yellow-orange claystone, Wanderfeld IV, southern coastal Namibia, basal Early Santonian. 10: *?Stichocibicides* sp. Attached to comminuted molluscan shell flake, superior view, specimen no. SAM-PQ-MF-2130, Mzamba Formation type locality at Mzamba cliff, bed A7, sample KK-1, Middle to Late Santonian. 11: *?Pseudosiderolites* sp. Side view, test fragment, specimen SAM-PQ-MF-2131, Mzamba Formation type locality at Mzamba cliff, bed A7, sample KK-1, Middle to Late Santonian. 12: *Citharina gracilana* Marie. Side view, specimen no. SAM-PQ-MF-2132, Mzamba Formation type locality at Mzamba cliff, bed A7, sample KK-1, Middle to Late Santonian. 13: Spherical Radiolaria. Specimen no. SAM-PQ-MF-2133, Mzamba Formation type locality at Mzamba cliff, bed A8, Middle to Late Santonian.

Santonian beds

The lower, Santonian half of the Mzamba Formation is characterized by benthic assemblages dominated by the smooth-walled *Epistomina supracretacea* Ten Dam (*sensu lato*), by the strongly ornamented (reticulate) *Epistomina pondensis* (Chapman), and by the less reticulate *Epistomina favosoides* (Egger), as illustrated and described by Makrides (1979). The last-named taxon is probably composed of deteriorated tests of the second-named species. These species are believed to have inhabited the Santonian palaeo-mudbelt, and probably lived in water depths of about 50 to 70 m, in relatively dysoxic muddy sea-floor conditions, for they are not typical shoreline species. The chronostratigraphic value of the inner neritic *Epistomina* assemblages of the KwaZulu Basin was first reported on by Smitter (1957b). Apart from the detailed taxonomic and biostratigraphic work on the later Santonian and Campanian of the KwaZulu Basin by Lambert (1971), no improvements or extension to Smitter's scheme have been made, despite its viability for most of the normal marine Cretaceous succession (Early Albian to Late Maastrichtian) of Southern Africa (see McMillan 2003, p. 559). The smooth-walled forms also display distinctive numbers and shapes of chambers, morphology of the sutures, and in some cases localized umbilical ornamentation as they evolved through the Late Cretaceous. Both the smooth-walled and the highly ornamented *Epistomina* forms in the Santonian part of the succession at Mzamba are known to be mainly limited to the Middle to Late Santonian portion of the succession encountered both in outcrops and in boreholes in the KwaZulu Basin, as defined by the ammonites (Klinger & Kennedy 1980), and by the scattered occurrence of the planktics *Dicarinella asymetrica* and *Sigalia* sp.

Detailed analysis of four extra samples (one each from beds A8 and A7 (KK1) from the lower cliff section, and two, B1/1 and B1/2, from the landward edge of the wave-cut platform); and one sample reprocessing (Pi5 or A5) from the Santonian portion of the Mzamba beds shows the following: in A8 extremely rare *Sigalia deflaensis* (Sigal); in A7 rare *Dicarinella asymetrica* and *Sigalia* sp.; in Pi5 (A5) very rare *Sigalia* sp.; and in B1/1 and B1/2 rare *D. asymetrica* and extremely rare *Sigalia* sp. These species were not found by Makrides (1979) at Mzamba, probably as a result of difficulties with sample processing. *Dicarinella asymetrica* is also known from southern coastal Tanzania (Singano & Karega 2000; Nicholas *et al.* 2006), but nearly all *Sigalia* tests encountered in Tanzania are referable to *S. deflaensis* and related species (Nicholas *et al.* 2006). Tanzanian examples of these and related species are illustrated by Singano & Karega (2000: pl. 1, figs 5–6 (*S. deflaensis*); pl. 5, figs 6a–c (*D. asymetrica*); pl. 6, fig. 3a–c (*D. concavata*)). Examination of the distribution of *Sigalia* species in the KwaZulu Basin shows that moderate numbers of *Sigalia deflaensis sensu stricto* (with raised sutures) are limited to the mid Santonian of boreholes ZB and ZC, the most distally-sited holes, whereas *Sigalia* sp. (distinguished by depressed sutures) is found in the contemporaneous beds in all the other eight more proximal boreholes. Their occurrence supports the Middle to Late Santonian age (Santonian II to Santonian III) of the lower half of the lower Mzamba succession gained from the ammonites (Klinger & Kennedy 1980). All 20

specimens of *Dicarinella asymetrica* found at Mzamba up to now are beautifully well-preserved tests, and all display the sharply angled and recessed chamber surfaces on the umbilical side of the test, with the well-defined third keel developed at the maximum test height [see Caron 1985: p. 43–44 (figs 17.3a–c; 17.4a–c), for details]. Juvenile tests of *Dicarinella asymetrica*, however, are close in morphology to juveniles of the distinctive Early Santonian marker species *D. concavata*, and identifications are best made on the adults. Ten of the 11 well-preserved tests of *Sigalia* sp. found up to now are quite unlike *Sigalia deflaensis*, because of their depressed suture lines, and may prove either to be a new austral (non-tropical) species, or a juvenile of *S. deflaensis*, or a variant limited to inner neritic environments. Our species of *Sigalia* from Mzamba has two distinctively-shaped, sub-circular, typically compressed, finely and vertically striated final chambers. Chamber arrangement is biserial throughout and no tests are multiserial; the sutures are depressed, and display the thickened, curved intercameral wall, typical of the genus *Sigalia*, which is clearly evident in external view. The distinctive striate ornamentation is relatively strongly developed, and the aperture is an unusual highly arched but narrow opening, anteriorly sited at the base of the last-formed chamber. The 11th test is a typical *S. deflaensis* specimen, found in bed A8. The most recent analysis of *Sigalia*, its species and their chronostratigraphy is by Nederbragt (1991).

The following nine samples have been studied, or reprocessed and re-studied from the Santonian succession:

- H. Klinger sample – Locality A, bed 8 (highest) – *Sigalia deflaensis*.
- H. Klinger sample KK1 – Locality A, bed 7 – *Sigalia* sp., *D. asymetrica*.
- Makrides sample 4404 – Locality A, bed Pi7.
- Makrides sample 4405 – Locality A, bed Pi5 – *Sigalia* sp.
- Makrides sample 4406 – Locality A, bed Pi3.
- Makrides sample 4407 – Locality A, bed Pi2.
- Makrides sample 4408 – Locality C, bed Piii6.
- David Broad 2 samples – both foreshore bed B1, close to base of cliff (lowest) – both *D. asymetrica* and *Sigalia* sp.
- Associated ammonites: data from Klinger & Kennedy (1980): HK-8: *Eulophoceras* sp.; HK-7: abundant *Pseudoschloenbachia umbulazi*; 4404: *Damesites/Amapondella amapondense*; 4405: *Pseudophyllites indra*; 4406: no ammonites; 4407: *Madrasites similis*; 4408: *Gaudryceras varicostata*.

The Santonian-Campanian boundary

Owing to circumstances of inaccessibility to the beds A9 up to A12, the Santonian-Campanian boundary at Mzamba remains unstudied, caused by thick vegetation and the vertical, poorly cemented and friable cliffline. It is unclear at which stratigraphic level the boundary occurs. Examination of the Santonian-Campanian (SC) boundary succession in the fully-cored deep boreholes (for example in a dip-line from borehole ZA to ZB) in KwaZulu Basin clearly shows the basal Campanian succession downlapping and progressively truncating in an offshore direction over a presumably eroded top Santonian surface, and this boundary is an

unconformity everywhere in the basin. In all KwaZulu Basin borehole sections the topmost Santonian lacks *Sigalia* species, in agreement with Nederbragt's (1991) essentially mid Santonian stratigraphic range for this genus. The first downhole appearance of Santonian succession is marked by a distinctive benthic faunal turnover, which includes the first downhole appearance of thin *Textularia* sp. (McMillan 2003). The presence of an erosional surface at the SC boundary in KwaZulu Basin implies that the latest Santonian (equivalent to upper Santonian III) is missing at the boundary. The planktic foraminifera species *Ventilabrella eggeri* ranges across the boundary in proximal boreholes (such as ZA), but in more distal holes (such as ZB and ZC), with a distinctly attenuated succession, this species displays a much thinner interval only in the basal Campanian. *V. eggeri* is yet to be found at Mzamba. The distribution of ammonites (Klinger & Kennedy 1977) and ostracods (Dingle 1980) across the SC boundary in cored shallow borehole 9 at Richards Bay have been published, but the foraminifera of this borehole remain to be studied.

Campanian beds

Nearly all samples from the Campanian portion of the Mzamba Cliff succession contain small numbers of a distinctive benthic agglutinated-walled species of *Cyclammina*. *Cyclammina* species are usually absent in the South African Cretaceous succession, except in the Maastrichtian interval of the Pletmos and Bredasdorp Basins. However, there is a thin interval (perhaps two intervals close together) bearing *Cyclammina* spp. in the mid Early Campanian succession drilled in some of the deep boreholes in the KwaZulu Basin (boreholes ZA, ZB, ZG 1/72, ZH 1/74 and ZU 1/77), an interval which is about 10 m thick, and appears to include the species of *Cyclammina* present in the Mzamba Campanian samples. If this correlation is correct, then the Campanian interval at Mzamba is only an extremely thin portion of the total Early Campanian succession seen in the KwaZulu Basin boreholes. Extant species of the genus *Cyclammina* are limited to abyssal, often dysoxic, depositional environments, whereas those from the South African Campanian and Maastrichtian succession clearly inhabited shelfal environments. They inhabited the proximal Campanian palaeo-mud-belt. *Cyclammina* appears not to have been found in samples from the Early Campanian car park exposure detailed by Cooper & Greyling (1996).

Epistomina tests in the Campanian interval are much smaller sized and decidedly less common than those in the Santonian interval. The unornamented *E. supracretacea* Ten Dam *sensu lato* forms in the Campanian are small planoconvex forms in the shape of a cone, with the umbilical side strongly convex, and the spiral side almost flat. The strongly ornamented forms are also smaller and conical in outline, with a larger, looser reticulation surface ornamentation than seen in *E. pondensis* in the Santonian.

As indicated above, *Globotruncanita elevata* has not yet been found in the Mzamba Cliff succession. Two planktic species that are both limited to the Campanian-Maastrichtian period, and episodically found through the Campanian (upper) portion of the Mzamba cliff succession, are *Rugoglobigerina rugosa* (Plummer) and more rarely *Gublerina ornatissima* Cushman & Church. This part of the succession

thus can be no older than basal Campanian, but no more detailed biostratigraphy is possible with the presently available samples and their sparse planktic assemblages.

The six Campanian samples are:

Makrides sample 4401 – Location A, bed Pi17 (1.2) (highest) – *Cyclammina* sp., *R. rugosa*.

Makrides sample 4400 – Location A, bed Pi17 (1.1) – *G. ornatissima*, *R. rugosa*, *Cyclammina* sp.

Makrides sample 4402 – Location A, bed Pi15 – *G. ornatissima*, *R. rugosa*.

H. Klinger sample – Location A, bed 15 – *Cyclammina* sp., *R. rugosa*.

H. Klinger sample – Location A, lower bed 15 – *Cyclammina* sp.

Makrides sample 4403 – Location A, bed Pi13 – (lowest) no microfossils (Campanian ammonites present).

Associated ammonites, data from Klinger & Kennedy (1980): 4401: no ammonites; 4400: no ammonites; 4402: *Baculites sulcatus*; HK-15: also *B. sulcatus*; HK-15: *Hauericeras madagascariensis*; 4403: Campanian ammonites present, but no details.

SANTONIAN AND CAMPANIAN DEPOSITIONAL ENVIRONMENTS

All Santonian and Campanian samples from the Mzamba Formation studied up to now display the predominance of both smooth-walled and highly ornamented *Epistomina* in the benthic assemblage. Claystone sediments are dark brown, dark grey or dark green-grey gritty and sandy, with variable shell, terrestrial plant debris, often abundant faecal pellets, and glauconite grains. There is variable carbonate cementing. The same benthic foraminifera assemblage can be recognized only in the proximal oil exploration boreholes drilled in the KwaZulu Basin (boreholes NZA, ZD 1/71, ZG 1/72, ZH 1/74 and ZU 1/77), and from the Wanderfeld IV outcrop in coastal southern Namibia. In deeper-water settings sediments are predominantly grey and greenish-grey claystones, but much more shelly and carbonate-rich, and the dominant benthic foraminifera is a large-sized, strongly-compressed *Lenticulina* with a broad peripheral keel. This more distal facies (middle to outer neritic) is present only in the distal deep boreholes (ZA, ZB, ZC, ZE 1/71, ZF 1/72), and it is devoid of *Epistomina* species. The stratigraphic and facies value of Late Cretaceous *Epistomina* was first noted by Smutter (1957b). There is no outcrop or borehole section yet found in which these two facies are interbedded, which would suggest no major sea-level rises and falls: either the entire Middle to Late Santonian section contains abundant *Epistomina*, or it contains abundant keeled *Lenticulina*. This argues for maximum sea-level changes of perhaps no more than about 15 m. The *Epistomina*-dominated proximal biofacies shows all the signs of being the Cretaceous mud-belt, since it shows many features in common with the Holocene mud belt (Dale & McMillan 1998).

The following characteristics argue for a mud-belt setting well away from shore (about 50 to 70 m deep), usually experiencing dysoxic sea-floor conditions. (i) Much irregular-sized siliciclastic debris, including large irregularly shaped quartz grains, some with silvery metallised sulphide

coatings. (ii) Local abundances of polychaete worm faecal pellets, of exactly the same dimensions as those from the Holocene mud-belt off South Africa (Dale & McMillan 1998). (iii) Abundant molluscan shell fragments, mainly disintegrated and comminuted gastropods, bivalves, oysters and *Inoceramus* prisms, with shell often bored, flaked or rotted, and frequently infested with attached foraminifera (similar to *Stichocibicides*, but probably a new genus, new species). (iv) Often abundant carbonized, land-derived plant stems, seeds, megaspores, and the supposed faecal pellets of certain termites, *Microcarpolithes hexagonalis* Vangerow (J-P. Colin, pers. comm. 2003). (v) Benthic foraminifera assemblages dominated by about six species occurring in abundance, together with occasional tests of genera regarded as typically deep-water (80 m or deeper?): especially *Allomorphina* and *Fronicularia*. (vi) There is generally a complete absence of shoreline or intertidal benthic foraminifera. These species inhabit turbulent environments in the wave-break zone and many attach to a substrate in life. The only obviously attached species is the ?*Stichocibicides* noted above, which, from its delicate apertural neck and thin test wall, must have inhabited quieter, deeper waters than the wave-break zone. There are also numbers of a species very similar to *Rosalina* species, which displays a plano-convex or concavo-convex test, and which was probably attached to a substrate while alive. Does this absence of shoreline benthics imply that the shoreline was in the main siliciclastic starved? Or, more likely, that there was no active sedimentation at the shoreline, and it was being uplifted? (vii) The finding of two broken tests of larger foraminifera (probably *Pseudosiderolites* sp.) in sample KK1 (A7), which must have inhabited a clear-water shoreline setting, changes perceptions of Mzamba greatly. These tests probably entered the mud-belt in debris flows. A comparable setting is envisaged for the Campanian portion of the succession.

Thus the general setting at Mzamba is interpreted to be at the proximal limits of the mud-belt, subject to the frequent development of a nepheloid layer (widespread turbid waters generated by energy in the water column impinging on sea-floor mud) in the lowest levels of the water column, and also subject to the periodic incursions of debris flows. The debris flows introduced much plant debris, and this argues for active river systems, while rare larger foraminifera tests argue for localized clear-water shoreline settings away from the river mouths.

PLANKTIC FORAMINIFERAL BIOSTRATIGRAPHY

Caron (1985, pp. 43–44) presented details on both *Dicarinella asymetrica* and *Dicarinella concavata*. The former name includes the junior synonyms *Globotruncana lobata* De Klasz, *Globotruncana fundiconulosa* Subbotina, and *Globotruncana (Globotruncana) ventricosa* White subsp. *carinata* Dalbiez. Caron (1985, figs 17.3a–c and 17.4a–c) illustrated the holotype of *D. asymetrica* by scanning electron microscope and by drawings. The holotype is from the *D. asymetrica* zone, Santonian, Ain-ed-Deffa, Algeria. Caron considers this species to be limited to the Middle to Late Santonian interval. *Dicarinella concavata* is illustrated by Caron (1985) with two specimens, by scanning electron microscope. One is from the *D. asymetrica* zone, Santonian,

Tarfaya Basin, Morocco; the second is from the *D. asymetrica* zone, Late Santonian, Wadi Madi section, Mount Carmel, Israel. From this it is evident that both species occur in the Late Santonian, and that the ranges of the two species overlap. However, previous tendency has been to consider *D. asymetrica* as typical of Middle to Late Santonian, and *D. concavata* as typical of Early Santonian (for example, see Postuma 1971).

The relative stratigraphic ranges of these two species are not entirely clear in borehole sections in the KwaZulu Basin, principally because of the apparent sparsity of planktic foraminifera assemblages through the Early Santonian succession, and the rarity of typical *D. concavata*. Inadequate micropalaeontological processing techniques are probably the cause of this. In the KwaZulu Basin there is a major high-gamma hemipelagic claystone interval, about 20 m thick, in the basal part of the Middle to Late Santonian interval (lowest *D. asymetrica* zone), below which *D. asymetrica* is not found.

It may be that the two species' ranges only overlap within the hemipelagic interval. It is possible that reprocessing of the samples through the Early Santonian succession would lead to a better understanding of the stratigraphic range of *D. concavata* in the KwaZulu Basin.

In the four fully-cored boreholes drilled by Anglo-Vaal in the KwaZulu Basin, the Middle to Late Santonian interval extends from 457.3 to 521.3 m (64 m thick) in borehole ZA; from 515.2 to 570.1 m (54.8 m thick) in borehole ZB; from 628 to 670.7 m (42.6 m thick) in borehole ZC; and from 22.8 to 30.4 m (7.6 m thick) in borehole NZA. The high-gamma hemipelagic claystone at the base of the succession is remarkably rich in planktic foraminifera (especially hedbergellids): this unit is about 18.3 m thick in ZA, ZB and ZC, but only 7.6 m in NZA because the top has been eroded off.

SUMMARY

- 1) Despite the extreme rarity of planktic foraminifera diagnostic of the Middle to Late Santonian at Mzamba Cliff, the species *Dicarinella asymetrica*, *Sigalia deflaensis* and *Sigalia* sp. occur intermittently, often in association, from bed B1 up to A8, and support the age dating previously gained from the ammonites by Kennedy & Klinger (1980).
- 2) These three planktic species also help define the Middle to Late Santonian succession, up to 64 m thick, in the four fully-cored Anglo-Vaal boreholes drilled in the KwaZulu Basin.
- 3) A similar Middle to Late Santonian succession occurs in southern coastal Tanzania (Singano & Karega 2000; Nicholas *et al.* 2006).
- 4) The outcrop at Wanderfeld IV, southern coastal Namibia, interpreted as exposing Early Santonian rocks, is distinguished by *Dicarinella concavata*, abundant hedbergellids and abundant *Epistomina pondensis* (McMillan 2003), but lacks *Dicarinella asymetrica* and *Sigalia* species.
- 5) These diagnostic Santonian planktic species (and by inference Middle to Late Santonian rocks) are missing in all borehole sections in the offshore Orange, Bredasdorp, Pletmos, Gamtoos and Algoa Basins off the west and south coasts of South Africa, and occur only in

the Thekwini Basin (boreholes Jc-B1 and Jc-D1) and KwaZulu Basin along the east coast.

- 6) The rock unit dated by McMillan as Late Santonian (2003, p. 566) is incorrectly dated, since it contains *Globo truncanita elevata* (Brotzen) in small but persistent numbers in the distally-sited Kudu boreholes drilled in the northern Orange Basin. Caron (1985) limits *Globo truncanita* to the Campanian and Maastrichtian. This unit should more properly be dated as Early Campanian, and its benthic foraminifera successions correlate closely with the Early Campanian succession preserved in the KwaZulu Basin. This Early Campanian unit occurs throughout the Orange, Bredasdorp, Pletmos, Gamtoos, Algoa and KwaZulu Basins, but not in the Thekwini Basin.

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APPENDIX

Bed-by-bed Foraminifera from the mid Santonian to earlier Campanian interval at Mzamba Cliff. *Species present in moderate numbers; ° planktic species.

Bed B1

Epistomina pondensis *
 'Carpenteria' sp.
Epistomina supracretacea s.l. *
Laevidentalina sp.
Gaudryina laevigata *
 ?*Amphicoryna* sp.
 ?*Stichocibicides* sp.*
Ceratobulimina cf. *lotosina*
Lenticulina spp.
Gyroidinoides nitida *
Gavelinella sp.
 thin *Spiroplectinella* sp.
 ?*Rosalina* sp. *
Nodosaria cf. *affinis*
Globulina sp.
Nodosaria cf. *zippei*
Allomorphina sp.
Fronicularia sp.
Citharina gracilana
Psilocitharella sp.
 ?*Pseudosiderolites* sp. (larger foraminifera)
Lagena cf. *oxystoma*
Bullopore laevis
Vaginulina legumen
Marginulinopsis sp.
Quinqueloculina itongaziana
Dicarinella asymetrica °
Dicarinella primitiva °
Globigerinelloides asper °
Hedbergella spp. °
Globotruncana linneiana °
Globotruncana tricarinata °
Heterohelix globulosa °
Contusotruncana fornicata °
Sigalia sp. °

Bed Ciii6 (4408)

Epistomina supracretacea s.l.
Angulogavelinella sp.
Osangularia sp.
Lagena lineata
Globotruncana linneiana °
Globigerinelloides asper °
Marginotruncana marginata °

Bed A2 (4407)

Epistomina supracretacea s.l.
Angulogavelinella sp.
Osangularia sp.
Lagena lineata
Epistomina favosoides
Gyroidinoides nitida
Gyroidinoides depressa
Gavelinella sandidgei
Vaginulina legumen
Nodosaria affinis

Gaudryina laevigata
Quinqueloculina sp. A
Quinqueloculina cf. *Q. angusta*
Lenticulina modesta
Guttulina cf. *G. cuspidata*
Dentalina catenula
Globigerinelloides asper °
Marginotruncana coronata °
Heterohelix globulosa °
Contusotruncana fornicata °
Marginotruncana marginata °
Globotruncana linneiana °

Bed A3 (4406)

Epistomina supracretacea s.l.
Angulogavelinella sp.
Osangularia sp.
Lagena lineata
Epistomina favosoides
Gyroidinoides nitida
Gyroidinoides depressa
Gavelinella sandidgei
Vaginulina legumen
Nodosaria affinis
Gaudryina laevigata
Quinqueloculina sp. A
Quinqueloculina cf. *angusta*
Lenticulina modesta
Guttulina cf. *cuspidata*
Lagena acuticosta
Marginulina plummerae
Vaginulina directa
Planularia sp.
Colomia californica
Globotruncana tricarinata °
Contusotruncana fornicata °
Heterohelix globulosa °
Marginotruncana coronata °
Globigerinelloides asper °
Globotruncana linneiana °

Bed A5 (4405)

Epistomina supracretacea s.l.
Angulogavelinella sp.
Osangularia sp.
Epistomina favosoides
Gyroidinoides nitida
Gyroidinoides depressa
Gavelinella sandidgei
Vaginulina legumen
Nodosaria affinis
Gaudryina laevigata
Guttulina cf. *cuspidata*
Praebulimina carseyae
Nodosaria proboscidea
 ?*Polymorphina* sp.
 ?*Marginulina silicula*
 ?*Enantiomorphina* sp.
Guttulina trigonula
Dentalina gracilis
Sigalia sp. °

Globotruncana linneiana °
Contusotruncana fornicata °
Heterohelix globulosa °
Marginotruncana coronata °

Bed A7 (4404)

Epistomina supracretacea s.l.
Epistomina favosoides
Gyroidinoides depressa
Vaginulina legumen
Nodosaria affinis
Gaudryina laevigata
Lenticulina modesta
Saracenaria triangulata
Epistomina pondensis

Bed A8

Epistomina pondensis *
Epistomina supracretacea s.l.
 Fat smooth *Marginulina* sp.
Quinqueloculina itongaziana
Praebulimina sp.
Rosalina sp.
 ?*Baggina* sp.
Vaginulina legumen
Globulina sp.
Gaudryina laevigata
Nodosaria cf. *zippei*
Haplophragmoides spp.
 ?*Bigenerina* sp.
Gavelinella sp.
 'Carpenteria' sp.
 ?*Angulogavelinella* sp.
Heterohelix globulosa °
Marginotruncana coronata °
 Large globular *Hedbergella* sp. °
Contusotruncana fornicata °
Dicarinella primitiva °
Globotruncana linneiana °
Globigerinelloides asper °
Sigalia deflaensis °
Dicarinella cf. *asymetrica* °
 Moderate numbers of sphere, disc and lens radiolaria

Bed A13

No foraminifera recovered.

Bed A15

Epistomina supracretacea s.l. (different species from the Santonian one)
Angulogavelinella sp.
Osangularia sp.
Lagena lineata
Gyroidinoides nitida
Gavelinella sandidgei
Gaudryina laevigata
Guttulina cf. *cuspidata*
Lenticulina modesta
Quinqueloculina cf. *angusta*
Praebulimina carseyae
Spiroplectinella semicomplanata

?*Stichocibicides* sp.

Allomorphina cretacea
Alabamina dorsoplana
Praebulimina kickapooensis
Epistomina sp.
Anomalina cf. *henbesti*
Cibicides sp.
Gavelinella sp.
Quinqueloculina sp. B
Dentalina basiplanata
Heterohelix cf. *complanata* °
Heterohelix striata °
Heterohelix pulchra °
Hedbergella cf. *delrioensis* °
Globigerinelloides asper °
Marginotruncana marginata °
Contusotruncana fornicata °
Heterohelix globulosa °
Globotruncana tricarinata °
Rugoglobigerina rugosa °

Bed A17

Epistomina supracretacea s.l. (different species from the Santonian one).
Gavelinella sandidgei
Angulogavelinella sp.
Osangularia sp.
Nodosaria affinis
Lagena lineata
Gyroidinoides nitida
Gyroidinoides depressa
Gaudryina laevigata
Quinqueloculina cf. *angusta*
Lenticulina modesta
Guttulina cf. *cuspidata*
Lagena acuticosta
Colomia californica
Praebulimina carseyae
Cyclammina sp.
Spiroplectinella semicomplanata
 ?*Stichocibicides* sp.
Allomorphina cretacea
Alabamina dorsoplana
Praebulimina kickapooensis
Epistomina sp.
Anomalina cf. *henbesti*
Cibicides sp.
Gavelinella sp.
Quinqueloculina sp. B
Dentalina basiplanata
Ceratobulimina cretacea
Pseudonodosaria sp.
Citharina gracilana
Lagena paucicosta
Lagena sphaerica
Lamarckina cf. *ripleyensis*
 ?*Svratkina* sp.
Quinqueloculina cf. *itongaziana*