

Biostratigraphy and macroinvertebrate palaeontology of the petroleum-rich Belfast Mudstone (Sherbrook Group, uppermost Turonian to mid-Santonian), Otway Basin, southeastern Australia

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ABSTRACT

The hydrocarbon-rich Turonian to Santonian Belfast Mudstone (Sherbrook Group) of the Otway Basin, southern Victoria, Australia, represents transgressive lower delta plain to prodelta conditions in inner to middle shelf depths to slope environments. Comprising relatively homogeneous mudstone that thickens to more than 1 km in the offshore Otway Basin, the biostratigraphic resolution has been enhanced by study here of both macro- and microfossil assemblages. Macrofossils consist of 12 species of bivalves from a relatively low diversity of genera (*Nucula s.l.*, *Nuculana*, *Mesosacella*, *Pinna*?, *Tethyoceramus*, *Oistrotrogonia*), gastropods (*Cerithioidea*, *Latiala*, *Ringiculidae*), cephalopods (*Eutrephoceras*?, *Borissiakoceras*), and cnidarians (*Trochocyathus* (*Platycyathus*?)). Other invertebrate groups such as echinoids and serpulids are too poorly represented and preserved for description. New and probably new taxa described include the bivalve *Oistrotrogonia austronana* sp. nov. (Trigoniidae), *Mesosacella* sp. nov.? (Nuculanidae) and ammonite *Borissiakoceras* sp. nov.? (Binneyitidae). The probable presence of the inoceramid bivalve and index taxon *Tethyoceramus madagascariensis* and binneyitid ammonite *Borissiakoceras* sp. nov.?, corroborated by known ranges of other macroinvertebrates and Foraminifera in the Belfast Mudstone from the offshore Otway Basin, constrain the age in cores 13 and 16 of the well Voluta-1 to the Coniacian Stage (probably equivalent to the *Tethyoceramus madagascariensis* Zone, lower part of Coniacian, ca. 89–88 Ma, for core 16 and late? Coniacian for core 13). All of the bivalves and gastropods are infaunal and/or semi-infaunal suspension and deposit feeders that preferred fine-grained facies, and these fossils and others support the interpretation of a low-energy hydrodynamic regime in a quiescent, deeper shelf setting.

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1. Introduction

During the Late Cretaceous the southern margin of Australia lay at around 70°S in a seaway separating Australia from Antarctica nearly 500 km wide (Fig. 1a). Thick sequences (up to 5 km) of Turonian to Maastrichtian deltaic to open marine sandstone and mudstone were deposited as the Sherbrook Group in the Otway Basin (Fig. 1b). Hydrocarbon exploration in the region has resulted in the discovery of economic gas reserves in the Turonian to Santonian strata. As a result, there are many wells that sample the Upper Cretaceous section in the Otway Basin. Our project focuses on the macrofossils in two cored intervals from Voluta-1 (Table 1). Previous

work by Gallagher et al. (2005) has described the stratigraphic and environmental setting of these strata primarily using Foraminifera and facies analysis. Gallagher et al. also provided a preliminary taxonomic list of the macrofossils from these two cores, which has been revised and enhanced here by descriptions and figures of all taxa. The two cores sample lower to upper? Coniacian strata (Fig. 2). The purpose of this contribution is: (1) to describe in detail the taxonomy of the macroinvertebrates in these cores, outlining many new occurrences for the Late Cretaceous of Australia (Figs. 3, 4); and (2) to interpret the age and palaeoenvironment of the cored intervals.

2. Stratigraphy

The Belfast Mudstone, a mostly homogeneous mudstone-dominated unit, forms part of an extensive subsurface sequence of Turonian to Santonian siliclastic rocks that reaches more than 2 km

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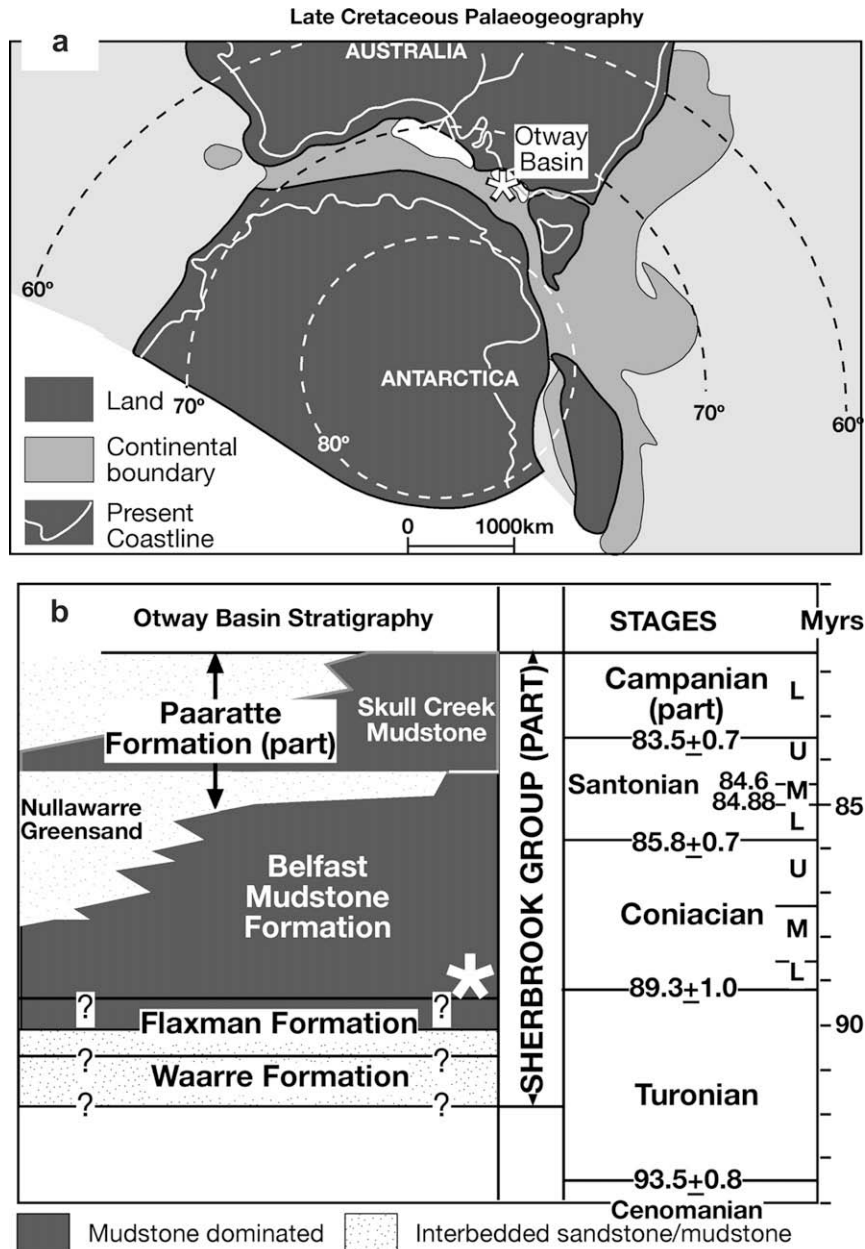


Fig. 1. (a) The Late Cretaceous palaeogeography of the Otway Basin (adapted from Gallagher et al., 2005 and Norvick and Smith, 2001). (b) The stratigraphic setting of the sections studied (adapted from Gallagher et al., 2005). * denotes the age of the samples. The timescale used is Gradstein et al., (2004).

thick in the Otway Basin of southern Victoria. This sedimentary package in turn comprises a part of a nearly 5 km thick succession of Turonian to Maastrichtian marine deltaic, shelfal to upper bathyal sediments that were deposited within two immense delta systems: the Hammerhead Delta supersequence in the Great Australian Bight and the Sherbrook Group of the Otway Delta in the Otway region. A Greenhouse interval of global warmth and low thermal stratification, even in the high southern latitudes, these sediments were laid down in warm seas of about 70°S in an oceanic inlet about 500 km wide, which was closed at the eastern end but open with marine communication to the west (see review by Gallagher et al., 2005). These authors also subdivided the Belfast Mudstone sequence into four biofacies, based on the relative abundances of macrofossils (mostly invertebrates), microfossil composition and to a lesser degree, the wireline character and

facies. These distinct biofacies conform to the concept of the term 'biofacies', which are coeval assemblages of fauna and flora forming under different conditions and lateral variations in the biologic aspect of a stratigraphic unit. The four defined biofacies are contrasted below.

Biofacies A to C (including Cores 13 and 16, Fig. 2) of the Belfast Mudstone are similar lithologically and comprise dark grey mudstone with a minor (1–5%) fine white sandstone and fine sand component which include rare, subrounded to rounded quartz grains from 0.5 mm to 4 mm sized granules. Glauconite is present in Biofacies A to C, but decreases in abundance towards the top of Biofacies C. The primary sedimentary structure is lamination and bioturbation is more common in Biofacies A. The lower 50 m of Biofacies D is lithologically comparable to Biofacies C, where the Biofacies C/D boundary is discerned on microfossil criteria, and the

Table 1
Location of wells discussed in text and C#1 refers to core numbers

Port Campbell-1	Exploration Well	Onshore
Latitude	–38.58 Longitude	142.96
	Total Depth	1819 m
Operator	Frome Broken Hill Co P/L Kelly Bushing/Rotary Table	RT 3 m
Voluta-1	Exploration Well	Offshore
Latitude	–38.43 Longitude	141.31
	Total Depth	3974 m
	Seafloor	–92 m MSL
Operator	Shell Dev (Australia) Pty. Ltd. Kelly Bushing/Rotary Table	DF 34 m
Drik Drik-1	Groundwater Bore	Onshore
Latitude	–37.99 Longitude	141.29
	Total Depth	1222 m
Operator	Department of Manufacturing & Industry Development, Victoria Kelly Bushing/Rotary Table	Unknown

upper 30 m of biofacies D is represented by an upwards-increasing influx of 20–50% fine sand in dark grey mudstone.

3. Systematic palaeontology

The macroinvertebrates described and figured in this paper (Table 2, Figs. 3, 4) are housed at the Museum Victoria (MV), Melbourne, Australia. All macro fossil specimens were coated with ammonium chloride prior to macrophotography and microfossils with gold for scanning electron microscopy.

Table 2
Systematic checklists of fossils and core samples

Mollusca
Bivalvia
<i>Nucula</i> s.l. sp. cf. <i>N. s.l. meadinga</i> Stilwell and Henderson, 2002 [Nuculidae] 13.1
<i>Nuculana</i> ? sp. cf. <i>N. bathurstensis</i> Stilwell and Henderson, 2002 [Nuculanidae] 13.7
<i>Mesosacella</i> sp. nov.? [Nuculanidae] 13.3, 13.6, 13.7
<i>Pinna</i> ? sp. [Pinnidae] 13.1
<i>Tethyoceramus madagascariensis</i> (Heinz, 1933) [Inoceramidae] 13.9, 16.1, 16.2, 16.3, 16.4, 16.5, Drik Drik-1
<i>Oistrotrigonia austronana</i> sp.nov. [Trigoniidae] Drik Drik-1, Pt Campbell#1 Core 17
Gastropoda
Cerithioidean, family and genus indeterminate 13.3
<i>Latiola</i> sp. cf. <i>L. mountnorrisi</i> (Skwarko, 1983) [Aporrhaidae] 13.8
Ringiculidae? genus and species indeterminate 13.3
Cephalopoda
<i>Eutrephoceras</i> ? sp. [Nautilidae] 13.4
<i>Borissiakoceras</i> sp. nov.? [Binneyitidae] 13.12, 13.5
Cnidaria
Scleractinia
<i>Trochocyathus (Platycyathus)?</i> sp. [Caryophylliidae] 13.10, 13.11

Phylum: Mollusca Linnaeus, 1758
 Class: Bivalvia Linnaeus, 1758
 Subclass: Paleotaxodonta Korobkov, 1954
 Order: Nuculoida Dall, 1889
 Superfamily: Nuculoidea Gray, 1824
 Family: Nuculidae Gray, 1824
 Subfamily Nuculinae Gray, 1824
 Genus *Nucula* de Lamarck, 1799

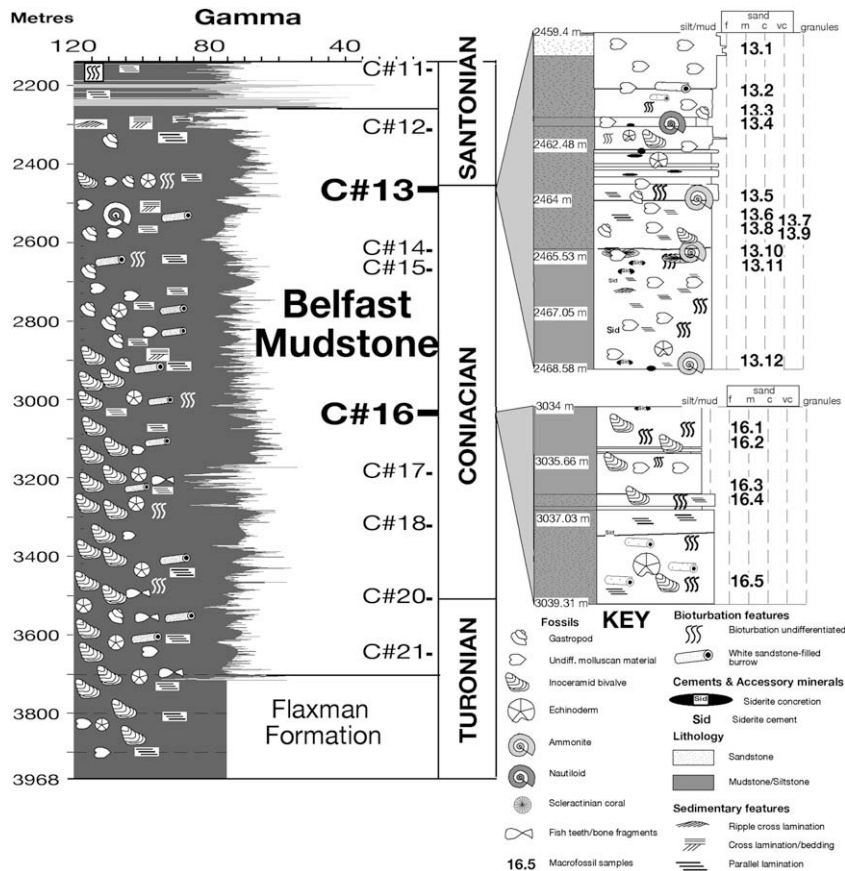


Fig. 2. A log of Voluta-1 showing gamma values with macrofossils documented in the cores and well cuttings. Wireline logs were used in addition to biostratigraphy and seismic data to correlate the Upper Cretaceous sections of Gallagher et al. (2005). A typical gamma profile of the Belfast Mudstone is shown in Fig. 2.

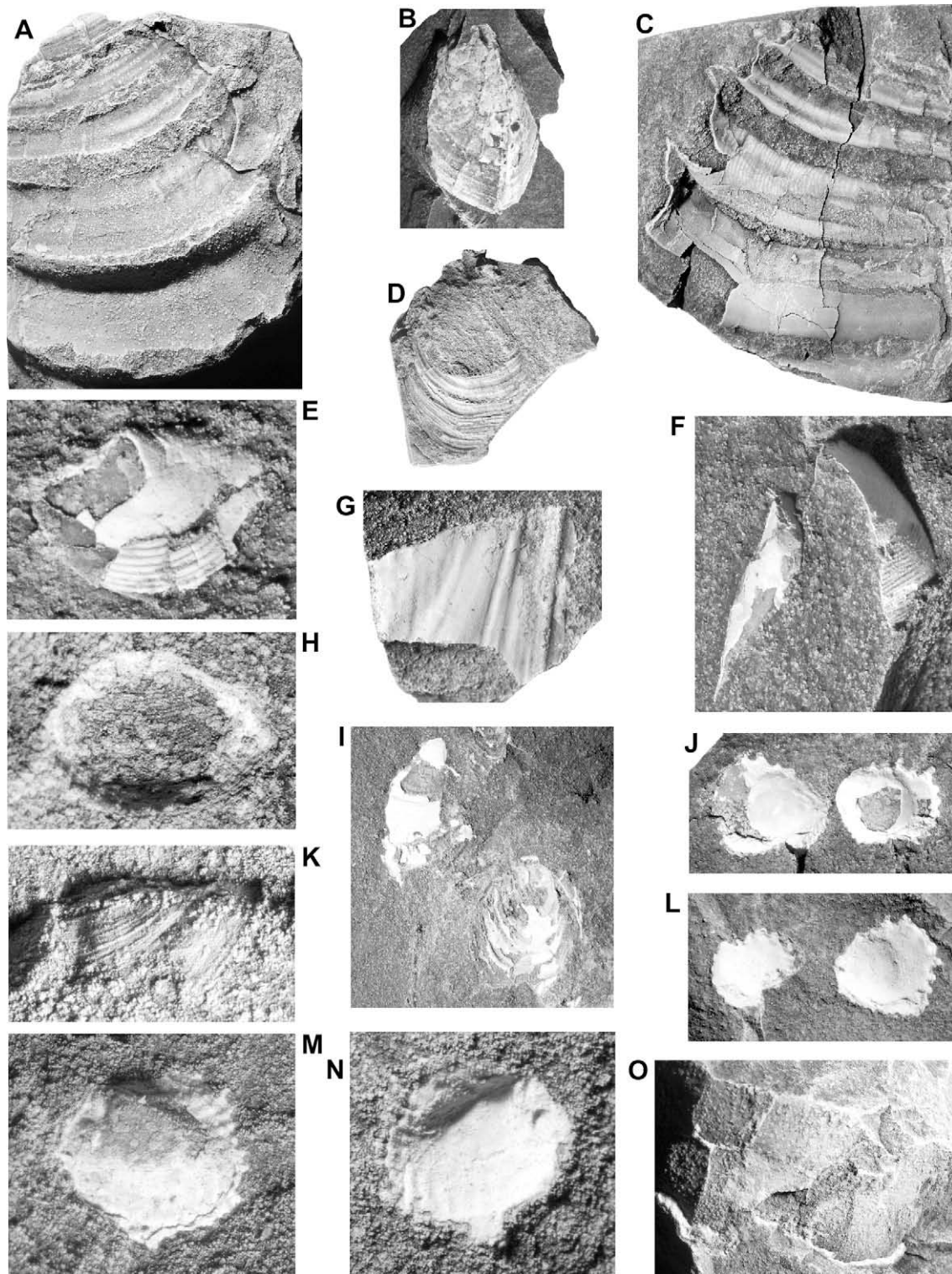


Fig. 3. A–D, I, *Tethyoceramus madagascariensis* (Heinz, 1933). A, C, P314022, Voluta-1, 16.5, disc fragment (part and counterpart), both $\times 1.5$; B, P315023, partially crushed juvenile?, Voluta-1, 13.9, $\times 1$; D, P314024, small disc fragment, Voluta-1, 16.4, $\times 1$; I, P314025, juvenile? Specimen, Drik Drik-1, Top 3279–3284, $\times 1.5$. E, H, *Mesosaccella* sp. nov.?, E, P314017, Drik Drik-1, Top 3279–3284, specimen with some ornament preserved, $\times 12$; H, P314019, right valve internal, Voluta-1, 13.3, $\times 10$. F, *Nucula* s. l. sp. cf. *N. s. l. meadinga* Stilwell and Henderson, 2002, hinge fragment and piece of disc of same specimen, Voluta-1, 13.1, $\times 3$. G, *Pinna*? sp., P314021, fragment exhibiting longitudinal ornament, Voluta-1, 13.1, $\times 3$. K, *Nuculana*? sp. cf. *N. bathurstensis* Stilwell and Henderson, 2002, P314016, eroded specimen, Voluta-1, 13.7, $\times 5$. J, L, M–N, *Oistotrigonia austronana* sp. nov., J, L, Paratype P314027, opened paired, valves, partially decorticated, parts and counterparts, Port Campbell #1, Core 17, 4757–4758, $\times 2$; M–N, Holotype, P314026, Port Campbell #1, Core 17, 4757–4758, immature specimen, part and counterpart, Drik Drik-1, 3279–3284 Top, $\times 10$. O, crushed irregular echinoid test of uncertain affinity (not discussed in text due to very poor preservation), P314082, Drik Drik-1, 3279–3286, $\times 2$.

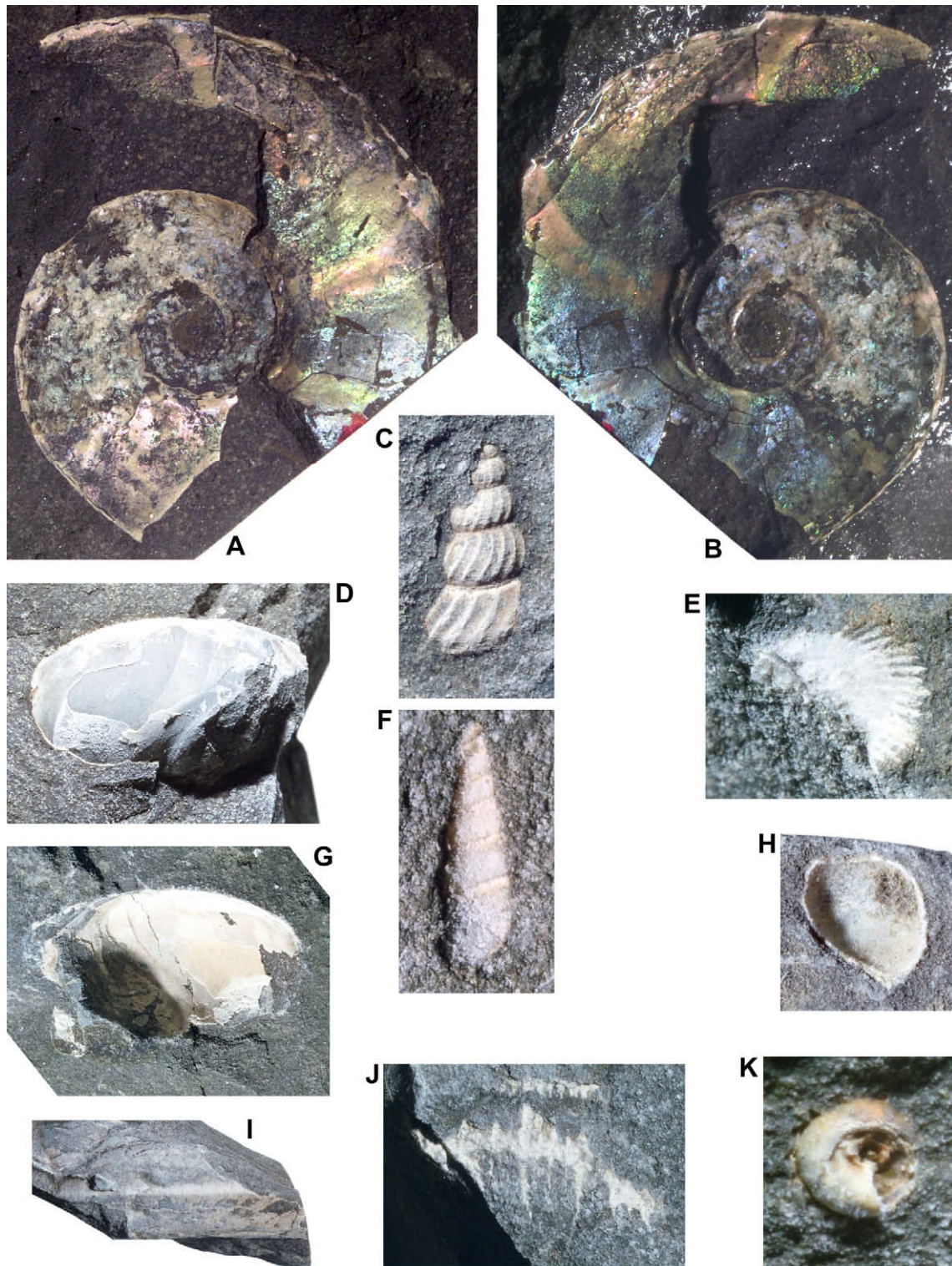


Fig. 4. A–B, *Borissiakoceras* sp. nov., P314033, original shell material preserved, part and counterpart, Voluta-1, 13.2, both $\times 2.5$. C, *Latalia* sp. cf. *L. mountrorrisi* (Skwarko, 1983), eroded protoconch and part of teleoconch with ornament preserved, P314030, Voluta-1, 13.8, $\times 6$. D, G, *Eutrephoceras*? sp., P314032, part and counterpart of phragmocone fragment with original shell material, Voluta-1, 13.4, both $\times 2$. E, J, *Trochocyathus* (*Platycyathus*)? sp., P314035, part of calice, Voluta-1, 13.11, $\times 8$; J, P314036, fragment/cross-section of calice, Voluta-1, 10.1, $\times 4.5$. F, Cerithioidean gastropod, family and genus indeterminate, P314029, eroded specimen lacking preserved ornamentation, Voluta-1, 13.3, $\times 8.5$. H, K, Ringiculidae? gen. et sp. indet., H, P314031, internal part of last whorl, Port Campbell 2, Core 3, 5910–5919, $\times 6$; K, P314081, apical view of fragment, Belfast 4, 4649–4655, $\times 14$. I, ammonite fragment of uncertain affinity, P314037, exhibiting distinct keel, Voluta-1, 13.12, $\times 2$.

Nucula de Lamarck, 1799, p. 87.

Type species: *Arca nucleus* Linnaeus, 1758 (by monotypy).

Nucula s.l. sp. cf. N. s.l. meadinga Stilwell and Henderson, 2002 Fig. 3F

Nucula s.l. sp. cf. N. s.l. meadinga Stilwell and Henderson, 2002, of Stilwell in Gallagher et al., 2005, Tab. 1, p. 329.

Cf. Nucula s.l. meadinga Stilwell and Henderson, 2002, p. 452, Fig. 2.1.

Dimensions: MV-P314015, *Voluta*-1, 13.1, length of hinge fragment 8.0 mm, height of fragment from separate piece (same specimen) 9.0 mm.

Discussion: The taxodont hinge combined with relatively large nuculomine shell, ornamented with closely spaced, irregularly undulating, bifurcating, commarginal riblets and very weak radial sculpture, is comparable to the mid-Cenomanian nuculid *Nucula s.l. meadinga* Stilwell and Henderson, 2002, from the Moonkinu Formation of Bathurst Island, Northern Australia. However, as the only available specimen from the *Voluta*-1 well (13.1) is a fragment of the hinge and part of the disc with excellently preserved ornament of bifurcating riblets, whether or not this species is conspecific to *N. s.l. meadinga* cannot be ascertained. Moreover, the Coniacian species from *Voluta*-1 is approximately five million years younger than the *N. s.l. meadinga*, but *N. s.l. meadinga* may well be a long-ranging nuculid, comparable to other known very long-ranging members of this conservative family.

Only a handful of Late Cretaceous nuculids have been recognised from the Australian continent, with the *Voluta*-1 species being the youngest Cretaceous form recorded. Until now, no Turonian to Maastrichtian taxa have been described. Stilwell and Henderson (2002, p. 452) noted that *Nucula s.l. meadinga* belongs to a small group of species of uncertain affinities with characteristic subtrigonally ovate outlines and a strong umbonal ridge, with sculpture of approximately 80 closely spaced, irregularly undulating commarginal riblets that bifurcate ventrally on the posterior portion of the disc. A probable congener is the Maastrichtian New Zealand species from Northland, *N. s.l. n. sp.* of Stilwell (1994, p. 250–253, pl. 1, figs. 3, 5, 7, 9–11), which has a slightly more subtrigonal outline and marked radial ornamentation that produces a more cancellate appearance on the posterior portion of the shell. No internal details are present in any of the material.

Superfamily: Nuculanoidea H. & A. Adams, 1858

Family: Nuculanidae H. & A. Adams, 1858

Subfamily: Nuculaninae H. & A. Adams, 1858

Genus *Nuculana* Link, 1807

Nuculana Link, 1807, p. 155.

Type species: *Arca rostrate* Chemnitz, 1774 (= *Arca pernula*) Müller, 1771 (by original designation).

Nuculana? sp. cf. *N. bathurstensis* Stilwell and Henderson, 2002 Fig. 3K

Cf. Nuculana bathurstensis Stilwell and Henderson, 2002, p. 452–453, fig. 2.3, 2.5.

Dimensions: MV-P314016 length 8.5 mm, height 3.5 mm incomplete, *Voluta*-1, 13.7.

Material: One incomplete specimen with vestiges of preserved ornamentation.

Discussion: This poorly known species is represented by a partial specimen with closely spaced primary commarginal riblets and interstitial threads that appear slightly stronger on the central part of the disc. Sculpture that is not too far removed from slightly older species such as *Nuculana bathurstensis* Stilwell and Henderson, 2002 (pp. 452–453, fig. 2.3, 2.5) from the mid-Cenomanian of Bathurst Island. Many nuculanid species-level taxa have been recognised from the Cretaceous of Australia, but nearly all are represented by articulated specimens with no observable internal details, or disarticulated poorly preserved single valves, similar to the Belfast Mudstone specimen.

Genus *Mesosaccella* Chavan, 1947

Mesosaccella Chavan, 1947, p. 197.

Type species: *Nucula foersteri* Müller, 1847 (by original designation).

Remarks: Puri in Moore (Ed.) (1969, p. N237) listed the age and geographic range of *Mesosaccella* Chavan, 1947, as Cretaceous of Europe, but this has been expanded to include the Middle Jurassic of South Island, New Zealand by Gardner and Campbell (1997, p. 487). In the Eromanga Basin of Australia, *Mesosaccella* has been recognised in the upper Aptian-lower upper Albian (Stilwell & Crampton in Henderson et al., 2000, p. 400), and its presence in the Belfast Mudstone extends its range into the Upper Cretaceous.

Mesosaccella sp. nov.?

Fig. 3E, H

Description: Shell small, but average for genus (up to 4 mm long), sublenticular to subovate, elongate, with weakly developed rostrum, thin, polished on well-preserved specimens; shell moderately to greatly inflated, much more so in central part of disc; umbones very small, opisthogyrous, only scarcely raised above dorsal margin; dorsal margin details wanting in available material so unknown whether or escutcheon and lunule present, but antero- and postero-dorsal margins moderately declivous; anterior margin convex; posterior margin more narrowly rounded; ventral margin broadly convex; only remnants of minute hinge teeth present; very regular, commarginal sculpture dominates ornamentation of shell with >50 closely and evenly spaced commarginal riblets or threads (approximately 10 riblets per 1 mm) separated by relatively deep furrows, mostly equal in strength from umbones to ventral margin, and only scarcely more bunched right at ventral margin; inner ventral margin smooth.

Dimensions: MV-P314017 length 3.0 mm, height 2.0 mm, Drik Drik-1 Top 3279–3284; MV-P314018 length 3.2 mm, height 1.5 mm, and partial hinge probably from the same individual length 2.0 mm, Drik Drik-1 Top 3279–3284; MV-P314019 length 3.5 mm, height 3.5 mm, showing some right valve internal details, *Voluta*-1, 13.3; MV-P314020 length 3.0 mm, height 2.0 mm, crushed specimen, revealing some external ornament, *Voluta*-1, 13.6.

Material: Four mostly crushed specimens with only partial sculpture present.

Discussion: At a length of no more than 3.5 mm this minute nuculanid species, attributed to the Late Jurassic to mid- Late Cretaceous genus *Mesosaccella*, is amongst the smallest of the Cretaceous Australian bivalves recorded. *Mesosaccella* sp. nov.? is comparable in size to the Cretaceous type species, *M. foersteri* (Müller, 1847) (see Puri in Moore, 1969, p. N237, Fig. A7, 6a–b), but is more lenticular in outline, compared with the subovate Belfast Mudstone species. The ornamentation of closely spaced commarginal riblets or threads is comparable in both species. As the available material is either crushed or eroded, this species is best left in open nomenclature, but is mostly likely to be new.

Order: Mytiloidea Férussac, 1822
 Superfamily: Pinnoidea Leach, 1819
 Family: Pinnidae Leach, 1819
 Genus *Pinna* Linnaeus, 1758

Pinna Linnaeus, 1758, p. 707.

Type species: Pinna rudis Linnaeus, 1758. (by subsequent designation, Children, 1823)

Pinna? sp.
 Fig. 3G

Pinna? sp., Stilwell in Gallagher et al., 2005, Tab. 1, p. 329.

Material: MV-P314021 fragment length 11.0 mm, Voluta-1, 13.1.

Discussion: The thin-walled shell and bifurcated nature of radial ribs of this small aragonitic bivalve fragment is consistent with the morphology of this wedge-shaped late Mesozoic to Recent group, but as it is merely a fragment, no further identification is possible. There is only one other record of a Cretaceous Australian species of *Pinna* from the Aptian? of the Eromanga Basin (Stilwell & Crampton in Henderson et al., 2000, p. 400).

Order: Pterioidea Newell, 1965
 Suborder: Pteriina Newell, 1965
 Superfamily: Inoceramoidea Giebel, 1852 [?=Ambonychioidea Miller, 1877]
 Family: Inoceramidae Giebel, 1852
 Genus *Tethyoceramus* Sornay, 1980

Tethyoceramus Sornay, 1980, p. 11.

Type species: Inoceramus (Tethyoceramus) basseae Sornay, 1980 (by original designation).

Tethyoceramus madagascariensis (Heinz, 1933)
 Fig. 3A–D, I

1933 *Stenoceramus (Stenoceramus) madagascariensis* Heinz; Heinz, p. 252, pl. 20, fig. 2 [?pars?non pl. 19, fig.2] (see Walaszczyk et al., 2004).

1933 *Cymatoceramus (Cymatoceramus) cf. koeneni* (Müller); Heinz, p. 253, pl. 19, fig. 3.

2004 *Tethyoceramus madagascariensis* Heinz, 1933; Walaszczyk et al., p. 559, 562, figs. 13, 14A, B, D, F (see extensive list of synonymies not repeated herein from 1957–1998).

2004 *Cremnoceras bicorrugatus bicorrugatus?* (Marwick, 1926); Gallagher et al., 2005, Table 1, p. 329.

Dimensions: MV-P314022 height of disc fragment 44.5 mm, length 39.0 mm, Voluta-1, 16.5; MV-P315023 length 18.0 mm, height 28.0 mm (crushed specimen), Voluta-1, 13.9; MV-P314024 height of small disc fragment 18.5 mm, Voluta-1, 16.3; MV-P314025 juvenile specimen length 9.0 mm, height 10.5 mm, Drik Drik-1, 3279–3284.

Cores and depths: 13.9, 16.1, 16.2, 16.4, 16.5, Drik Drik-1 (3279–3284 Top).

Material: Several fragments of adult and juvenile specimens; only one nearly complete specimen from Drik Drik-1 with several other broken individuals in the same core horizon.

Discussion: Inoceramid bivalve disc fragments and outer prismatic layer pieces of the ostracum abound in the Belfast Mudstone

cores, and are the most common macrofossil encountered. Small- to medium-sized, inequivalve, inequilateral, weakly opisthocline fragments of disc sections of with regular, broad, commarginal folds and costae/rugae, separated by narrow flat furrows, and nearly complete immature, subquadrate-subovate individuals compare well with the genus *Tethyoceramus* Sornay, 1980, specifically with coeval figured specimens of *T. madagascariensis* (see Crampton, 1996, for extensive discussion and many figures, fig. 35, pl. 16I–O, 17E; Walaszczyk et al., 2004, p. 559, 562, fig. 13, 14A, B, D, F, and references therein), from the lowermost part of the lower Coniacian of Madagascar, New Zealand?, Antarctica?, and Patagonia?. Although there is now no question that a closely related species from New Zealand is conspecific with a coeval species from Antarctica based on close inspection of a wide range of material (originally thought to be allied with *T. madagascariensis* by Crampton, 1996), whether or not they are conspecific with *T. madagascariensis* or *Inoceramus nukeus* Wellman, 1959 (see discussion in Crampton, 1996; Speden & Keyes, 1981; Crampton et al., 2001), remains to be determined (J. Crampton, pers. commun. 2007). *Inoceramus andinus* Wilckens, 1907, from Patagonia has also been assigned to *T. madagascariensis* (Crampton, 1996), based on study of collections in Santiago, Chile. As consistent with *T. madagascariensis*, the shell fragments of the Belfast Mudstone inoceramids reveal a suboval, weakly inflated shell with rugae that sub-regularly increase in spacing away from the umbo region, and raised growth lines. The material available from the Belfast cores is insufficiently preserved to ascertain the presence or absence of Anwachsmarken at the margins of rugae, quite characteristic of species of *Tethyoceramus* and *Cremnoceras*. Anwachsmarken represent the characteristic growth lines or crests of rugae so typical of cremnoceramid bivalves (Walaszczyk et al., 2004).

As would be expected in core samples with a diameter of only 74 mm, either immature individuals or pieces of adults of inoceramid bivalves would be available for study, especially given that the largest complete specimens recorded of *T. madagascariensis* are almost without exception <90 mm high and <60 mm long (Walaszczyk et al., 2004, p. 570, Table 1). The marked intraspecific variation of *T. madagascariensis* with respect to “degree of inequivalveness, valve inflation and outline (particularly of the RV), and the ornament” (Walaszczyk et al., 2004, p. 562), renders differentiation of morphologically similar (superficially or otherwise) and other Austral Coniacian taxa such as the New Zealand species, *Inoceramus? nukeus* Wellman, 1959, and small species of *Cremnoceras* Cox, 1969 (see Walaszczyk, 1992) from the early Coniacian of Europe (Crampton, 1996), very much a challenge. Until more research is completed on this significant group, we follow the use of *T. madagascariensis* in the broad sense of Crampton (1996).

Subclass: Palaeoheterodonta Newell, 1965

Order: Trigonoida Dall, 1889

Superfamily: Trigonioidea Lamarck, 1819

Family: Trigoniidae Lamarck, 1819

Subfamily: Myrophorellinae Kobayashi, 1954

Genus *Oistotrigonia* Cox, 1952

Oistotrigonia Cox, 1952, p. 60.

Type species: Trigonia spinosa Parkinson, 1811 (by original designation).

Remarks: *Oistotrigonia* is one of the longest ranging trigonid genera that ranged from the Upper Jurassic of Japan and possibly northwestern India, but became restricted to the Austral Realm during the latter part of the Cretaceous (Fleming, 1987). Trigoniid bivalve diversity decreased substantially from the Early to Late

Cretaceous in Australia, with more than 11 genus- and subgenus-level taxa recorded from the 'Neocomian' to Albian and only 4 from the Cenomanian to Maastrichtian (see Skwarko, 1963; Stilwell & Crampton in Henderson et al., 2000, p. 400). Oistotrigonia represents one of several morphologically plastic and cosmopolitan forms that were widespread in the Cretaceous of the Southern Hemisphere, with occurrences in southern India, Malagasy, Australia, New Guinea, New Zealand, New Caledonia, and Antarctica (see review by Darragh and Kendrick, 1991, p. 84–85). In many species, the oblique or transverse ribs of the area correspond to one on the flank. This rib configuration creates a chevron-like sculpture pattern, but in most Austral forms, including the Australian taxa, the flank ribs join at the variable strong to weak carina at a low angle. As there are fewer ribs, only a couple meet their partners on the flank of the disc (Fleming, 1987).

Oistotrigonia austronana sp. nov.

Fig. 3J, L, M–N

Etymology: New species named for its Australian occurrence and from the Latin *nanus* meaning 'dwarf', for its minute size, compared with other recorded members of the genus.

Diagnosis: Very small Oistotrigonia (available specimens no more than 7 mm length), almost circular and scarcely ovate, reflecting rounded and only scarcely declivous antero- and posterodorsal margins; area makes up more than half of valve; oblique and flank costae wide, irregular, but weakly tuberculate, with weak commarginal threads; inner and outer margins strongly crenulate, reflecting broad nature of radial costae.

Description: Shell minute for genus (ca. 7 mm long maximum), more subcircular than subovate, slightly inequilateral, moderate to strongly convex and inflated, moderately thick for genus; umbones small, positioned slightly in front of midpoint of length, projecting scarcely above the dorsal margin, creating a more obtuse angle compared with type, *O. spinosa*; anterodorsal and posterodorsal margins sloping gently, merging with well-rounded, steep anterior and posterior margins; ventral margin moderately convex; marginal carina not well-preserved in material, but seemingly indistinct; area wide, weakly defined, comprising more than half of valve; schizodont hinge of right valve with strongly bifid teeth, remnants of 2a moderately long for minute size, subparallel with anterodorsal margin, but slightly steeper, 2b apparently relatively robust and large, crenulated remnant of PII long, nearly flush with posterodorsal margin; anterior adductor scar strongly impressed, smaller than posterior adductor, which is only partially preserved; ornamentation mostly absent from disc, but margins with broad, irregular, obliquely positioned, weakly costate ribs and poorly developed nodes, and weak commarginal riblets; external ventral margin crenulated, reflecting oblique and flank costae; inner margins with well-developed irregular crenulations.

Dimensions: Holotype MV-P314026, juvenile specimen, length 3.2 mm, height 3.4 mm (Drik Drik-1, 3279–3284 Top); Paratype MV-P314027, opened paired valves, length ca. 6.1 mm, height 5.5 mm (partially decorticated), Pt. Campbell #1, Core 17, 4757–4758; Paratype MV-P314028, fragments of same specimen?, length of larger fragment 6.0 mm, and smaller 5.0 mm, illustrating crenulated nature of ventral margin (Drik Drik -1, 3279–3284, Top).

Material: Holotype MV-P314026; Paratypes MV-P314027–314028, and many other small fragments.

Discussion: *Oistotrigonia austronana* sp. nov. is the only described myophorelline trigoniid described from the Upper Cretaceous of Australia. Previously, only *Linotrigonia* (*Oistotrigonia*) sp. of Darragh and Kendrick (1991, p. 84–85, Fig. 23 F, G) from the Maastrichtian Miria Formation of Carnarvon Basin, north-western Australia, was noted from two worn, articulated

specimens with no internal details available. These two species are probably closely allied, but *O. austronana* sp. nov. is half the size of *O. sp.* and the transverse costae are more robust and broader in the Turonian species, relatively to its small size. The only other Austral Upper Cretaceous species comparable to *O. austronana* sp. nov. is *O. piripauana* Fleming, 1987 (p. 51–52, pl. 7, figs. 23–26), from the Santonian-Campanian of South Island, New Zealand (see also Stilwell, 1994, Pl. 17, Figs. 7–8, 13, 17), which varies from sub-circular to sub-ovate with scarcely a submedian carina, but is twice the size of the new Belfast Mudstone species. Interestingly, the Australian forms are much more circular, compared with most other congeneric taxa, which are sub-ovate or elliptical to trigonal (e.g., *Oistotrigonia pygoscelium* (Wilckens, 1910), from the Maastrichtian of Antarctica; *O. lima* (Glaessner, 1958) from the Cenomanian? of New Guinea). The available material of *O. austronana* sp. nov. is mostly decorticated, but enough information is present on the specimens to differentiate it easily from other Late Cretaceous and older taxa.

Class: Gastropoda Cuvier, 1797

Subclass: Prosobranchia Milne-Edwards, 1848

Order: Caenogastropoda Cox, 1959

Suborder: Neotaenioglossa Haller, 1892

Superfamily: Cerithioidea Fleming, 1822

Cerithioidean, family and genus indeterminate

Fig. 4F

Dimensions: MV-P314029 height 4.5 mm, diameter of last whorl 1.3 mm (mostly decorticated shell), Voluta-1, 13.3.

Material: One eroded specimen.

Discussion: The very small shell, elevated, slender, turritellid to turriculate spire are consistent with the superfamily Cerithioidea, of which there are several genera represented in the Upper Cretaceous of Australia. The possible candidates for the Belfast Mudstone species include procerithiids *Cirsoerithium* and *Cimolithium*, but the specimen at hand is too eroded to distinguish between genera. Only vestiges of axial ornament with tubercles is present on MV-P314029, not far removed from the sculpture of low axial folds of the Maastrichtian gastropod, Cerithioidean, family and genus undetermined, species B, of Darragh & Kendrick (1994, p. 32–33, fig. 5G) from the Miria Formation of Western Australia.

Superfamily: Stromboidea Rafinesque, 1815

Family: Aporrhaidae Mörch, 1852

Subfamily Arrhaginae Popenoe, 1983

Genus *Latiala* Sohl, 1960

Latiala Sohl, 1960, p. 101.

Type species: *Anchura lobata* Wade, 1926 (by original designation)

Latiala sp. cf. *L. mountnorrisi* (Skwarko, 1983)

Fig. 4C

?*Arrhoges* (*Latiala*) *mountnorrisi* Skwarko, 1983, p. 76, 77, pl. 1, figs. 1–3, 5, 6, 8.

Cf. *Latiala mountnorrisi* Skwarko, Stilwell & Henderson, 2002, p. 459, 461, figs. 4.5–4.7, 4.9–4.17.

Latiala sp. cf. *L. mountnorrisi* (Skwarko, 1983), Stilwell in Gallagher et al., 2005, Tab. 1, p. 329.

Figured specimen: MV-P314030, Voluta-1, 13.8.

Dimensions: MV-P314030 height of incomplete specimen 5.5 mm.

Discussion: This Coniacian species of *Latiala* is the youngest recorded member of the Cretaceous genus from Australia. *Latiala* has been identified previously from the Cenomanian of Mountnorris Bay in Arnhem Land (Skwarko, 1983) and Bathurst Island (Stilwell and Henderson, 2002) in northern Australia. The only other Austral occurrence is from the probable Maastrichtian species, *Alaria suteri* Trechmann, 1917 (p. 304, pl. 19, fig. 5), from the 'Selwyn Rapid Beds' of South Island, New Zealand (Stilwell, 1994, p. 616–617, pl. 39, figs. 1–2). The incomplete Voluta-1 specimen of six preserved whorls is characterised in having a weakly reticulate pattern of closely spaced spiral and almost orthocone threads on the otherwise smooth protoconch, and markedly sculptured teleoconch whorls that commence abruptly by the third to fourth whorls, consistent with *L. mountnorrisi*. As the specimen is imperfectly preserved, apart from beautifully preserved ornament, the species is left in open nomenclature; however, if proved in the future to be conspecific, this would represent a significant geologic range extension from the mid-Cenomanian into the Coniacian.

Subclass: Opisthobranchia Milne-Edwards, 1848
 Order: Cephalospidea Fischer, 1883
 Suborder: Acteonidea d'Orbigny, 1842
 Family: Ringiculidae Philippi, 1853

Ringiculidae? gen. et sp. indet.
 Fig. 4H, K

Figured specimen: MV-P314031, Port Campbell 2, Core 3, 5910–5919; MV-P314081, Belfast 4, 4649–4655.

Material: MV-P315031 diameter of last whorl fragment 3.0 mm; MV-P314081 diameter of fragment 1.5 mm.

Discussion: Kenley (1959, p. 55) was the first to note the presence of ringiculid gastropods in the Belfast No. 4 Bore at Port Fairy, having identified a 'fairly common' small member of the family similar to *Eriptycha punamutica* Wilckens, 1922, from the Santonian? to Maastrichtian of New Zealand. Species of *Avellana*, *Biplica*, and *Cinulia* have been recognised from the Aptian to Maastrichtian in Australia (Stilwell & Crampton in Henderson et al., 2000, p. 401). The only fragment available for study represents an internal, nearly translucent, portion of the last whorl from the Port Campbell 2 Core 3 section. This opisthobranch piece is relatively capacious with closely spaced, punctate spiral threads, consistent with ringiculids such as *E. punamutica* and *Biplica antichthona* Stilwell and Henderson, 2002 (p. 466, Fig. 6.10, 6.11) from the mid-Cenomanian of Bathurst Island, northern Australia. The broken shell reveals at the upper edge of the last whorl that the next older whorl is much smaller, and thus, a dramatic increase in inflation from the penultimate to the last whorl, indicating that it has a relatively low spire, consistent with this group. For the time being, this species is tentatively assigned to the Ringiculidae, but Acteonidae cannot be entirely discounted.

Class: Cephalopoda Cuvier, 1797
 Subclass: Nautiloidea Cuvier, 1797
 Order: Nautiloidea Agassiz, 1847
 Family: Nautilidae de Blainville, 1825
 Genus: *Eutrephoceras* Hyatt, 1894

Eutrephoceras Hyatt, 1894, p. 555.

Type species: *Nautilus dekayi* Morton, 1834 (by original designation).

Eutrephoceras? sp.
 Fig. 4 D, G

Dimensions: MV-P314032 diameter of fragment 18.5 mm, width 11.0 mm, Voluta-1, 13.4.

Discussion: Henderson et al. (2000, p. 360) stated that the Cretaceous record of Australasian nautiloid cephalopods is in general poor, and the Australian occurrences of the group are likewise patchy with a single Lower Cretaceous (Albian) species, *Eutrephoceras hendersoni* (Jack and Etheridge, 1892) recorded from Queensland and South Australia (see Ludbrook, 1966; Hill et al., Eds., 1968; Day, 1969) and a species of *Cimomia* from the uppermost Cretaceous (Maastrichtian) of Western Australia (Glenister et al., 1956). A single small fragment of a probable nautiloid from Voluta-1 (13.4) may represent a species of *Eutrephoceras*, as it is quite globose and smooth, apart from fine growth pauses, with no detectable ornament and slightly sinuous sutures. This species of uncertain affinity represents only the second occurrence of nautiloids in the Late Cretaceous of Australia.

Subclass: Ammonoidea Zittel, 1884
 Order: Ammonitida Zittel, 1884
 Suborder: Ammonitina Zittel, 1889
 Superfamily: Haploceratoidea Zittel, 1884
 Family: Binneyitidae Reeside, 1927
 Genus *Borissiakoceras* Arkhangelsky, 1916

Borissiakoceras Arkhangelsky, 1916, p. 55.

Discussion: *Borissiakoceras* represents a group of micromorph Late Cretaceous ammonites that is characteristically platycone with much reduced sutures, and in the literature has confused with the superficially similar Early Cretaceous aconeceratid genera *Aconecerat* and *Sanmartinoceras*. *Borissiakoceras* is the only binneyitid with confirmed dimorphism. The genus extends from the middle Cenomanian to the lower Coniacian, and the only known Austral occurrences are in New Zealand, Zululand and Australia (see Kennedy & Klinger, 1979; Skwarko, 1983; this work). Australian occurrences are in the middle Cenomanian of Mountnorris Bay in Arnhem Land, and the Coniacian of the Belfast Mudstone.

Type species: *Borissiakoceras mirabile* Arkhangelsky, 1916 (by original designation).

Borissiakoceras sp. nov.
 Fig. 4A–B

Engonoceratidae, gen. et sp. nov.?, Henderson, 1973, p. 106, fig. 14, no. 8, fig. 15.

Description: Small- to medium-sized (diameter 28 mm) *Borissiakoceras* with compressed, moderately evolute platycone shell; umbilicus small, about 12.5% of the diameter of shell; ornamentation feeble, flanks mostly smooth with indistinct, biconcave growth striae and well spaced falcoid ribs (probably macroconch–male?), sutures simple with narrow, bifid lobes, and indistinct bifid or trifold? saddles; no evidence of keel.

Dimensions: MV-P314033 diameter of shell 28.0 mm, Voluta-1, 13.2; MV-P314034 diameter of distorted, crushed specimen 9.0 mm, Voluta-1, 13.5.

Material: One moderately well-preserved specimen with original aragonitic nacre preserved, and another smaller crushed individual.

Discussion: The Belfast Mudstone species, represented by one nicely preserved specimen with original mother of pearl and other crushed individual, is probably not conspecific with *Borissiakoceras* sp. of Skwarko (1983, p. 78, pl. 1, fig. 11) from the middle Cenomanian of Arnhem Land, as the Belfast Mudstone ammonite is twice the size and more circular in outline with more developed falcoid ribs. The rostrum, imperfectly preserved in *Borissiakoceras*

sp. of *Skwarko*, is moderately developed in *B. sp. nov.* Both species are probably new, but have been left in open nomenclature due to paucity of appropriately preserved material. Another morphologically similar species is *Sanmartinoceras?* sp. of *Skwarko* (1967, p. 23, pl. 4, fig. 5) from the Aptian? of the Gibson Desert, central Western Australia, but the keel of this species is seemingly more developed, as well as the falcoid sculpture, compared with *B. sp. nov.?* *Borissiakoceras* sp. of Kennedy & Klinger (1979, p. 116, figs 14D–F, 15A–E) from the middle Cenomanian of Zululand is much smaller than either Australian species with a slightly larger umbilicus relative to the diameter of the shells. Kennedy and Klinger (1979, p. 116) stated that Henderson's (1973) figured, incomplete specimen of a small ammonite that he ascribed to Engonoceratidae gen. et sp. nov. "belongs here [*Borissiakoceras*]", but they gave no further analysis. Comparison of the Belfast Mudstone species and the New Zealand form from the Lookout Formation tuffs of Lee Brook, Awatere Valley of Ngaterian to Arowhanan? age (Cenomanian-Turonian?; *Scaphites equalis coverhamensis* Henderson, 1973, ammonite Assemblage Zone), indicates a very close relationship, but probably not conspecific, given the age difference. Both ammonites have a very small (in the New Zealand specimen, VC 545a-c, S35/705, diameter 11.0 mm, but incomplete), compressed, discoidal shell, narrowly umbilicate, weak ornament restricted to the flanks, and simple sutures. As with the Belfast Mudstone species, the ornamentation comprises well-spaced radial ridges that are restricted to the mid-flanks of the shell. Although the number of specimens is limited, a distinction, apart from size due to incomplete material, between the New Zealand and Australian specimens, cannot be made. As such, they are definitely congeneric, but probably not conspecific. More material is needed to firmly confirm relationships.

Phylum: Cnidaria Hatschek, 1888
 Order: Scleractinia Bourne, 1900
 Suborder: Caryophylliina Vaughn & Wells, 1943
 Superfamily: Caryophylliioidea Gray, 1847
 Family: Caryophylliidae Gray, 1847
 Subfamily: Caryophylliidae Gray, 1847

Genus *Trochocyathus* Milne-Edwards and Haime, 1848

Type species: Turbinolia mitrata Goldfuss, 1827 (by subsequent designation, Milne-Edwards and Haime, 1850).

Subgenus *Platycyathus* de Fromentel, 1863

Type species: Trochocyathus terquemi Milne-Edwards and Haime, 1857 (by subsequent designation, Wells, 1933).

Trochocyathus (Platycyathus?) sp.
 Fig. 4E, J

Dimensions: MV-P314035 height 3.0 mm almost complete, diameter of calice about 3.7 mm, *Voluta-1*, 13.11; MV-P314036 length of fragment 8.5 mm, *Voluta-1*, 10.1.

Material: One small fragmented specimen and another piece.

Discussion: Cretaceous corals are poorly represented in Australia, especially in the Upper Cretaceous. The small Belfast Mudstone coral is a solitary, free-living, ahermatypic form that is short, thin and subturbinate with a strongly contracted base and wide calice. The largest fragment is ca. 8.5 mm long. A similar species is recorded from the Paleocene/Eocene boundary of the Dilwyn Formation, Otway Basin, Victoria, which was described by Stilwell (2003, p. 270, Fig. 7K–M) as *Trochocyathus (Platycyathus)* sp. nov.?, this species has also beaded, simple trabeculae comparable to the Belfast Mudstone

species. Species of *Trochocyathus* today range into deep water environments. Given the fragmentary nature of the material at hand, only a tentative assessment is warranted.

4. Biostratigraphic significance

The first report here of the inoceramid bivalve, *Tethyoceramus madagascariensis* (Heinz, 1933), an index fossil for the Madagascar Late Cretaceous (Manasoa section, Onilahy Rivre, SW part of the country), constrains the age of the Belfast Mudstone to the early Coniacian (*Tethyoceramus madagascariensis* Subzone of Walaszczyk et al., 2004, which according to Gradstein et al. (2004) time-scale is ca. 89–88 Ma). The occurrence of the group in Australia expands the geographic distribution of the genus. Previously, *T. madagascariensis* was reported also from W–SW Africa and possibly from New Zealand, Antarctica and Patagonia, but the latter records are still contentious and more work is required to resolve the complex nature of the morphologic plasticity of closely related forms. One of these taxa, *Inoceramus? nukeus*, from New Zealand may be slightly younger at early? to middle? early Coniacian, and according to Walaszczyk et al. (2004), *I.? nukeus* is almost certainly not conspecific with *T. madagascariensis*. '*Tethyoceramus madagascariensis*' is probably early? to middle Coniacian in New Zealand (J. Crampton, pers. commun., 2008). Recent work by Walaszczyk et al. (2004) indicates that the inoceramids from the uppermost Turonian and Coniacian of Madagascar are nearly identical to taxa from Zululand, but different to the Euramerica assemblage. Thus, a close link and affinity with faunas of the Indo-Pacific region is probable. Of the six successive inoceramid zones identified in the Manasoa section, *T. madagascariensis* represents the oldest zone of the Coniacian, and is marked by the lowest occurrence of this index taxon and the top of the zone by the lower occurrence of *T. basseae*. Adding strength to this age range is the identification of the ammonite *Borissiakoceras* sp. nov. in 13.12 and 13.15, which is congeneric and possibly conspecific (but a bit younger) with a figured, Ngaterian to Arowhanan? Stage specimen from the Awatere Valley in New Zealand (Henderson, 1973). Adding further corroboration to this age assignment, all mollusc taxa named above at genus-level (e.g., *Oistrotrogonia*, *Latiala*, and others) support a Turonian-Coniacian age with several species revealing similarities to other Australian Late Cretaceous species.

The presence of the aporrhaid gastropod, *Latiala* sp. cf. *L. mountrorisi* (Skwarko, 1983), in the Belfast Mudstone is approximately coincident to a global, species-level increase in diversity of the group during the Late Cretaceous (Stilwell and Henderson, 2002), especially during the Coniacian-Santonian (see Kiel and Bandel, 2002). Other genus-level taxa in the Belfast Mudstone (e.g. *Messosacella*, *Nucula s.l.*, *Nuclana*) belong to long-ranging Cretaceous forms and are not particularly age diagnostic.

Microfossil data support the Coniacian age of cores 13 and 16 (Gallagher et al., 2005), represented by diverse, agglutinated-dominated foraminiferal assemblages, and relatively uncommon planktonic foraminifera, which forms usually about 1–10% of the total fauna. It is believed that the low diversity and percentage of planktonic foraminifera in the Belfast Mudstone in part reflects the relatively high sedimentation rates estimated for the unit with also associated abundance of mostly terrestrially derived organic carbon in *Voluta-1* further related to increased sedimentation (Gallagher et al., 2005).

5. Palaeoecology

Few macrofaunal assemblages, apart from the Belfast Mudstone and the Moonkinu Formation (mid-Cenomanian) of Bathurst Island (see Stilwell and Henderson, 2002), are well-preserved with jewel-

like preservation of original composition of shells and little to no diagenetic alteration. The Belfast Mudstone represents probably a low-energy hydrodynamic regime in a quiescent, mid-to outer(?) shelf environment and the broken nature of some observed fossils may indicate a degree of post mortem disturbance from associated ichnofauna rather than swift current activity (Gallagher et al., 2005; this work). Fossils are generally scattered in the cores, sparse and of low species-level diversity. Rare scleractinian corals in the Belfast Mudstone attributed tentatively to the Cretaceous to Recent subgenus, *Trochocyathus* (*Platyocyathus?*), are significant in that they most likely flourished as ahermatypic, solitary forms in deeper waters in muddy or fine-grained substrates. Other fossils identified in the cores comprise poorly preserved, crushed, irregular echinoids and serpulid worms, but these taxa do not yield additional specific information on the palaeoenvironments preserved in the cores. Although fish teeth, bone fragments and scales are present in the cores, they do not provide any detailed palaeoecologic information.

The dominant macrofossil recorded in the Belfast Mudstone is the inoceramid bivalve, *T. madagascariensis*, preserved in the cores as partial discs of adults or immature individuals and prismatic fragments, reflecting both taphonomic processes and also the restricted nature of available core. Most specimens of this species reveal the inner ostracum with a few fragments preserving a part of the outer prismatic ostracum. It is likely that another younger inoceramid species represents the younger Coniacian and Santonian inoceramid fragments in the cores, but identifiable remains are not present. *Tethyoceramus madagascariensis* was probably an epifaunal form, doubtfully semi-infaunal (J. Crampton, pers. commun. 2008), in the soft muddy substrates of a mid- to outer shelf environment (see Crampton, 1996). It probably lived with its expanded, flattened anterior face on the substrate (i.e., as an edgewise recliner in the descriptive inoceramid language of Crampton (1996). Alternatively, it may have had a life habit as a 'mudsticker' with the dorsal part of the shell buried in the sediment, or thus as an edgewise or 'snowshoe recliner' lying on the substrate. As *T. madagascariensis* exhibits marked rugae and an expanded disc, this would have increased stability and buoyancy by increasing the area of shell in contact with the substrate (*sensu* Crampton, 1996). Most inoceramids probably lived on or partially within quite soft sediments that would exclude many other invertebrates, both epi- and infaunal. The presence of this species in dark, organic-rich facies is consistent with other records of the group that suggest that they lived in dysaerobic environments that consisted of depauperate assemblages of epibenthic organisms apart from the inoceramids that flourished (see Crampton, 1996, and references therein). In terms of total organic carbon, values in the Belfast Mudstone are high with occasional peaks in Biofacies B and C greater than 3% (where Gallagher et al. (2005) used a scale of 'very high organic carbon = $\geq 2\%$ TOC). In some deposits, inoceramid bivalves are the sole macrofossil group present. Indeed, few other taxa are recorded in the cores (see Table 2) and all of the bivalves and gastropods are infaunal and/or semi-infaunal suspension and deposit feeders that preferred fine-grained substrates.

The combined information of macro- and microfossils, facies analyses, and geochemical data indicate that there was an enhancement of dysoxic conditions during the Coniacian-Santonian that was associated with the migration of the oxygen minimum zone across the shelf break (Gallagher et al., 2005). These conditions propagated from upper bathyal depths to the shallow shelf and into the prodelta environments, as evidenced by fossils and sediments. Specifically, this dysoxic interval correlates with Ocean Anoxic Event 3, which was the last before the dissipation of the warm Cretaceous Greenhouse event and the inception of the modern conditions of the

oceanic system that we see today (Gallagher et al., 2005). The present work and also that of Gallagher et al. (2005) corroborate the idea that dysoxic conditions were more widespread than thought previously and were present in high latitude regions of the Southern Hemisphere such as warm inland seas of the Otway in Victoria, and not just confined to low latitude areas.

6. Conclusions

The Otway Basin represents one of the best Upper Cretaceous marine sections along the southern margin of Australia, and active hydrocarbon exploration in the Upper Cretaceous Sherbrook Group (including the uppermost Turonian to Santonian Belfast Mudstone) has resulted in the discovery of economic gas reserves. Research on the Otway Basin has led to considerable amounts of available seismic and well data, which have aided interpretations of facies and palaeoenvironments. This paper focuses on the Belfast Mudstone, which contains the best-documented Coniacian macro- and microfaunal assemblages from Australia. Described and figured herein are 12 species of macroinvertebrates (bivalves, gastropods, cephalopods, echinoids, and cnidarians). Both macro- and microfossils constrain the age of core 16 to the early part of the Coniacian Stage ca. 89–88 Ma, and core 13 is slightly younger and late? Coniacian in age. The presence of *Tethyoceramus madagascariensis* (Heinz, 1933), a zonal fossil for the Coniacian of Madagascar, in the Belfast Mudstone cores 16 and 13?, corroborates the age of this unit. The sheer abundance of inoceramid fragments in the cores and associated low diversity of other macroinvertebrates attests to the high-latitude dysaerobic environments in organic-rich facies in the Otway Basin region of Australia during the mid-Cretaceous Greenhouse phase.

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References

- Arkhangelsky, A.D., 1916. Les mollusques du Crétacé Supérieur du Turkestan. Trudy Geologicheskogo Komiteta, Novaya Seriya [in Russian]. n.s. 152, 1–57.
- Chavan, A., 1947. L'évolution des faunes marines de mollusques dans le Nord-Ouest de l'Europe, de la fin du Crétacé à celle de l'Eocène. Société Géologique de France Bulletin 5 (16), 193–212.
- For dates of volumes see Chemnitz, J.H., 1769–1795. In: Martini, F.H., Chemnitz, W.A., Chemnitz, J.H. (Eds.), Neues systematisches Conchylien-Cabinet, = c. Nürnberg, 11 vols., Volumes 1–2, 1769–1777 by Martini, Volumes 4–11, 1780–1795 by Chemnitz, Volumes 1–5, Univalves, Volumes 6–11, Bivalves and Supplement. Newton, R.B., 1891, p. 316 Systematic List of the Frederick E. Edwards collection of British Oligocene and Eocene Mollusca in the British Museum (Natural History). British Museum (Natural History), London, pp. 365.
- Children, J.G., 1822–1824. Lamarck's genera of shells translated from the French with plates from original drawings by Miss Anna Children. Quarterly Journal of Science 14, 64–86 (1822), 14, 298–322 (1823), 15, 23–52 (1823), 15, 216–258 (1823), 16, 49–79 (1823), 16, 241–264 (1824).
- Cox, L.R., 1952. Notes on the Trigonidae with outlines of a classification of the family. Proceedings of the Malacological Society of London 29, 45–70, pl. 3, 4.
- Cox, L.R., 1969. Family Inoceramidae Giebel, 1852. P. N314–N321. In: Moore, R.C., Teichert, C., McCormick, L., Williams, R.B. (Eds.), Treatise on Invertebrate Paleontology, Part N, Mollusca 6, Bivalvia 1, 1st ed. Geological Society of America, Inc., and University of Kansas, Boulder, Colorado.
- Crampton, J.S., 1996. Inoceramid bivalves from the Late Cretaceous of New Zealand. New Zealand Institute of Geological and Nuclear Sciences Monograph 14, 188.
- Crampton, J.S., Raine, I., Strong, P., Wilson, G., 2001. Integrated biostratigraphy of the Raukumara Series (Cenomanian-Coniacian) at Mangaotane Stream, Raukumara

- Peninsula, New Zealand. *New Zealand Journal of Geology and Geophysics* 44, 365–389.
- Darragh, T.A., Kendrick, G.W., 1991. Maastrichtian Bivalvia (excluding Inoceramidae) from the Miria Formation, Carnarvon Basin, north Western Australia. *Records of the Australian Museum Supplement* 36, 102.
- Darragh, T.A., Kendrick, G.W., 1994. Maastrichtian Scaphopoda and Gastropoda from the Miria Formation, Carnarvon Basin, northwestern Australia. *Records of the Australian Museum Supplement* 48, 76.
- Day, R.W., 1969. The lower Cretaceous of the Great Artesian Basin, 140–173. In: Campbell, K.W.S. (Ed.), *Stratigraphy and Palaeontology. Essays in honour of Dorothy Hill*. Australian National University Press, Canberra.
- Fleming, C.A., 1987. New Zealand Mesozoic bivalves of the superfamily Trigoniacea. *New Zealand Geological Survey Palaeontological Bulletin* 53, 104.
- de Fromental, L.-E.G., 1862–1887. *Zoophytes. Paléontologie française, Terrain Crétacé*. Paris vol. 8, 624.
- Gallagher, S.J., Taylor, D., Apthorpe, M., Stilwell, J.D., Boreham, C.J., Holdgate, G.R., Wallace, M.W., Quilty, P.G., 2005. Late Cretaceous dysoxia in a southern high latitude siliclastic succession, the Otway Basin, southeastern Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 223, 317–348.
- Gardner, R.N., Campbell, H.J., 1997. The bivalve genus *Grammatodon* from the Middle Jurassic of the Catlins District, South Otago, New Zealand. *New Zealand Journal of Geology and Geophysics* 40, 487–498.
- Glaessner, M.F., 1958. New Cretaceous fossils from New Guinea. *Records of the South Australian Museum* 13 (2), 199–226. pls. 24–26.
- Glenister, B.F., Miller, A.K., Furnish, W.M., 1956. Upper Cretaceous and Early Tertiary nautiloids from Western Australia. *Journal of Paleontology* 30, 492–503.
- Goldfuss, A., 1827–1844. *Petrefacta Germaniae...oder Abbildungen und Beschreibungen der Petrefacten Deutschlands und der angränzenden Länder unter Mitwirkung des Herrn Grafen Georg zu Münster. Arnz and Co., Düsseldorf*. 3 vols.
- Gradstein, F.M., Ogg, J.G., Smith, A.G., et al., 2004. *A Geological Time Scale*. Cambridge University Press, Cambridge, pp. 600.
- Henderson, R.A., Crampton, J.S., Dettmann, M.E., Douglas, J.G., Haig, D., Shafik, S., Stilwell, J.D., Thulborn, R.A., 2000. Biogeographical observations on the Cretaceous biota of Australasia. Appendix by J.D. Stilwell and J.S. Crampton. In: Floras, A.J., Wright, G.C., Young, J.A., Talent, Laurie, J.R. (Eds.), *Palaeobiogeography of Australasian Faunas. Memoir of the Australasian Association of Palaeontologists*, 23, pp. 355–404.
- Heinz, R., 1933. Inoceramen von Madagaskar und ihre Bedeutung für die Kreide-Stratigraphie. Beiträge zur Kenntnis der Inoceramen XII. *Zeitschrift der Deutschen Geologischen Gesellschaft, Berlin* 85, 241–259.
- Henderson, R.A., 1973. Clarence and Raukumara Series (Albian–?Santonian) Ammonoidea from New Zealand. *Journal of the Royal Society of New Zealand* 3 (1), 71–123. 20 figs.
- Hill, D., Playford, G., Woods, J.T. (Eds.), 1968. *Cretaceous Fossils of Queensland*. Queensland Palaeontographical Society, Brisbane, p. 35.
- Hyatt, A., 1894. Phylogeny of an acquired characteristic. *Proceedings of the American Philosophical Society* 32, 349–647.
- Jack, R.L., Etheridge Jr., R., 1892. *The Geology and Palaeontology of Queensland and New Guinea, with sixty-eight plates and a geological map of Queensland*. Dulau and Co., London. Vol. 1 (768 p.), Vol. 2 (68 pls.).
- Kenley, P.R., 1959. The occurrence of marine Cretaceous sediments in the Belfast No. 4 Bore, Port Fairy. *Mining and Geological Journal*, 55–56.
- Kennedy, W.J., Klinger, H.C., 1979. Cretaceous faunas from Zululand and Natal, South Africa. The ammonite superfamily Haplocerataceae Zittel, 1884. *Annals of the South African Museum* 77 (6), 85–121.
- Kiel, S., Bandel, K., 2002. About some aporrhaid and strombid gastropods from the Late Cretaceous. *Paläontologische Zeitschrift* 76 (1), 83–97.
- de Lamarck, J.B., 1799. *Prodrome d'une nouvelle classification des coquilles, comprenant une rédaction appropriée des caractères génériques, et l'établissement d'un grand nombre de genres nouveaux*. *Mémoires de la Société d'Histoire Naturelle de Paris* 1, 63–91.
- Link, H.F., 1806–1808. *Beschreibung der Naturalien-Sammlung der Universität zu Rostock* [see Palmer 1958, p. 310 for parts].
- Linnaeus, C., 1758. *Systema naturae, per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis*, vol. 1(6), regnum animale, 10th, reformata ed. Holmiae, Laurentii Salvii, pp. iv + 824.
- Ludbrook, N.H., 1966. Cretaceous biostratigraphy of the Great Artesian Basin in South Australia. *Bulletin of the Geological Survey of South Australia* 40, 223.
- Moore, R.M. (Ed.), 1969. *Treatise on Invertebrate Paleontology*. Part 6, Volumes 1–2: Bivalvia. Geological Society of America and University of Kansas Press, Lawrence, p. 952.
- Marwick, J., 1926. Cretaceous fossils from Waipu Subdivision. *New Zealand Journal of Science and Technology* 8, 379–382.
- Milne-Edwards, H., Haime, J., 1848–1850. *Recherches sur les Polyces*. *Annales des Sciences naturelles* [see Wells 1956 for parts].
- Milne-Edwards, Haime, J., 1857–1860. *Histoire naturelle des Coralliaires*. Paris, vol. 1 (1857, 326 p.); vol. 2 (1857, 633 p.); vol. 3 (1860, 560 p.); atlas (1857, 31 pls.).
- Morton, S.G., 1834. *Synopsis of the Organic Remains of the Cretaceous Group of the United States Illustrated by Nineteen Plates to which is added an appendix, containing a tabular view of the Tertiary fossils hitherto discovered in North America*. Key and Biddle, Philadelphia. 88 p. + Appendix (8 p.), 19 pls.
- Müller, J.M., 1847. *Monographie der Petrefacten der Aachener Kreideformation*. Part 1. Bonn, Germany, pp. 48, 2 pl.
- Müller, O.F., 1771. *Von Würmen des süßen und salzigen Wassers, mit Kupfern*. Heineck and Faber, Kopenhagen, pp. 200.
- Norvick, M.S., Smith, M.A., 2001. Mapping the plate tectonic reconstruction of southern and southeastern Australia and implications for petroleum systems. *APPEA Journal* 41, 15–35.
- Parkinson, J., 1811. *Organic Remains of a Former World...vol. 3*. London, pp. 479, 22 pls.
- Skwarko, S.K., 1963. Australian Mesozoic trigoniids. *Bulletin of the Bureau of Mineral Resources Geology and Geophysics* 67, 55.
- Skwarko, S.K., 1967. Mesozoic Mollusca from Australia and New Guinea. 1. Lower Cretaceous Mollusca of the Great Artesian Basin type in the Gibson Desert, central western Australia. *Bulletin of the Bureau of Mineral Resources Geology and Geophysics* 75, 89–101.
- Skwarko, S.K., 1983. Cenomanian (Late Cretaceous) Mollusca from Mountnorris Bay, Arnhem Land, northern Australia. In *Palaeontological Papers*, 1983. *Bulletin of Bureau of Mineral Resources, Australia* 217, 73–83.
- Sohl, N.F., 1960. *Archaeogastropoda, Mesogastropoda, and stratigraphy of the Ripley, Owl Creek, and Prairie Bluff Formations*. United States Geological Survey Professional Paper 331-A, 151.
- Sornay, J., 1980. Révision du sous-genre d'inocécime *Tethyoceramus* Heinz, 1932 (Bivalvia) et de ses représentants Coniaciens a Madagascar. *Annales de paléontologie (invertébrés)* 66, 135–150.
- Speden, I.G., Keys, I.W., 1981. *Illustrations of New Zealand Fossils*. In: DSIR Information Series, 1st ed., 150. Government Printer, Wellington, pp. 109.
- Stilwell, J.D., 1994. Latest Cretaceous to earliest Paleogene molluscan faunas of New Zealand: changes in composition as a consequence of the break-up of Gondwana and extinction. Unpublished PhD dissertation, University of Otago, Dunedin, New Zealand, pp. 1630, 84 pls.
- Stilwell, J.D., 2003. *Macropalaeontology of the Trochocyathus-Trematotrochus band (Paleocene/Eocene boundary), Dilwyn Formation, Otway Basin, Victoria*. Alcheringa 27, 245–275.
- Stilwell, J.D., Henderson, R.A., 2002. Description and paleobiogeographic significance of a rare Cenomanian molluscan faunule from Bathurst Island, Northern Australia. *Journal of Paleontology* 76 (3), 447–471.
- Trechmann, C.T., 1917. *Cretaceous Mollusca from New Zealand*. *Geological Magazine* (n.s.), Decade vi 4, 294–305. and 337–342, pl. 19–21.
- Formation of Coon Creek, Tennessee Wade, B., 1926. *The fauna of the Ripley*. United States Geological Survey Professional Paper 137, 192.
- Walaszczyk, I., 1992. Turonian through Santonian deposits of the Central Polish Uplands; their facies development, inoceramid paleontology and stratigraphy. *Acta geologica Polonica* 42, 122.
- Walaszczyk, I., Marcinowski, R., Praszkiec, T., Dembiczyk, K., Bięńkowska, M., 2004. Biogeographic and stratigraphical significance of the latest Turonian and Early Coniacian inoceramid/ammonite succession of the Manasoa section on the Onilahy River, south-west Madagascar. *Cretaceous Research* 25, 543–576.
- Wellman, H.W., 1959. Divisions of the New Zealand Cretaceous. *Transactions of the Royal Society of New Zealand* 87, 99–163.
- Wells, J.W., 1933. Corals of the Cretaceous of the Atlantic and Gulf plains and western interior of the United States 18, 85–288.
- Wilckens, O., 1907. *Die Lamellibranchiaten, Gastropoden etc. der oberen Kreide Sudpatagoniens*. *Berichten der Naturforschenden Gesellschaft zu Freiburg i. Br.* 15, 97–166.
- Wilckens, O., 1910. *Die Anneliden, Bivalven und Gastropoden der Antarktischen Kreideformation*. *Wissenschaftliche Ergebnisse der Swedische Südpolar Expedition 1901–1903* 3, 42, 4 pl.
- Wilckens, O., 1922. *The Upper Cretaceous gastropods of New Zealand*. *New Zealand Geological Survey Paleontological Bulletin* 9, 132, 5 pl.