

A magnetostratigraphically-constrained chronology for late Miocene bolboformids and planktic foraminifers in the temperate Southwest Pacific

Martin P. Crundwell¹ and Campbell S. Nelson²

¹GNS Science, P.O. Box 30368, Lower Hutt, New Zealand

²Department of Earth Sciences, University of Waikato, PB 3105, Hamilton, New Zealand
email: m.crundwell@gns.cri.nz

ABSTRACT: High-resolution bolboformid and planktic foraminiferal distribution data from the upper Miocene section of ODP Site 1123, Chatham Rise, New Zealand, have been integrated with the magnetostratigraphic record from the same site to establish a magnetobiochronology based on the geomagnetic polarity time scale (GPTS-95). Although the upper Miocene sequence is adversely affected by dissolution, 33 bioevents are identified based on dissolution resistant taxa that are also found at DSDP Site 593 – an important biostratigraphic reference section for the Neogene in the Tasman Sea. A scatter plot based on the stratigraphic positions of shared bioevents at these oceanic sites approximates a linear line of correlation. The tight grouping of the biostratigraphic data around the line of correlation and the consistency of their stratigraphic order suggest most events are synchronous or nearly so, even though the sites are more than 1400km apart and associated with different water masses. This implies that even though the biostratigraphic construct is based on only two oceanic sites, it provides a robust late Miocene biochronostratigraphic framework for the temperate Southwest Pacific.

Shared bolboformid events include the appearances and disappearances of *Bolboforma subfragoris* s.l. (11.56-10.61 Ma), *B. gruetzmacheri* (10.46-10.31 Ma), *B. capsula* (10.20-10.13 Ma), *B. pentaspinosa* (10.15-10.08 Ma), *B. gracilireticulata* s.l. (9.75-9.61 Ma), *B. metzmacheri* s.s. (lower occurrence interval 9.54-9.34 Ma, upper occurrence interval 9.01-8.78 Ma), *B. metzmacheri ornata* (8.45-8.28 Ma), *B. praeintermedia* (8.25-8.21 Ma), and abundance spikes associated with the uppermost *B. subfragoris* s.l. occurrence interval BBs-1123/D (10.61 Ma) and the lower *B. metzmacheri* s.s. occurrence interval BBm-1123/A (9.54 Ma). Shared planktic foraminiferal events include dextral coiling excursions in *Globoconella miotumida* (10.92-10.82 Ma and 9.62-9.42 Ma), the regional disappearance of *Globoquadrina dehiscens* (8.88 Ma), and the evolutionary appearances of *Globoconella conomiozea* (ca. 6.87 Ma), *Globoconella mons* (ca. 5.72 Ma), *Globoconella sphericomiozea* (ca. 5.53 Ma), *Globoconella pliozea* (ca. 5.39 Ma), *Truncorotalia crassaformis* (ca. 5.15 Ma), and *Globoconella puncticulata* (ca. 5.11 Ma).

INTRODUCTION

High quality age models for deep-sea sections are a key component in the correlation and synthesis of global data sets for the study of paleoceanographic processes. The establishment of a robust biochronostratigraphic framework for marine microfossils is complex and often involves several correlation steps, the most important being the correlation between biostratigraphic events and the global polarity time scale (GPTS). Although microfossil events have been calibrated to the GPTS in different parts of the world (e.g. Hodell and Kennett 1986; Chaisson and Leckie 1993; Sprovieri et al. 1996), no reliable late Miocene biochronostratigraphic framework exists for the temperate Southwest Pacific. Presently, chronologies in this region are based on a small number of tenuous paleontological, magnetostratigraphic, and stable isotope correlations with dated horizons or interpolated horizons from uplifted marine sections on land in New Zealand (e.g. Kennett and Vella 1975; Wright et al. 1985; Edwards 1987; Roberts et al. 1994), and from outside of the region (e.g. Lazarus et al. 1995; Spencer-Cervato 1999). Because these paleontological data often lack internal consistency, and biostratigraphic events are often diachronous across major water mass boundaries (Jenkins 1992; Spencer-Cervato 1994), there is a need to establish a more reliable regional biochronostratigraphic framework in order to gain a better perspective of oceanographic and climatic changes in southern mid-latitudes. This is particularly important in the late Miocene

where there is a paucity of events suitable for biostratigraphic correlation.

Ocean Drilling Program (ODP) Site 1123, Chatham Rise, New Zealand, allows for the first time the development of a high quality late Miocene magnetobiochronology in the temperate Southwest Pacific (text-fig. 1). Late Miocene calcareous microfossil assemblages at the site have been variably affected by differential dissolution, but dissolution-resistant bolboformids and planktic foraminifers are sufficiently well represented to establish a sequence of bioevents that can be correlated with Deep Sea Drilling Project (DSDP) Site 593 (text-fig. 1), an important biostratigraphic reference section for the Neogene in the Tasman Sea (Jenkins and Srinivasan 1986; Lohmann 1986; Hoskins 1990; Scott 1992; Grützmacher 1993; Crundwell 2004). The primary aim of this paper is to establish a regional magnetobiochronology for these data based on bioevents at Site 1123 and the geomagnetic polarity time scale GPTS-95 (Cande and Kent 1995).

MATERIAL AND METHODS

ODP Site 1123 was reported in the Initial Reports for Leg 181 to have a virtually complete Neogene magnetostratigraphic record that extends back to Chron C6r – ca. 20 Ma (Shipboard Scientific Party 1999a). However, a subsequent review of the magnetostratigraphy (Crundwell et al. 2004) has identified an interval in the latest Miocene between Chron C3Br.2n to

C3n.1n (7.34–4.29 Ma) where the polarity record is ambiguous – it encompasses the upper part of the studied section (text-fig. 2). The magnetostratigraphy of the lower part of the section, between Chron C5An.1r and C3Br.2n (12.18–7.34 Ma), has a virtually complete polarity record, but there is a suspected break in the sequence of less than 100kyr within Chron C4Ar.2r (Shipboard Scientific Party 1999a).

While the resolution of shipboard biostratigraphic sampling was adequate for the interpretation of the paleomagnetic record, the sample interval (ca. 190–320kyr) was too coarse to identify or define short-lived bioevents and to allow a reliable magnetobiochronology to be established. To improve biostratigraphic resolution through the late Miocene, a suite of 353 micropaleontological samples has been examined from the base of core 1123B-44X (427.40 r-mcd; revised-metres composite depth) to the top of core 1123B-18X (170.20 r-mcd). All samples are fossiliferous, but preservation is highly variable. The adopted sample spacing (ca. 22kyr) is about three times coarser than the biostratigraphic resolution of Site 593 (Crundwell 2004), but is sufficient to identify most short-lived bolboformid and planktic foraminiferal events should they be present.

The interval reported in this study was cored continuously with the extended core barrel, but there are potential gaps in the record between some cores where there was less than 100% recovery (Table 1). This places a cautionary caveat on the location of some bioevents in the cored succession, although physical properties measurements of the core and downhole logging (Shipboard Scientific Party 1999a) suggest much of the variability in core recovery was caused by core deformation during coring and retrieval operations.

All paleontological data from the site relate to ODP Hole 1123B and depths are reported in revised-metres composite depth (r-mcd). Depth translations from metres below seafloor (mbsf) to r-mcd are based on core splice data and linear transforms given in Table 1. Biostratigraphic events are reported in the text in terms of the sample in which they are found, but magnetostratigraphic and chronostratigraphic assignments are based on horizons between the sample with the named event and the closest constraining sample (i.e. interpolated depth).

Distribution (presence/absence) data were initially compiled for all planktic foraminifers from systematic scans of the >150µm fractions. No foraminifera were removed from samples, but all bolboformids were picked and mounted onto two-hole slides to allow identifications to be checked before bolboformid census data were compiled. The bolboformid data were then supplemented with picks of all bolboformids from the >125µm fraction to provide more detailed census information. Planktic-benthic foraminiferal ratios, and coiling data for *Globoconella miotumida* and *Gc. conomiozea*, were also compiled, based wherever possible on counts of at least 100 specimens in the >150µm fraction. All fossil materials from this study – washed residues, mounted slides, and figured specimens – are lodged in the DSDP/ODP collections at GNS Science, Lower Hutt, New Zealand.

The adopted bolboformid taxonomy is based on Spiegler and Daniels (1991), Grützmacher (1993), and Spiegler (1999), and employs population concepts of Crundwell et al. (2005). To a large extent, the higher taxonomy of planktic foraminifers follows Kennett and Srinivasan (1983), except the genus/subgenus ranking of each phylogenetic group is raised to that of a genus (e.g. *Globorotalia* (*Globoconella*) = *Globoconella*; *Globo-*

rotalia (*Truncorotalia*) = *Truncorotalia*). Adopted species concepts are largely based on Hornibrook (1982), Hornibrook et al. (1989), and Scott et al. (1990). The type references of bolboformid and planktic foraminiferal species identified at Site 1123 are listed in Appendix 1 and an explanation of bioevents and bolboformid zones is given in Appendix 2.

OCEANOGRAPHIC SETTING

ODP Site 1123 is located at 42°47.147'S, 171°29.941'W on the northeastern slope of the Chatham Rise, about 1000km east of central New Zealand (text-fig. 1). The site lies at a depth of 3290m, and it is near the northern limit of the modern Subtropical Front (STF).

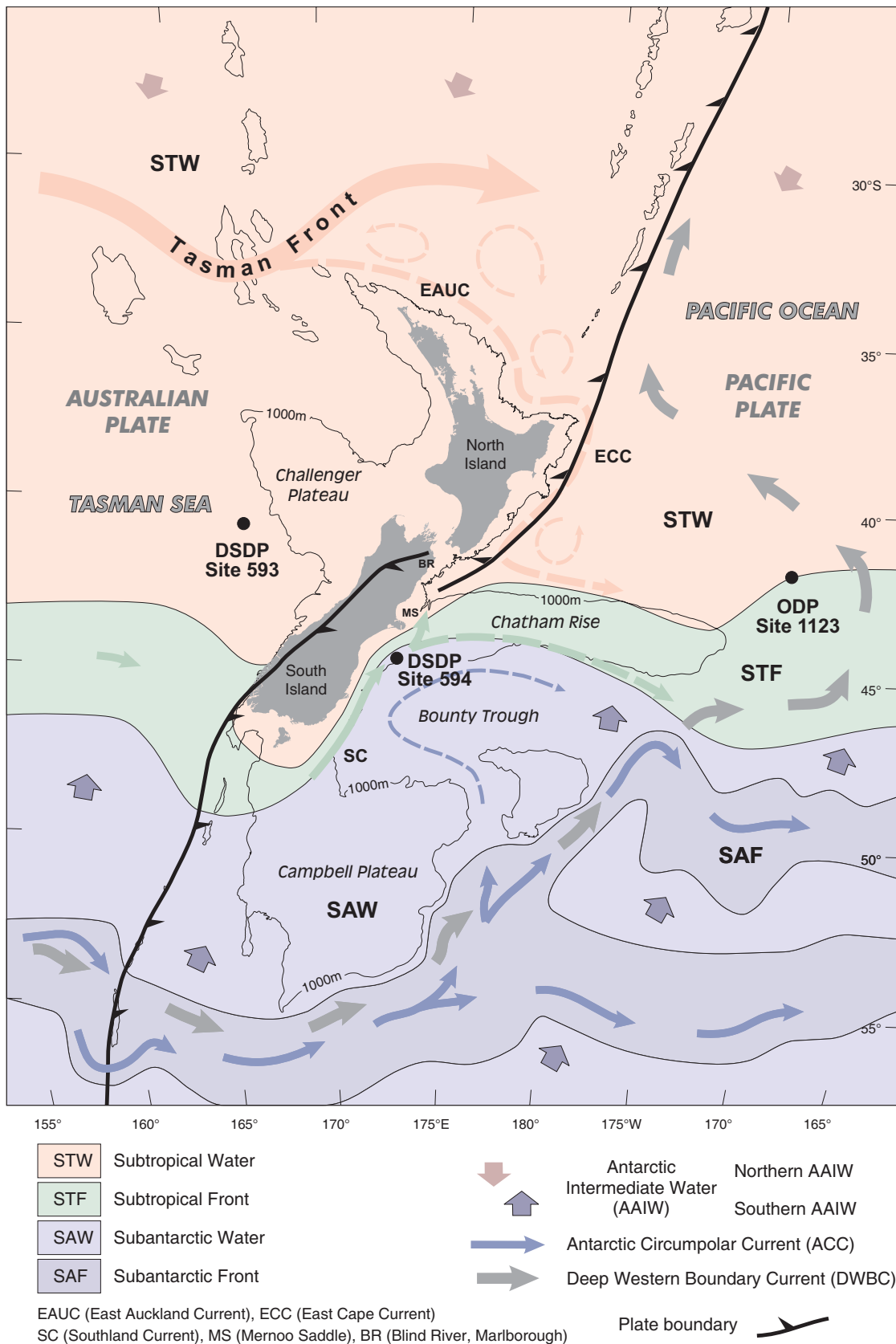
Presently, Site 1123 is dominated by warm Subtropical Surface Water, associated with the East Cape Current (ECC) – a series of semi-permanent, deep-seated eddies that pass south along the eastern North Island margin, before turning east along the northern flank of Chatham Rise (Heath 1985; Chiswell and Roemmich 1988). The STF is displaced by the New Zealand subcontinent and linked around the south-eastern margin of the South Island margin by the Southland Current (SC). At Mernoo Saddle, a branch of the SC continues north and the remainder of the SC flows east along the southern flank of Chatham Rise (Chiswell 1994). The strongest temperature gradients occur along the shallow crest of Chatham Rise (Uddstrom and Oien 1999), where the STF occupies a band ca. 150km wide, between the ECC and SC (Carter et al. 1998). Off eastern Chatham Rise, where the currents bounding the STF are less constrained by bathymetry, the front is up to 400km wide. Satellite SST data (www7320.nrlssc.navy.mil/global_ncom) show summer–winter amplitude variations of 4–6°C at Site 1123 and across the STF.

In the deeper ocean, off eastern New Zealand, oxygen-rich Antarctic Intermediate Water flows northwards across Site 1123 at depths of 600–1450m (Wyrki 1962; Shipboard Scientific Party 1999a). Circumpolar Deep Water (CDW) associated with the Antarctic Circumpolar Current passes northwards along the eastern margin of the New Zealand subcontinent, below a depth of 1450m (Shipboard Scientific Party 1999a), and Antarctic Bottom Water (AABW) flows northwards, to the east of the site. During winter months, a northwards-directed flow of Subantarctic Mode Water moves across the site at depths of 150–450m.

Although seafloor spreading between Australia and Antarctica has shifted the New Zealand subcontinent northwards by as much as 5° of latitude since the beginning of the late Miocene (Weissel et al. 1977) the present-day pattern of oceanic circulation in the region appears to have remained substantially unchanged over the last 10 myr (Edwards 1975; Nelson and Cooke 2001). However, significant glacial–interglacial climatic variability has been recorded at Site 593 during the Miocene (Cooke et al. in review) and at Site 1123 during the Pleistocene (Crundwell et al. in review). Glacial–interglacial variability is also evident in proxy carbonate data from the Pliocene and Miocene section of Site 1123 (Shipboard Scientific Party 1999b).

BOLBOFORMIDS

Bolboformids are an enigmatic group of calcareous microfossils that have generally been interpreted as phytoplanktic organisms (Rogl and Hochuli 1976; Tappan 1980; Spiegler and Daniels 1991), although comparative oxygen isotope data from the analysis of bolboformid shells (Poag and Karowe 1986; Spiegler



TEXT-FIGURE 1

Bathymetric map of the New Zealand subcontinental region (1000m contour), Tasman Sea, and Southwest Pacific Ocean, showing the location of ODP and DSDP sites referred to in this study, the positions of major fronts at the ocean surface (summer situation), and the flow of Antarctic Intermediate Water, Antarctic Circumpolar, and Pacific Deep Western Boundary currents (Shipboard Scientific Party 1999b).

and Erlenkeuser 2001) suggest they spent at least part of their lifecycle below the photic zone, in mid to lower levels of the water column. They are important index fossils that supplement calcareous nannofossil and planktic foraminiferal zonations in mid- to high-latitude regions of Europe and the Atlantic and southern Indian oceans (Spiegler and Daniels 1991; Spiegler and Müller 1992). Their high resistance to dissolution makes them particularly important for the correlation of oceanic sequences affected by calcite dissolution (Müller et al. 1985). The discovery of bolboformids in late Miocene oceanic sequences of the Southwest Pacific and Tasman Sea regions (Poag and Karowe 1986; Grützmacher 1993) and in uplifted marine sequences in New Zealand (Crundwell et al. 1997a) offers considerable scope for improving biostratigraphic resolution and global correlations in this region. The most studied bolboformid sequence in this region is at DSDP Site 593, where there is a well-defined succession of short-lived appearances and disappearances of monospecific bolboformid populations, with peak abundances sometimes reaching several thousand specimens per gram of sediment (Grützmacher 1993; Crundwell et al. 1997a). Bolboformids have also been noted at other oceanic sites in the Southwest Pacific and Tasman Sea regions – ODP Site 1120 (50°S), DSDP Sites 594 (46° S), 592 (36° S), and 590B (31° S) – but their abundance and diversity generally decreases at lower latitudes (Grützmacher 1993).

Bolboformids are reported to be rare in the Initial Reports for ODP Site 1123 (Shipboard Scientific Party 1999a), but the present study identifies a well-defined sequence of short-lived appearances and disappearance of monospecific bolboformid populations between cores 1123B-41X and 32X. The bolboformids are moderately well preserved, even in samples where planktic foraminifers are severely affected by dissolution. The predominantly early late Miocene bolboformid succession spans about 3.4 million years and it is similar to the succession at DSDP Site 593 (Crundwell 2004). It includes at least 18 well-defined events – lowest and highest occurrences, and distinctive abundance spikes (text-fig. 3). The persistence of monospecific populations is relatively high (60–100%) and the disappearance of each species is usually followed by a barren interval of 30–330kyr where there are no bolboformids. Although the occurrence intervals of most species are well defined, additional higher-resolution sampling may extend the ranges of some species, particularly where specimen numbers are low. Abundance spikes may also be better resolved with higher-resolution sampling.

Bolboformid biostratigraphy and biochronology

Bolboformid events at Site 1123 are described in ascending stratigraphic order. The distribution and abundance of bolboformids are shown in text-fig. 3, and species are illustrated in text-figure 4.

***Bolboforma subfragoris* s.l. taxon-range zone (11.56–10.50 Ma):** In the context of this study, *B. subfragoris* s.l. encompasses several morphologically similar spirospinose species, subspecies, and morphotypes. The range zone of *B. subfragoris* s.l. at Site 1123 includes four occurrence intervals that are separated by barren intervals without bolboformids. For descriptive purposes, the occurrence intervals are referred to in ascending order as the BBs-1123/A to BBs-1123/D intervals. The lowest and highest intervals, BBs-1123/A and BBs-1123/D, include highly serrated spiral-flanged specimens (text-fig. 4/12 and 4/10) that closely resemble spirospinose forms of *B.*

subfragoris from Site 593 (Grützmacher 1993), and intervals BBs-1123/B and BBs-1123/C near the middle of the taxon range zone, include small smooth-walled forms with weak nodular surface ornament (text-fig. 4/11).

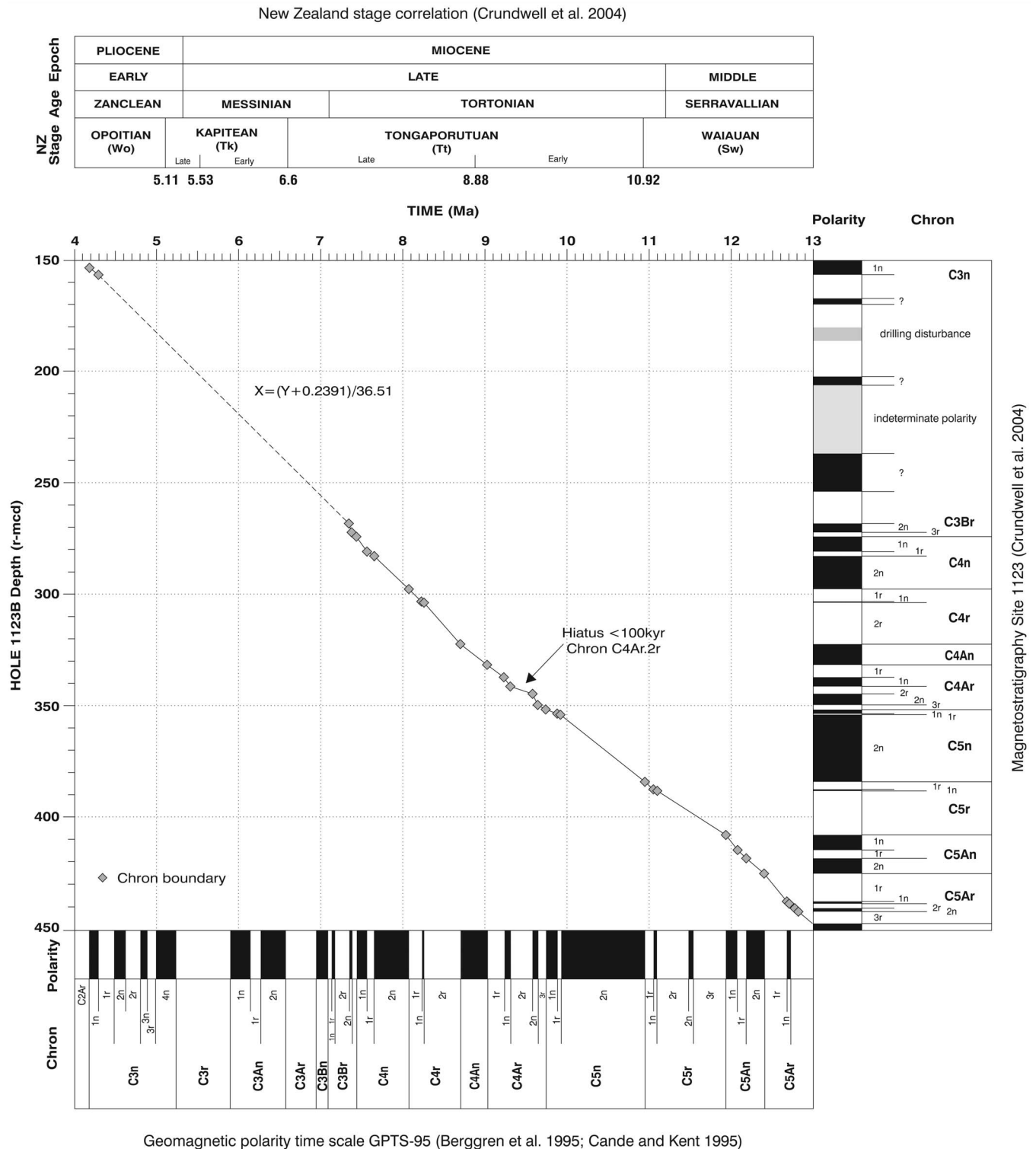
The lowest occurrence of *B. subfragoris* s.l. is at the base of the BBs-1123/A interval in sample 1123B-41X-6, 0–5cm. This is close to the base of core 1123B-41X, which has only 86.3% of core recovery, although downhole logs and shipboard measurements of physical core properties suggest the core is relatively complete and that the datum is reliably located. The lowest occurrence datum is 14m below the base of the *Gc*-1123/A coiling zone – a distinctive interval of dextrally-coiled *Globoconella miotumida* (text-fig. 5), which is correlated with the base of the Tongaporutuan Stage (Crundwell et al. 2004). It occurs in Chron C5r.2r(0.55) and has an interpolated magnetostratigraphic age of 11.56 Ma.

The highest occurrence of *B. subfragoris* s.l. occurs at the top of the BBs-1123/D interval. Immediately prior to its disappearance in sample 1123B-39X-1, 100–104cm, it occurs in nine consecutive samples. Following a barren interval without bolboformids, monospecific populations of the succeeding species *Bolboforma gruetzmacheri*, first appear 1.6m (ca. 60kyr) higher in the core. The highest occurrence of *B. subfragoris* s.l., which marks the top of the *B. subfragoris* s.l. taxon-range zone at Site 1123, occurs in Chron C5n.2n(0.56) and it has an interpolated magnetostratigraphic age of 10.50 Ma.

The base of the BBs-1123/D interval, the uppermost occurrence interval of the *B. subfragoris* s.l. taxon-range zone, is marked by a prominent abundance spike in sample 1123B-39X-4, 50–53cm where abundances in the >125µm sediment size fraction peak at about 3800 specimens per gram (text-fig. 3). The abundance spike occurs above the *Gc*-1123/A coiling zone in Chron C5n.2n(0.71) and it has an interpolated magnetostratigraphic age of 10.61 Ma.

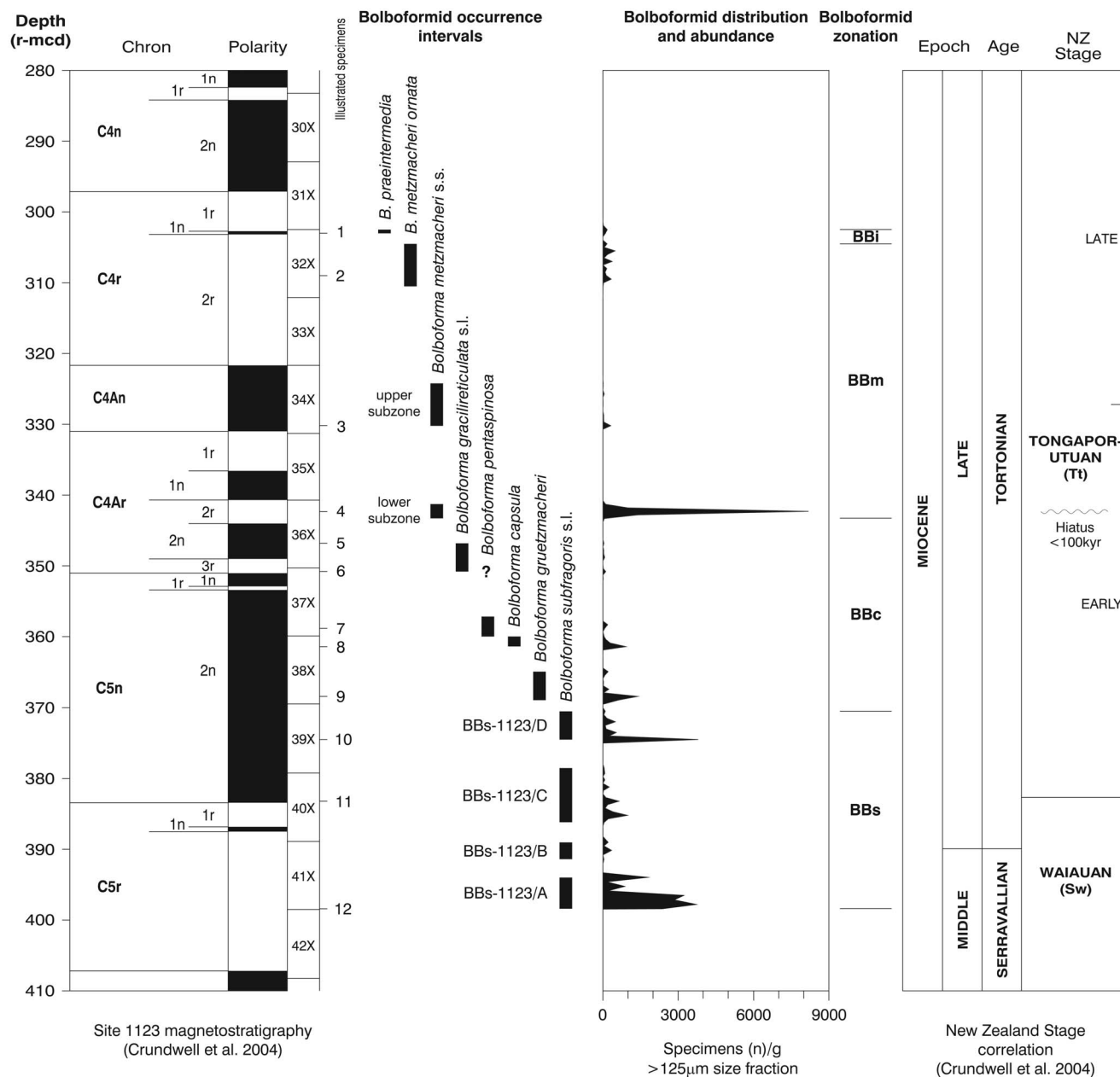
***Bolboforma gruetzmacheri* occurrence interval (10.46–10.31 Ma):** *Bolboforma gruetzmacheri* is a very distinctive bolboformid ornamented with irregular, widely spaced blind and interconnected blade-like ridges (text-fig. 4/9). It has previously been identified by Grützmacher (1993) at oceanic sites in the Southwest Pacific as *Bolboforma* sp. H. At Site 1123 it has a very short occurrence interval that extends from 1123B-38X-7, 0–4cm to 1123B-38X-4, 50–54cm. It is a persistent species that occurs in eight out of nine samples. It is most common near the base of its range, where abundances in the >125µm sediment size fraction peak at 1385 specimens per gram (text-fig. 3). Very low abundances in the upper part of the species stratigraphic range diminish the reliability of its highest occurrence, although following a barren interval without bolboformids, monospecific populations of the succeeding species, *B. capsula*, first appear 3.5m (ca. 120kyr) higher in the core. The *B. gruetzmacheri* occurrence interval extends from Chron C5n.2n(0.53) to C5n.2n(0.38) and it has an interpolated magnetostratigraphic age of 10.46–10.31 Ma.

***Bolboforma capsula* occurrence interval (10.20–10.13 Ma):** *Bolboforma capsula* is another very distinctive species with a moderately smooth, bell-like, axially corrugate and tuberculate, encapsulated test (text-fig. 4/8). It is confined to four consecutive samples inclusive of 1123B-38X-2, 0–4cm and 1123B-38X-1, 10–14cm. Specimen numbers, however, are very low and there is uncertainty regarding the reliability of its lowest and highest occurrences. The occurrence interval of *B.*



TEXT-FIGURE 2

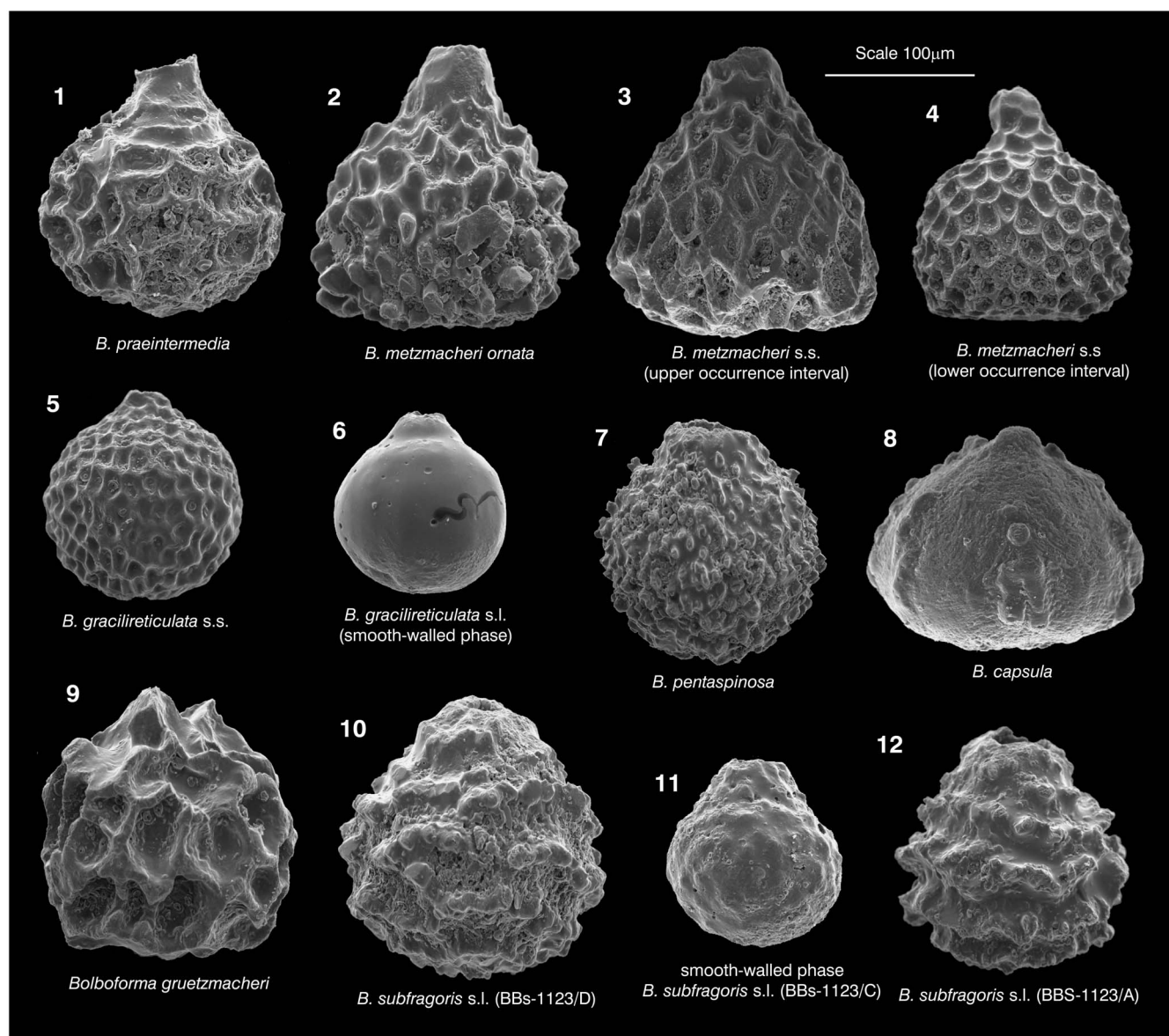
Cross-plot of magnetostratigraphic data from Site 1123 and the geomagnetic polarity time scale (GPTS-95) – the basis of the site's chronology. The lower part of the magnetostratigraphic sequence is virtually complete, except for a short hiatus within Chron C4Ar.2r and a possible short hiatus in the uppermost part of Chron C5n. The upper part of the magnetostratigraphic sequence from the top of Chron C3Br.2r to the base of C3n.1n is poorly constrained. All ages for this interval are interpolated (dashed line).



Species	Depth (r-mcd)	Max abundance	Species	Depth (r-mcd)	Max abundance
<i>Bolboforma praeintermedia</i>	302.50 - 303.00	171	<i>Bolboforma capsula</i>	360.00 - 361.40	918
<i>Bolboforma metzmacheri ornata</i>	304.50 - 310.50	480	<i>Bolboforma guetzmacheri</i>	364.90 - 368.90	1385
<i>Bolboforma metzmacheri</i> s.s.			<i>Bolboforma subfragoris</i> s.l.		
– upper occurrence interval	324.20 - 330.20	310	– 1123/D occurrence interval	370.50 - 374.50	3791
– lower occurrence interval	341.30 - 343.30	8189	– 1123/C occurrence interval	378.50 - 386.20	978
<i>Bolboforma gracilireticulata</i> s.l.	346.80 - 350.80	109	– 1123/B occurrence interval	389.02 - 391.43	341
<i>Bolboforma pentaspinoso</i>	358.30 - 360.00	188	– 1123/A occurrence interval	393.97 - 398.42	2836

TEXT-FIGURE 3

Bolboformid distribution and abundance data (see Appendix 3). The numbered horizons of illustrated specimens (1-12) correspond to Figure 4. Max abundance = specimens (n) /g in the >125µm sediment size fraction. Bolboformid zonation based on Spiegler and Daniels (1991) and Grützmaier (1993). BBi = *Bolboforma intermedia* Interval Zone, BBm = *B. metzmacheri* Taxon-range Zone, BBc = *B. capsula* Interval Zone, BBs = *B. subfragoris* s.l. Taxon-range Zone. Definitions of biozones are given in Appendix 2.



TEXT-FIGURE 4

SEM photomicrographs of bolboformids from Hole 1123B. All images are shown to the same scale.

- | | |
|--|--|
| 1 <i>Bolboforma praeintermedia</i> Spiegler; 32X-1, 50-55cm | 7 <i>Bolboforma pentaspinosa</i> Spiegler; 37X-6, 100-104cm |
| 2 <i>Bolboforma metzmacheri ornata</i> Spiegler; 32X-5, 50-55cm | 8 <i>Bolboforma capsula</i> Spiegler; 38X-2, 0-4cm |
| 3 <i>Bolboforma metzmacheri</i> s.s. (Clodius) upper occurrence interval; 34X-6, 100-105cm | 9 <i>Bolboforma gruetzmacheri</i> Crundwell; 38X-6, 100-104cm |
| 4 <i>Bolboforma metzmacheri</i> s.s. (Clodius) lower occurrence interval; 36X-2, 10-14cm | 10 <i>Bolboforma subfragoris</i> s.l. Spiegler (BBs-1123/D occurrence interval); 39X-4, 50-53cm |
| 5 <i>Bolboforma gracilireticulata</i> s.s. Spiegler; 36X-5, 10-14cm | 11 Small smooth-walled form <i>Bolboforma subfragoris</i> s.l. Spiegler (BBs-1123/C occurrence interval); 40X-3, 100-103cm |
| 6 <i>Bolboforma gracilireticulata</i> s.l. Spiegler; 37X-1, 50-54cm | 12 <i>Bolboforma subfragoris</i> s.l. Spiegler (BBs-1123/A occurrence interval); 41X-6, 0-5cm |

capsula extends from Chron C5n.2n(0.27) to C5n.2n(0.21) and it has an interpolated magnetochronologic age of 10.20–10.13 Ma.

The top of the *B. capsula* occurrence interval overlaps with the base of the *B. pentaspinosa* occurrence interval (Appendix 3). Although this suggests there may have been contemporary bolboformid populations in the vicinity of Site 1123, for a short period at least, the overlap is an unusual feature of the bolboformid distribution and other sedimentary factors, such as bioturbation and reworking, may have been involved.

***Bolboforma pentaspinosa* occurrence interval (10.15–10.08 Ma):** *Bolboforma pentaspinosa* is distinguished from other highly spinose bolboformid species by its small subspherical shell and low collar-like apertural neck (text-fig. 4/7). It is confined to a short interval between samples 1123B-38X-1, 10–14cm and 1123B-37X-6, 50–54cm. The base of the *B. pentaspinosa* occurrence interval overlaps with the top of the *B. capsula* occurrence interval. It extends from Chron C5n.2n (0.22) to C5n.2n (0.16) and has an interpolated magnetochronologic age of 10.15–10.08 Ma.

A specimen of *B. pentaspinosa* has also been noted higher in the section, in sample 1123B-37X-2, 0–4cm, but it is an isolated occurrence and it is thought to be either reworked or a contaminant. Rare specimens of *B. pentaspinosa* were also noted in the Initial Reports for Site 1123, in samples 1123B-27X CC, 30X CC and 32X CC (Shipboard Scientific Party 1999a), but a re-examination of shipboard samples failed to confirm the occurrences.

***Bolboforma gracilireticulata* s.l. occurrence interval (9.75–9.61 Ma):** In the context of this study, *B. gracilireticulata* s.l. encompasses an intergrade of small finely sculptured cancellate forms (*B. gracilireticulata* s.s.) and smooth-walled forms that have previously been identified as bolboformid cysts (e.g. Grützmacher 1993) or *B. laevis* (text-figs. 4/5 and 4/6). Although this small species is relatively uncommon at Site 1123, peak abundances of >20,000 specimens per gram have been noted at Site 593 in the 125–150µm sediment size fraction (Crundwell 2004). At Site 1123, *B. gracilireticulata* s.l. occurs in six out of nine samples between 1123B-37X-1, 50–54cm and 1123B-36X-5, 10–14cm. The lower part of the species stratigraphic range consists almost entirely of smooth-walled forms, and the upper part includes subequal numbers of *B. gracilireticulata* s.s. and small smooth-walled forms. The *B. gracilireticulata* s.l. occurrence interval extends from the base of Chron C4Ar.3r to Chron C4Ar.2n(0.51) and has an interpolated magnetochronologic age of 9.75–9.61 Ma.

***Bolboforma metzmacheri* s.s. taxon-range zone (9.54–8.78 Ma):** *Bolboforma metzmacheri* s.s. is ornamented with a coarsely cancellate-ridged sculpture. It superficially resembles the benthic foraminifer *Oolina hexagona*, but is distinguished by its flattened aboral surface and the more irregular pattern of its surface ornament (text-fig. 4/4). The taxon-range zone range of *B. metzmacheri* s.s. includes occurrence intervals in its lower and upper parts that are separated by an extended barren interval where there are no bolboformids. The lower occurrence interval extends from 1123-36X-2, 110–114cm to 1123-36X-1, 60–64cm, and the upper occurrence interval extends from 1123-34X-6, 100–105cm to 1123-34X-2, 100–105cm.

The base of the lower *B. metzmacheri* s.s. occurrence interval occurs 2.5m above the top of the Gc-1123/B coiling zone

(text-fig. 5; see later discussion). This well-defined interval extends from C4Ar.2r(0.86) to C4Ar.2r(0.11) and has an interpolated magnetochronologic age of 9.54–9.34 Ma. It includes a prominent abundance spike in sample 1123-36X-2, 10–14cm where abundances in the >125µm sediment size fraction peak at about 8200 specimens per gram (text-fig. 3). The spike in abundance, which is the largest such spike noted at Site 1123, coincides with a possible hiatus of <100kyr within Chron C4Ar.2r (text-fig. 2; Shipboard Scientific Party 1999a). It has an interpolated magnetochronologic age of 9.44 Ma, but the hiatus places a cautionary caveat on the reliability of the age.

The base of the upper *B. metzmacheri* s.s. occurrence interval coincides with the entry of moderate numbers of bolboformids and is well defined, but bolboformid numbers decrease in the upper part of the interval and occurrences are intermittent (Appendix 3). The upper *B. metzmacheri* s.s. occurrence interval extends from C4An(0.94) to C4An(0.25) and has an interpolated magnetochronologic age of 9.01–8.78 Ma. The regional disappearance of the planktic foraminifer *Globoquadrina dehiscens* occurs near the middle of the upper *B. metzmacheri* s.s. occurrence interval.

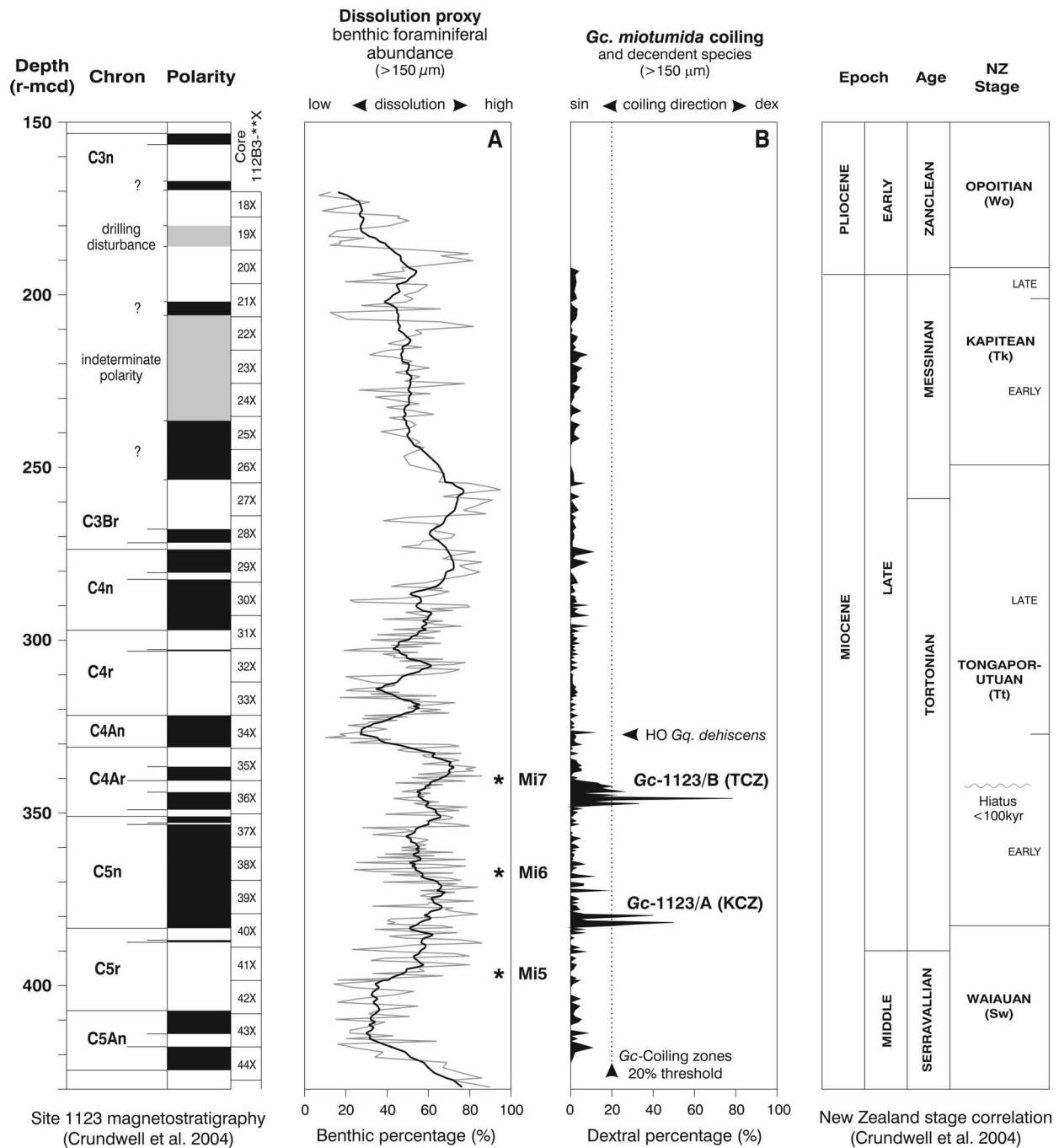
***Bolboforma metzmacheri ornata* occurrence interval (8.45–8.28 Ma):** *Bolboforma metzmacheri ornata* is distinguished from *B. metzmacheri* s.s. by the presence of short aborally-pointing spines at the junctions of the cancellate-ridged ornament (text-fig. 4/2). It first appears in sample 1123-32X-6, 50–55cm and its stratigraphic range extends upward to 1123-32X-2, 50–55cm. *B. metzmacheri ornata* is a relatively common and persistent species that occurs in 12 out of 13 samples that span the species stratigraphic range (Appendix 3). Its lowest occurrence is close to the base of core 1123-32X, for which there was only 91.7% recovery, but downhole logs and shipboard logs of physical parameters suggest the core is relatively complete and the datum is reliably located. The *B. metzmacheri ornata* occurrence interval extends from Chron C4r.2r(0.44) to C4r.2r(0.06) and has an interpolated magnetochronologic age of 8.45 to 8.28 Ma.

***Bolboforma praeintermedia* occurrence interval (8.25–8.21 Ma):** The irregular spiro-concentric ridged ornament of *B. praeintermedia* (text-fig. 4/1) represents a marked morphological change from the cancellate ornament of *B. metzmacheri* species that precede it. It superficially resembles *Bolboforma gruetzmacheri*, but the ridged-ornament tends to be more evenly spaced and better interconnected. At Site 1123, it is confined to a very short interval that extends over three consecutive samples, from 1123B-32X-1, 50–55cm to 1123-31X-7, 0–5cm. The *B. praeintermedia* occurrence interval extends from the base of Chron C4n.1n to C4n.1r(0.81) and it has an interpolated magnetochronologic age of 8.25–8.21 Ma.

The disappearance of *B. praeintermedia* at 8.21 Ma represents the regional extinction of bolboformids in the Southwest Pacific (Grützmacher 1993).

Bolboformid zonation and correlation

Despite the taxonomic confusion and uncertainty surrounding this enigmatic group of calcareous microfossils (Poag and Karowe 1986), bolboformid assemblages from Site 1123 and other oceanic sites in the temperate Southwest Pacific share many common species with assemblages in the North Atlantic (e.g. Spiegler and Daniels 1991; Spiegler 1999). The order of species appearances and disappearances and ages of important



TEXT-FIGURE 5

Magnetostratigraphy of Site 1123 compared to stratigraphic plots of benthic foraminiferal abundance (dissolution proxy), *Globoconella miotumida* coiling data, and New Zealand Stages. A) High benthic abundances correspond to high dissolution, grey curve (benthic percentage), black curve (11-point moving average), calibrated oxygen isotope events Mi5, Mi6, and Mi7 from Wright and Miller (1992). B) Subzone Gc-1123/A corresponds to the Kaiti Coiling Zone (KCZ, Scott 1995), and Gc-1123/B corresponds to the Tukemokihi Coiling Zone (TCZ) identified at Site 593 and uplifted marine sections in New Zealand (Crundwell et al. 1997b; Crundwell et al. 2004).

zonal events are also very similar (Table 2). This allows the bolboformid zonation in the North Atlantic and southern Indian Ocean (Spiegler and Daniels 1991) to be used with minimal modification in the Southwest Pacific (Grützmacher 1993).

In this study, four of Spiegler and Daniels bolboformid zones are recognized, although improvements in taxonomy (Crund-

well et al. 2005), the close sampling interval, and the very well defined ranges of most species has necessitated minor changes to the zones to make them easier to apply in the Southwest Pacific. The emended zones include:

1) The *B. subfragoris* s.l. taxon-range zone (BBs-Zone) which extends from the lowest to the highest occurrence of *B.*

subfragoris s.l., and includes four occurrence intervals of *B. subfragoris* s.l. separated by three barren intervals without bolboformids (see above). At Site 1123, the BBs-Zone has a magnetostratigraphic age of 11.56–10.50 Ma. This is similar to the reported age of 11.7–10.6 Ma age for the BBs-Zone in the North Atlantic (Spiegler 1999).

2) The *B. capsula* partial range zone (BBc-Zone) encompasses the interval from immediately above the highest occurrence of *B. subfragoris* s.l. to immediately below the lowest occurrence of *B. metzmacheri* s.s. The BBc-Zone includes the occurrence intervals of *B. gruetzmacheri*, *B. capsula*, *B. pentaspinosa*, and *B. gracilireticulata* and four barren intervals without bolboformids; an interval at the base of the BBc-Zone, intervals between the occurrence intervals of *B. gruetzmacheri* and *B. capsula*, and *B. pentaspinosa* and *B. gracilireticulata*, and an interval at the top of the BBc-Zone. At Site 1123, the BBc-Zone has a magnetostratigraphic age of 10.50–9.54 Ma. This is similar to the 10.6–9.7 Ma age for the BBc-Zone in the North Atlantic (Spiegler 1999).

3) The *B. metzmacheri* taxon range zone (BBm-Zone) extends from the lowest occurrence of *B. metzmacheri* s.s. to the highest occurrence of *B. metzmacheri ornata* and includes the lower and upper occurrence intervals of *B. metzmacheri* s.s., the occurrence interval of *B. metzmacheri ornata*, and two barren intervals without bolboformids that separate the occurrence intervals. At Site 1123, the BBm-Zone has a magnetostratigraphic age of 9.54–8.78 Ma. In the North Atlantic the base of the BBm-Zone has a similar age of 9.7 Ma, but the top of the zone at 7.7 Ma is much younger.

4) The *B. intermedia* partial range zone (BBi-Zone) is incomplete in the Southwest Pacific and extends upwards from immediately above the highest occurrence of *B. metzmacheri ornata* to the highest occurrence of *B. praeintermedia*. The upper part of the BBi-Zone is missing in the Southwest Pacific (Grütz-macher 1993); although in the southern Indian Ocean and the North Atlantic the BBi zone extends through to the latest Miocene (5.6 Ma, Spiegler 1999).

The general similarity between the magnetostratigraphic ages for the bolboformid zones at Site 1123 and the reported ages for the same zones in the North Atlantic (Spiegler 1999) suggest some bolboformid events may be isochronous, or nearly so, between the Southwest Pacific and North Atlantic and are potentially useful for regional and interregional correlation.

Paleoceanographic implications of the bolboformid record

The well-defined sequence of short-lived appearances and disappearances of monospecific bolboformid populations at Site 1123 is very similar to the sequence of appearances and disappearances at Site 593 (Table 3) – a much shallower oceanic site in the Tasman Sea (text-fig. 1) with very well preserved calcareous microfossil assemblages. Although it is still only possible to speculate about the causes of these appearances and disappearances, the general increase in bolboformid abundance and diversity that occurs between DSDP Sites 590 and 594 (Grütz-macher 1993) points to their introduction from higher southern latitudes. Because the northward transport of bolboformids is orthogonal to the regional paleoceanographic pattern of surface-water circulation and oceanic fronts in the late Miocene (Edwards 1975; Nelson and Cooke 2001) it has been postulated that the bolboformids were entrained in the northward flow of subsurface water masses (Cooke et al. 2002; Crundwell et al.

2005). Furthermore, the presence of bolboformids at relatively shallow oceanic sites where the seafloor is bathed by Antarctic Intermediate Water (AAIW; e.g. Sites 593 and 594) suggests the distribution of bolboformids may have been coextensive with the distribution of this water mass. In this respect, the punctuated record of bolboformid appearances and disappearances at Site 1123 – average duration 150kyr (Table 2) – may record periodic episodes of intensified AAIW formation at the Antarctic Polar Front. In this context, it is speculated that bolboformid abundance spikes, where bolboformid numbers in the >150µm sediment size fraction sometimes reach several thousand specimens per gram, may record condensed intervals, or diastems.

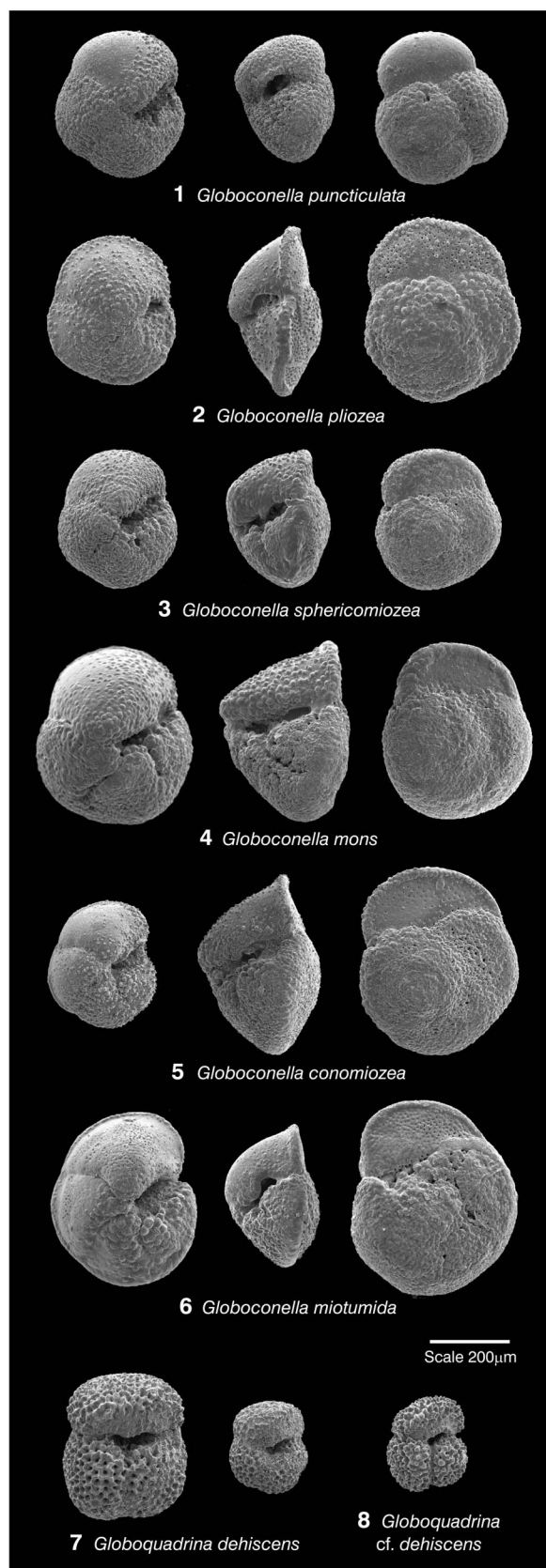
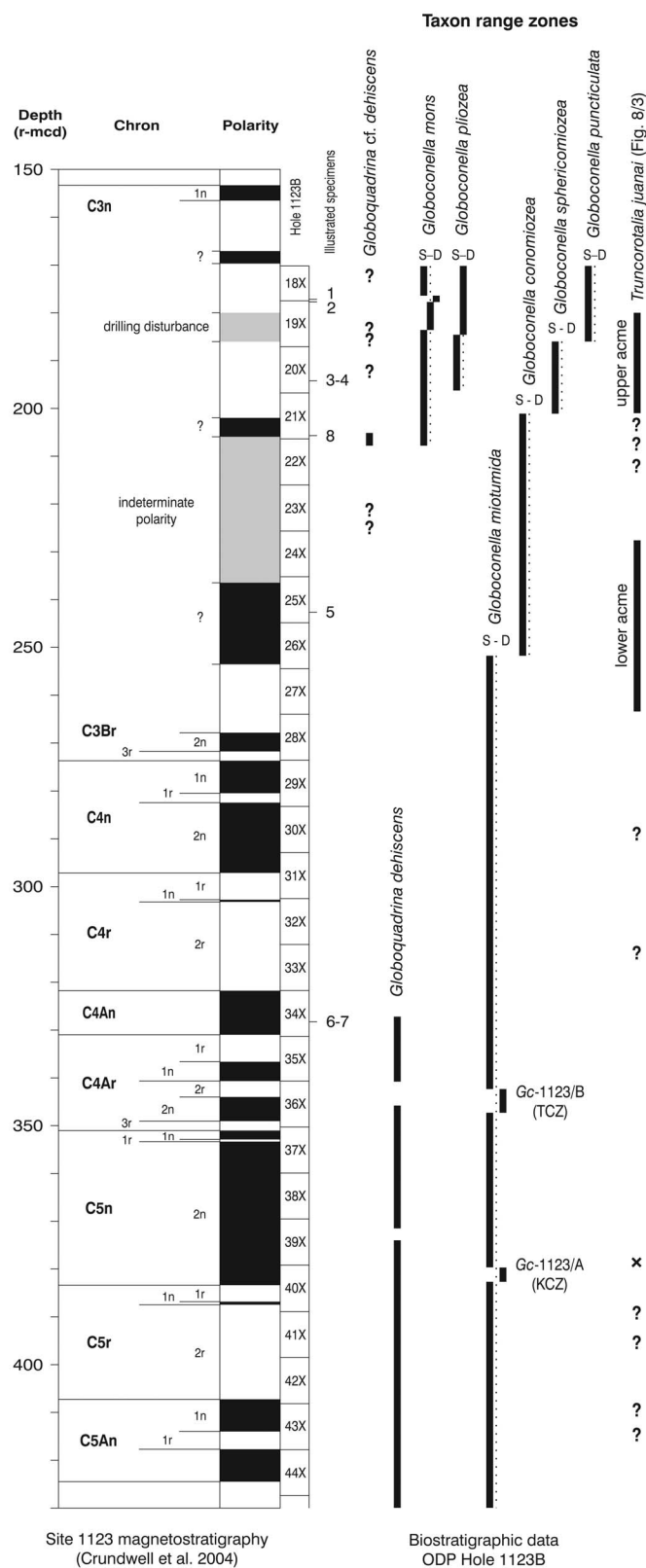
The extinction of bolboformids in the Southwest Pacific at 8.21 Ma occurs about 4myr earlier than their extinction in the southern Indian Ocean, in the late early Pliocene, Zanclean (Spiegler and Daniels 1991; Mackensen and Spiegler 1992), and 5.4myr before their extinction in the North Atlantic (Spiegler 1999). The reason for the early extinction of bolboformids in the Southwest Pacific is not known. We would speculate, however, that the late Miocene restriction of the Indonesian Gateway (Gasperi and Kennett 1993) and subsidence of the Norfolk Ridge (Herzer et al. 1997) may have intensified the counter-flow of higher salinity AAIW that interrupts the northward flow of low-salinity AAIW in the Southwest Pacific and Tasman Sea (e.g. Wyrki 1962). The northward flow of AAIW is unlikely to have ceased completely, but a reduction in the intensity of the flow may have been sufficient to interrupt the entrained supply of bolboformids in such a water mass (Cooke et al. 2002). Further studies of bolboformid distribution patterns are clearly needed on regional and global scales to elucidate the paleoceanographic circulation patterns of intermediate water masses.

PLANKTIC FORAMINIFERS

Planktic foraminifers, including species that are used for the recognition and correlation of New Zealand stages, are present throughout the upper Miocene section of Site 1123, although their preservation and abundance are highly variable (text-fig. 5). The large number of fragmented and partially dissolved shells in many samples and the dominance of heavily encrusted morphotypes, particularly *Globoconella*, *Zeaglobigerina*, and *Neoglobobulimina*, suggest calcareous faunas were subject to differential dissolution. Faunas that have been severely affected by dissolution contain mostly benthic specimens and they have few whole or nearly whole specimens. This reduces the potential biostratigraphic resolution of some planktic foraminiferal events, particularly those that have a low resistance to dissolution.

Planktic foraminiferal biostratigraphy and biochronology

The biostratigraphic data from Site 1123 (Appendix 3) identify at least 13 planktic foraminiferal events based on species and morphotypes that have a high resistance to dissolution. They include dextral coiling excursions in *Globoconella miotumida* (Gc-1123/A and Gc-1123/B), the regional disappearance of *Globoquadrina dehiscens*, an acme zone of *Truncorotalia juanai*, and the evolutionary appearances of *Globoconella conomiozea*, *Gc. mons*, *Gc. sphericomiozea*, *Gc. pliozea*, and *Gc. punctulata*. Taxa that are less resistant to dissolution (e.g. *Neoglobobulimina mayeri* s.l., *Nq. pachyderma*, and *Truncorotalia crassaformis*) are poorly represented at Site 1123, even though they are relatively common in well preserved temperate



TEXT-FIGURE 6
Distribution of important dissolution-resistant planktic foraminifers at Site 1123B. The numbered horizons of illustrated specimens (1-8) correspond to the adjacent SEM images. All images are shown to the same scale. *Gc*-1123/A and *Gc*-1123/B (see caption to text-figure 5). S = sinistral-coiled, D = dextral-coiled.

planktic foraminiferal assemblages (Scott et al. 1990). Their poor preservation and patchy distribution at Site 1123 adversely affects their utility as biochronostratigraphic markers, but does not rule out their use for correlating sequences with better preservation.

Gc-1123/A coiling zone (10.92–10.82 Ma): The Gc-1123/A coiling zone is clearly defined in coiling data from Site 1123 (text-fig. 5). It is associated with intermittent acmes of dextral-coiled shells that interrupt the long-term succession of sinistrally-dominated populations of *Globoconella miotumida*, near the base of the upper Miocene (Tongaporutuan Stage). Even though the abundance of planktic foraminifers is highly variable through the upper Miocene section, most faunas have sufficient whole and fragmented specimens of *Gc. miotumida* to give reliable estimates of coiling directions. The base of the Gc-1123/A coiling zone is placed at the horizon where populations of *Gc. miotumida* first contain 20% or more of dextral shells. This occurs in 1123B-40X-3, 0–3cm. The datum is correlated with Chron C5n.2n(0.97) and has an interpolated magnetostratigraphic age of 10.92 Ma. Although the relative abundance of dextral shells within the coiling zone sometimes drops below 20%, the top of the zone is placed at the level where there is a persistent return to *Gc. miotumida* populations with less than 20% and in most instances less than 5%, of dextral shells. The top of the Gc-1123/A coiling zone, so defined, occurs in sample 1123B-40X-1, 0–3cm, within Chron C5n.2n(0.87) and has an interpolated magnetostratigraphic age of 10.82 Ma.

On the basis of its position near the base of the upper Miocene, the Gc-1123/A coiling zone is correlated with the Kaiti Coiling Zone (KCZ) – a coiling zone that has been recognized in neritic and marginal oceanic sequences exposed in New Zealand and at oceanic sites in the Tasman Sea, including Site 593 (Scott 1995). The KCZ occurs at the base of the Tongaporutuan Stage (Crundwell et al. 2004), and provides a useful criterion for the stage boundary in oceanic and deep-water sequences lacking age diagnostic species of *Bolivinita*. Morgans et al. (1996) have previously assigned an age of 11.26 Ma to the stage boundary, but on the basis of the present study the boundary is assigned an age of 10.92 Ma.

Gc-1123/B coiling zone (9.62–9.42 Ma): The Gc-1123/B coiling zone has previously been identified at Site 593 and at uplifted marine sequences in New Zealand (Crundwell et al. 1997b; Crundwell 2004). It is a very short and well-defined zone associated with acmes of dextrally-coiled *Globoconella miotumida*, similar to the Gc-1123/A coiling zone. An arbitrary 20% threshold of dextral-coiled specimens of *Gc. miotumida* – about four-times the long-term dextral average at Site 1123 – defines the stratigraphic limits of the coiling zone, although the relative abundance of dextral shells within the zone is highly variable and sometimes falls below 20%. It extends from 1123B-36X-5, 60–64cm to 1123B-36X-2, 10–14cm. The base of the coiling zone is correlated with Chron C4Ar.2n(0.71) and the top of the coiling zone with Chron C4Ar.2r(0.41). It has an interpolated magnetostratigraphic age of 9.62–9.42 Ma.

On the basis that the Gc-1123/B coiling zone is closely associated with *Bolboforma metzmacheri* s.s. and the regional disappearance of *Globoquadrina dehiscens*, it is correlated with the Tukemokihi Coiling Zone (TCZ), the youngest of three late Miocene intervals of dextrally-coiled *Gc. miotumida* (Crundwell et al. 2004). The Mapiri Coiling Zone (MCZ), which oc-

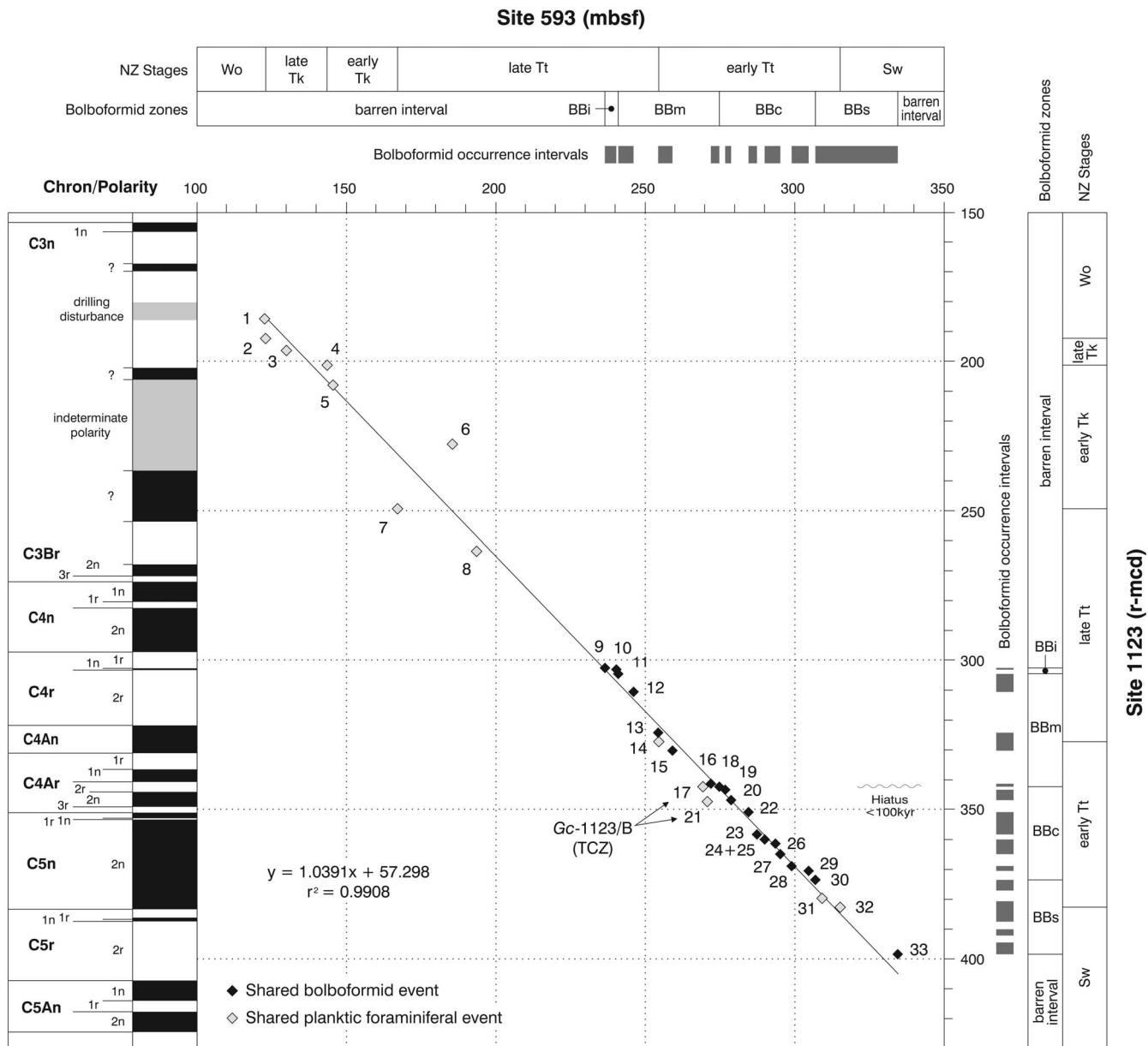
curs between the KCZ and TCZ (Crundwell et al. 2004), is not recognized at Site 1123. It is presumably cut-out by the hiatus in Chron C4Ar.2r (see earlier).

HO *Globoquadrina dehiscens* (8.88 Ma): *Globoquadrina dehiscens* is a deep dwelling warm-water species that occurs in low numbers throughout the lower upper Miocene section of Site 1123. It is relatively persistent and is found in 85% of early late Miocene samples, including 19 out of 20 samples in the interval immediately prior to its disappearance (Appendix 3). Most specimens are small and heavily encrusted and this appears to have been a factor in their preservation, particularly in intervals severely affected by dissolution. The highest occurrence of *Gq. dehiscens* is in sample 1123B-34X-4, 100–105cm. In the interval immediately prior to the species disappearance there is an abrupt change from high to low dissolution (text-fig. 5), the largest and most rapid baseline shift in the upper Miocene dissolution curve. The highest occurrence of *Gq. dehiscens* occurs within Chron C4An(0.57) and it has an interpolated magnetostratigraphic age of 8.88 Ma. This is significantly younger than 10.1 Ma reported by (Morgans et al. 1996) and it results in a more-or-less equal subdivision of the Tongaporutuan Stage into lower and upper parts. This ameliorates the paradox whereby most onland sections in New Zealand appeared to have sedimentary thicknesses that were disproportionate to the duration of these intervals.

The highest occurrence of *Gq. dehiscens* is well defined at Site 1123, although very rare specimens of *Gq. cf. dehiscens* occur higher in the late Miocene section, most notably between samples 1123B-22X-1, 140–145cm and 1123B-21X-6, 90–95cm (Appendix 3). These specimens are very small and they resemble the Paleogene taxon *Acarinina primitiva* in having a strongly muricate test and only three to three and one-half chambers in the outer whorl (text-fig. 6/8). Most have a flattened, steeply inclined umbilical face and an exterior-marginal-umbilical aperture, but they lack the well-developed tooth-like projection that is typical of large specimens of *Gq. dehiscens*. As there is no evidence to substantiate reworking, the specimens are considered to be expatriates that have been reintroduced to the New Zealand region from low latitudes, where the range of *Gq. dehiscens* extends up to the Miocene–Pliocene boundary (Kennett and Srinivasan 1983; Berggren et al. 1995; Li et al. 2006).

Similar enigmatic occurrences of *Gq. dehiscens* have also been noted in the latest Miocene and early Pliocene in Marlborough and eastern North Island, New Zealand (Edwards 1987), but there are no records of expatriates in oceanic sequences from similar latitudes in the Tasman Sea (Jenkins and Srinivasan 1986). This suggests that in the latest Miocene there may have been a flow or periodic flow of relatively warm subtropical surface water off eastern New Zealand. This supports a major reorganisation of oceanic circulation in the late Miocene and the development of an early western Pacific warm pool (Li et al. 2006).

***Truncorotalia juanai* acme zone (7.23–6.23 Ma):** *Tr. juanai* is a relatively uncommon species and it has a patchy distribution in the upper Miocene section of Site 1123. Persistent records of *Tr. juanai* are only found between 1123B-27X-7, 0–5cm to 1123B-24X-2, 50–55cm, and 1123B-21X-3, 40–45cm to 1123B-17X-7, 0–5cm (text-fig. 6). The lower interval is moderately well defined and it includes spirally-domed morphotypes of *Tr. juanai* similar to those found in the middle acme zone of



Site 1123 magnetostratigraphy
(Crundwell et al. 2004)

TEXT-FIGURE 7

Shaw-plot of shared bolboformid and planktic foraminiferal events from Sites 1123 and 593, bolboformid occurrence intervals, bolboform zonation, and New Zealand Stage correlation at both sites. An explanation of numbered bioevents is given in Table 3.

Tr. juanai at Site 593. It extends from Chron C3Br.2r to the lower part of an interval of indeterminate polarity and has an interpolated magnetostratigraphic age of ca. 7.23–6.23 Ma. The upper interval of *Tr. juanai* is in the vicinity of the Miocene–Pliocene boundary and corresponds to the upper *Tr. juanai* acme zone at Site 593 (Crundwell 2004; Crundwell et al. 2004). It is a poorly defined interval and includes a range of biconvex to ventroconical morphotypes (*Truncorotalia* aff. *crassaformis*). The interval is significant in that it marks the permanent colonisation of the New Zealand region by *Trunco-*

rotalia and the beginning of an extended period of truncorotalid evolution.

LO *Globoconella conomiozea* (ca. 6.87 Ma): There is considerable confusion concerning *Gc. conomiozea*, with some biostratigraphers considering it to be an intraspecific variant of *Gc. miotumida* (Scott 1979; Cifelli and Scott 1986; Scott et al. 1990), while others argue that it evolved from *Gc. miotumida* as a discrete taxonomic entity (Kennett 1966; Malmgren and Kennett 1981, 1982; Hornibrook 1982). Despite these opposing

views, nearly all workers agree that although the degree of conicity may vary within upper Miocene elements of the *Gc. miotumida* plexus, there is a modal decrease in the number of chambers in the outer whorl in successively younger populations. For the purpose of this study, the entry of *Gc. conomiozea* is placed at the horizon where 10% or more of adult specimens in late Miocene populations of *Gc. miotumida-conomiozea* with high-arched apertures have less than four and one-half chambers in the outer whorl (text-fig. 6/5). This occurs in core 1123B-26X-2, 30-35cm, within the lower *Tr. juanai* acme zone, and it is correlated with the lower part of an interval of indeterminate polarity. The lowest occurrence of *Gc. conomiozea* has an interpolated age of ca. 6.87 Ma.

LO *Globoconella mons* (ca. 5.72 Ma): The entry of *Gc. mons* is marked by compactly coiled four-chambered variants of the *Gc. miotumida* plexus with reduced or closed umbilici, slit-like apertures, and conical to subconical axial profiles (text-fig. 6/4). The first such specimens are found in 1123B-22X-1, 140-145cm, between the top of the lower *Tr. juanai* acme zone and the lowest occurrence of *Gc. sphericomiozea*. This occurs within the lower part of an interval of indeterminate polarity and the datum has a poorly constrained interpolated age of ca. 5.72 Ma.

LO *Globoconella sphericomiozea* (ca. 5.53 Ma): The morphological transformation in populations of *Gc. conomiozea-sphericomiozea* occurs in an interval where globoconellids are relatively common, but most specimens are heavily encrusted and keels are often obscured by calcite overgrowth. This makes identification of the lowest occurrence of *Gc. sphericomiozea* difficult and reduces the reliability of the datum. Very rare non-carinate morphotypes are first noted in sample 1123B-27X-6, 50-55cm, but they become more persistent above 1123B-22X-1, 140-145cm. However, based on the population threshold for the lowest occurrence of *Gc. sphericomiozea* – sensu Scott (1980) where 5% or more of specimens are non-carinate – the species lowest occurrence is identified in 1123B-21X-2, 90-95cm. The datum occurs within an unidentified interval of reversed polarity and has an interpolated age of ca. 5.53 Ma.

At Blind River, an uplifted marine section in New Zealand (text-fig. 1), the lowest occurrence of *Gc. sphericomiozea* occurs within Chron C3r (Roberts et al. 1994) and it has an assigned age of 5.5 Ma (Morgans et al. 1996). Berggren et al. (1995) report a similar age of 5.6 Ma for the appearance of *Gc. sphericomiozea* at subtropical Site 588, in the Southwest Pacific. Despite the potential errors involved in locating the datum at Site 1123, it would appear to be reliably correlated with the GPTS.

LO *Globoconella pliozea* (ca. 5.39 Ma): The adopted species concept for *Gc. pliozea* is based on relatively compressed, compactly coiled, biconvex, keeled morphotypes within the *Gc. miotumida* plexus with less than four and one half chambers in the outer whorl of adult specimens (text-fig. 6/2). The entry of such specimens occurs above the lowest occurrence of *Gc. sphericomiozea* in 1123B-20X-2, 9-14cm, within the upper part of an unidentified interval of reversed polarity. In terms of the GPTS-95 time scale (Cande and Kent 1995), the interpolated age of 5.39 Ma is consistent with the datum occurring within the upper part of an interval of reversed polarity (Chron C3r), but is younger than the 5.6 Ma age reported by Berggren et al. (1995) from subtropical Site 588 in the Southwest Pacific.

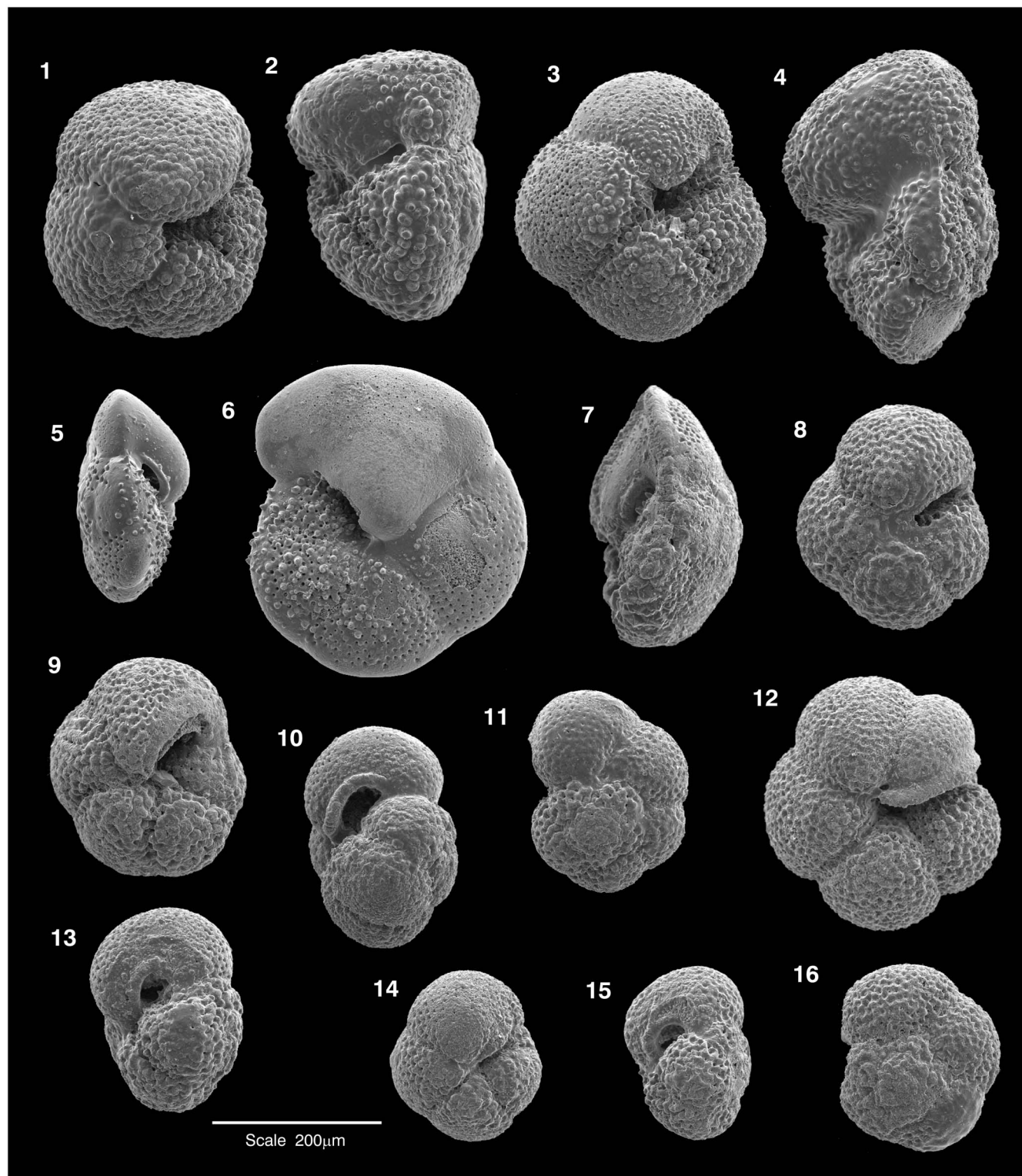
LO *Truncorotalia crassaformis* (ca. 5.15 Ma): The lowest occurrence of *Tr. crassaformis* is marked by the first appearance of distinctly ventroconical morphotypes in populations of *Tr. juanai-crassaformis*. This occurs in sample 1123B-20X-1, 10-14cm in an unidentified interval of reversed polarity, and it has an interpolated age of ca. 5.15 Ma. Below this horizon, however, planktic foraminiferal assemblages are very poor and it is unlikely that the lowest occurrence of *Tr. crassaformis* is located accurately.

The morphological transformation between *Tr. juanai* and *Tr. crassaformis* occurs rapidly at Site 1123 and intermediate morphotypes (*Tr. aff. crassaformis*) are confined to an interval of less than 20m (ca. 0.5myr). More detailed study of this plexus is needed, but it may be possible to refine correlations near the Miocene–Pliocene boundary and establish a morphometrically-based phylo-zonation in well-preserved sequences (e.g. Malmgren and Kennett 1982).

TEXT-FIGURE 8

SEM images of dissolution resistant globorotalid species from Site 1123B. All images are shown to the same scale.

- | | |
|--|---|
| 1 <i>Truncorotalia crassaformis</i> (Galloway and Wissler); 18X-6, 5-10cm | 8 <i>Neogloboquadrina pachyderma</i> (Ehrenberg); 20X-6, 50-55cm |
| 2 <i>Truncorotalia crassaformis</i> (Galloway and Wissler); 18X-5, 100-105cm | 9-11 <i>Paragloborotalia mayeri</i> (Cushman and Ellis); 43X-4, 100-105cm |
| 3 <i>Truncorotalia juanai</i> (Bermúdez and Bolli); 20X-5, 100-105cm | 12 <i>Neogloboquadrina acostaensis</i> (Blow); 18X-6, 5-10cm |
| 4 <i>Truncorotalia aff. crassaformis</i> ; 20X-5, 100-105cm | 13-16 <i>Paragloborotalia continua</i> (Blow); 43X-4, 100-105cm |
| 5-6 <i>Hirsutella scitula</i> (Brady); 20X-5, 100-105cm | |
| 7 <i>Hirsutella panda</i> (Jenkins); 1123B-43X-1, 100-103cm | |



LO *Globoconella puncticulata* (ca. 5.11 Ma): The lowest occurrence of *Gc. puncticulata* is placed at the level where more than 95% of large adult specimens in *Gc. sphericomiozea-puncticulata* populations are non-carinate. Based on this population concept, the lowest occurrence of *Gc. puncticulata* is identified in 1123B-19X-7, 0-5cm, in an interval with large well-preserved populations of encrusted specimens. The datum, however, is associated with an interval of drilling disturbance and indeterminate polarity and its position is unlikely to be accurate. It has an interpolated age of ca. 5.11 Ma.

At subtropical DSDP Sites 590 and 516, the lowest occurrence of *Gc. puncticulata* occurs close to the base of Chron C3n.4n (Dowsett 1989) and it has an assigned age of 5.2 Ma (Morgans et al. 1996). Given the uncertainty of the magnetostratigraphic correlation associated with the entry of *Gc. puncticulata* at Site 1123 and the difficulty of locating the entry of the species in rapidly evolving populations (e.g. Scott et al. 1980), the species entry would appear to be a more or less synchronous southern mid-latitude event. It also suggests the interval of drilling disturbance and indeterminate polarity at Site 1123 may include Chron C3n.4n and that the underlying interval of reversed polarity, where *Gc. pliozea* and *Gc. sphericomiozea* enter, may correspond to Chron C3r. This interpretation of the magnetostratigraphy is consistent with the entry of the latter species at Blind River (Roberts et al. 1994) and it suggests the magnetostratigraphic age calibration of bioevents at Site 1123 may be improved in the vicinity of the Miocene–Pliocene boundary.

COMPARISON OF BIOSTRATIGRAPHIC DATA IN SITES 1123 AND 593

The sequence of bolboformid and planktic foraminiferal bioevents identified at Site 1123 is correlated with Site 593 in the Tasman Sea – a very well preserved late Miocene biostratigraphic reference section (Jenkins and Srinivasan 1986; Lohmann 1986; Hoskins 1990; Scott 1992; Grützmacher 1993; Crundwell et al. 2004). A scatter-plot (text-fig. 7) based on 33 shared bioevents (Table 3) allows a line of correlation to be drawn between the two sections (Shaw 1964; Dowsett 1989).

These biostratigraphic data approximate a linear trendline and indicate the relative rate of sediment accumulation at the two sites was more-or-less constant through the late Miocene, even though the sites were more than 1400km apart and associated with different water masses. The tight grouping of the biostratigraphic data around the line of correlation ($r^2 = 0.9908$) and the consistency of their order, suggest most bioevents are synchronous or nearly so.

In the lower part of the upper Miocene section at Site 1123, the only demonstrably diachronous events relate to the *Gc*-1123/B coiling zone. It plots out of sequence with respect to the highest occurrence of *B. gracilireticulata* s.l., the top and bottom of the lower *B. metzmacheri* s.s. occurrence zone and its associated abundance spike; bolboformid events that plot very close to the linear line of correlation between the sites (text-fig. 7). Although there may be a short hiatus immediately above the *Gc*-1123/B coiling zone (Shipboard Scientific Party 1999b) and there may be some uncertainty about the precise correlation of the lower *B. metzmacheri* occurrence zone, these factors alone would not explain the stratigraphic transposition of the bioevents. The possibility of a hiatus at Site 1123 and the apparent diachrony of the *Gc*-1123/B coiling zone (ca. 320kyr) between Southwest Pacific Site 1123 and Tasman Sea Site 593, place a caveat on the reliability of the coiling zone as a regional biochronostratigraphic marker, but they do not preclude its use for local correlations.

The upper part of the biostratigraphic sequence at Site 1123, following the disappearance of bolboformids, has a relatively small number of events compared to the lower part of the sequence at the same site (text-fig. 7). Most of the events in the upper part of the sequence are based on the evolutionary appearances of globoconellid species that are relatively common. The dominance, however, of heavily encrusted morphotypes and the high number of broken specimens in dissolution-affected samples make the interpretation of transitional populations difficult. Although this may adversely affect the reliability of some bioevents, most plot close to the linear line of correlation, ex-

TEXT-FIGURE 9

SEM images of dissolution resistant globigerine species from Site 1123B. All images are shown to the same scale.

- | | |
|---|---|
| 1–3 <i>Sphaeroidinellopsis seminulina</i> (Schwager); 32X-1, 50-55cm | 10 <i>Zeaglobigerina woodi</i> (Jenkins); 26X-2, 30-35cm |
| 4 <i>Globigerinoides quadrilobatus</i> (d'Orbigny); 34X-5, 50-55cm | 11 <i>Catapsydrax parvulus</i> (Olli, Loeblich, and Tappan); 21X-7, 0-5cm |
| 5 <i>Globigerinoides trilobus</i> (Reuss); 34X-5, 50-55cm | 12 <i>Globigerinita glutinata</i> (Egger); 43X-4, 100-105cm |
| 6 <i>Globoquadrina dehiscens</i> (Chapman, Parr, & Collins); 34X-5, 50-55cm | 13 <i>Globigerina bulloides</i> d'Orbigny; 26X-2, 30-35cm |
| 7 <i>Globoquadrina venezuelana</i> (Hedberg); 18X-3, 0-5cm | 14 <i>Globigerina</i> sp.; 42X-1, 50-53cm |
| 8 <i>Zeaglobigerina nepenthes</i> (Todd); 34X-5, 50-55cm | 15 <i>Globigerina angustumbilicata</i> Bolli; 21X-6, 90-95cm |
| 9 <i>Zeaglobigerina druryi</i> (Akers); 42X-1, 50-53cm | 16 <i>Globigerinopsis obesa</i> (Bolli); 26X-2, 30-35cm |

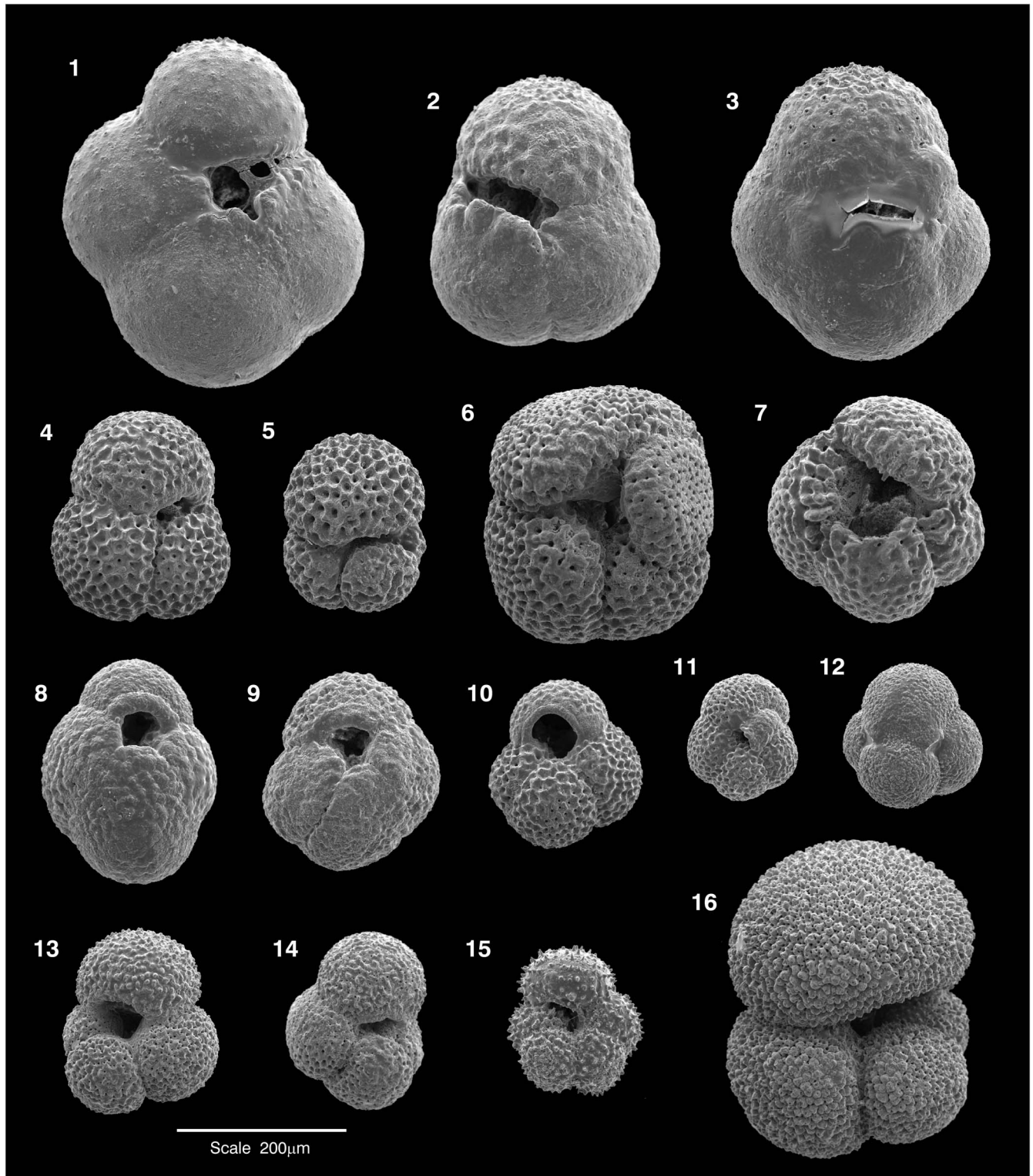


TABLE 1

Coring summary and core splice data Hole 1123B-18X to 44X. Core deformation during the coring and retrieval operation probably accounts for most of the variability in core recovery (average recovery 97.5%). For cores 23X, 26X, and 41X-44X that have less than 90% recovery this table gives a slope (m) and intercept (b) for a linear transformation from reported mbsf to stretched mbsf. Stretched mbsf = (m x mbsf) + b. To subsequently translate a sample to stretched r-mcd (revised-metres composite depth), add the offset in the last column of this table. For the other cores listed in this table, to translate a sample from mbsf to r-mcd, just add the offset.

Hole	Core	Top (mbsf)	Bottom (mbsf)	Recovered core (m)	Section drilled	Recovery (%)	Slope (m)	Intercept (b)	Offset (M)
1123-B	18X	155.40	163.79	8.39	7.30	114.9			14.80
1123-B	19X	162.70	172.41	9.71	9.50	102.2			14.80
1123-B	20X	172.30	182.05	9.75	9.50	102.6			14.80
1123-B	21X	181.90	191.37	9.47	9.50	99.7			14.80
1123-B	22X	191.60	201.47	9.87	9.50	103.9			14.80
1123-B	23X	201.20	208.96	7.76	9.50	81.7	1.2703	-54.40	14.80
1123-B	24X	210.80	220.55	9.75	9.50	102.6			14.80
1123-B	25X	220.40	230.10	9.70	9.50	102.1			14.80
1123-B	26X	230.00	234.18	4.18	9.50	44.0	2.500	-345.06	14.80
1123-B	27X	239.60	249.42	9.82	9.50	103.4			14.80
1123-B	28X	249.20	258.79	9.82	9.50	103.4			14.80
1123-B	29X	258.80	268.59	9.79	9.50	103.1			14.80
1123-B	30X	268.40	278.05	9.65	9.50	101.6			14.80
1123-B	31X	278.10	287.59	9.49	9.50	99.9			14.80
1123-B	32X	287.70	296.41	8.71	9.50	91.7			14.80
1123-B	33X	297.30	306.95	9.65	9.50	101.6			14.80
1123-B	34X	306.90	316.68	9.78	9.50	102.9			14.80
1123-B	35X	316.50	326.12	9.62	9.50	101.3			14.80
1123-B	36X	325.90	335.57	9.67	9.50	101.8			14.80
1123-B	37X	335.50	345.30	9.80	9.50	103.2			14.80
1123-B	38X	345.10	354.89	9.79	9.50	103.1			14.80
1123-B	39X	354.70	364.58	9.88	9.50	104.0			14.80
1123-B	40X	364.40	374.16	9.76	9.50	102.7			14.80
1123-B	41X	374.10	382.30	8.20	9.50	86.3	1.2703	-101.13	14.80
1123-B	42X	383.70	388.54	4.84	9.50	50.9	2.1364	-436.08	14.80
1123-B	43X	393.40	399.62	6.22	9.50	65.5	1.5932	-233.39	14.80
1123-B	44X	403.00	408.42	5.42	9.50	57.1	1.8725	-351.65	14.80

cept for the top of the *Truncorotalia juanai* acme zone and the lowest occurrence of *Globoconella conomiozea* (text-fig. 7, bioevents 6 and 7). The order of these events is transposed and they plot some distance from the line of correlation. This suggests that the stratigraphic level of these events, at Site 1123, may not be reliable.

CONCLUSIONS

The excellent biostratigraphic correlation between Southwest Pacific Site 1123 and Tasman Sea Site 593, suggests the late Miocene magnetostratigraphically constrained biochronology from Site 1123 can be used in the temperate Southwest Pacific and Tasman Sea regions with a high degree of reliability. It also allows the ages of bioevents that are poorly defined or missing at Site 1123, including those that are associated with other microfossils groups, to be calibrated at other sites in the region by way of second-order GPTS correlations. This will undoubtedly lead to further refinements in late Miocene biochronology in the region. It will also advance the use of modern high-resolution stratigraphic tools and our ability to orbitally-tune and

correlate sedimentary sequences on a refined scale not previously possible.

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TABLE 2

Comparison of dated bolboformid datums between Site 1123 and North Atlantic. North Atlantic bolboformid datums have been dated from interpolations of second-order nannofossil and planktic foraminiferal correlations with GPTS-95 (Spiegler 1999). Bolboformid zonation emended after Spiegler and Daniels (1991) and Grützner (1993) for use in the Southwest Pacific. Definitions of biozones are given in Appendix 2. HO = highest occurrence, LO = lowest occurrence.

Event	Site 1123 (Ma)	Interval duration (kyr)	Bolboform zonation	North Atlantic (Ma)
HO <i>Bolboforma praeintermedia</i>	8.21	30	<i>B. intermedia</i> Interval Zone (BBI)	7.7
LO <i>Bolboforma praeintermedia</i>	8.25			
HO <i>Bolboforma metzmacheri ornata</i>	8.28	160	<i>B. metzmacheri</i> Taxon-range Zone (BBm)	
LO <i>Bolboforma metzmacheri ornata</i>	8.44			
HO <i>Bolboforma metzmacheri</i> s.s. (top upper occurrence interval)	8.78	230		
LO <i>Bolboforma metzmacheri</i> s.s. (base upper occurrence interval)	9.01			
HO <i>Bolboforma metzmacheri</i> s.s. (top lower occurrence interval)	9.34	200		9.7
LO <i>Bolboforma metzmacheri</i> s.s. (base lower occurrence interval)	9.54			
HO <i>Bolboforma gracilireticulata</i> s.l.	9.61	140		
LO <i>Bolboforma gracilireticulata</i> s.l.	9.75			
HO <i>Bolboforma pentspinosa</i>	10.08	70	<i>B. capsula</i> Interval Zone (BBc)	
HO <i>Bolboforma capsula</i>	10.13			
LO <i>Bolboforma pentspinosa</i>	10.15	70		
LO <i>Bolboforma capsula</i>	10.20			
HO <i>Bolboforma gruetzmacheri</i>	10.31	150		
LO <i>Bolboforma gruetzmacheri</i>	10.46			
HO <i>Bolboforma subfragoris</i> s.l. (top occurrence interval BBs-1123/D)	10.50	150		10.6
Base occurrence interval BBs-1123/D	10.65			
Top occurrence interval BBs-1123/C	10.77	270	<i>B. subfragoris</i> s.l. Taxon-range Zone (BBs)	
Base occurrence interval BBs-1123/C	11.04			
Top occurrence interval BBs-1123/B	11.15	130		
Base occurrence interval BBs-1123/B	11.28			
Top occurrence interval BBs-1123/A	11.36	200		
LO <i>Bolboforma subfragoris</i> s.l. (base occurrence interval BBs-1123/A)	11.56			

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TABLE 3

Shared bioevents in Sites 1123 and 593. (r-mcd) = revised metres composite depth (G.S. Wilson pers. comm. 2002). Closest = closest constraining sample listed in the range chart (Appendix 3) to a datum. Midpoint = first and last occurrences recorded between the closest samples listed in the range chart. Persistence = presence/absence ratio of a taxon through its occurrence interval leading up to or following a datum; maximum of 20 samples. Chron/subchron = correlations give the proportional position from its younger end. Age = interpolated from the sites magnetostratigraphy (Shipboard Scientific Party 1999a, emended G.S. Wilson pers. comm. 2002), based on GPTS-95 (Berggren et al. 1995; Cande and Kent 1995). Age limit = age difference between samples constraining a datum. Site 593 = biostratigraphic data from Crundwell (2004). LO = lowest occurrence, HO = highest occurrence. *Bioevents that do not maintain homotaxial order (see text-figure 7).

Site 1123 (Hole B)										Site 593		Ref.	Lowest and highest occurrences, coiling zones, and bolboformid abundance spikes
Core	Sect.	Upp. (cm)	Low. (cm)	Depth (mbsf)	Depth (r-mcd)	Closest (m)	Midpoint (r-mcd)	Persistence	Chron/Subchron	Age (Ma)	Age limit (Ma)	Midpoint (mbsf)	
19X	7	0	5	170.82	185.62	1.58	186.41	1.00	indeterminate	5.11	±0.01	123.01	1 LO <i>Globoconella puncticulata</i> s.s. (<5% weakly carinate) Wo/Tk proxy
20X	1	10	14	172.40	187.20	0.90	187.65	0.65	reversed	5.15	±0.01	129.30	2 LO <i>Truncorotalia crassaformis</i>
20X	7	0	5	181.40	196.20	0.90	196.65	1.00	reversed	5.39	±0.01	130.10	3 LO <i>Globoconella plozea</i>
21X	3	140	145	186.30	201.10	0.98	201.59	1.00	reversed	5.53	±0.01	143.69	4 LO <i>Globoconella sphericomiozea</i> s.s. upper-lower Tk proxy
22X	1	140	145	193.00	207.80	1.37	208.49	0.95	indeterminate	5.72	±0.02	145.72	5 LO <i>Globoconella mons</i>
24X	2	50	55	212.80	227.60	-0.90	227.15	0.50	indeterminate	6.23	±0.01	185.27	6* Top <i>Truncorotalia juanai</i> acme zone (middle acme zone Site 593)
26X	2	30	35	231.80	249.24	1.50	249.99	1.00	indeterminate	6.87	±0.03	167.25	7* LO <i>Globoconella conomiozea</i>
27X	7	0	5	248.60	263.40	1.00	263.90	0.80	C3Br.2r	7.23	±0.01	193.71	8 Base <i>Truncorotalia juanai</i> acme zone (middle acme zone Site 593)
31X	7	0	5	287.10	301.90	-0.50	301.65	1.00	C4r.1r(0.81)	8.21	±0.01	236.42	9 HO <i>Bolboforma praeintermedia</i>
32X	1	50	55	288.20	303.00	0.50	303.25	1.00	base C4n.1n	8.25	±0.01	240.42	10 LO <i>Bolboforma praeintermedia</i>
32X	2	50	55	289.70	304.50	-0.50	304.25	0.92	C4r.2r(0.06)	8.28	±0.01	240.82	11 HO <i>Bolboforma metzmacheri ornata</i>
32X	6	50	55	295.70	310.50	1.70	311.35	0.92	C4r.2r(0.44)	8.45	±0.02	246.17	12 LO <i>Bolboforma metzmacheri ornata</i>
34X	2	100	105	309.40	324.20	-0.50	323.95	0.69	C4An(0.25)	8.78	±0.01	254.19	13 HO <i>Bolboforma metzmacheri</i> s.s. (upper occurrence interval)
34X	4	100	105	312.40	327.20	-0.50	326.95	0.90	C4An(0.57)	8.88	±0.01	254.38	14 HO <i>Globoquadrina dehiscens</i> (upper-lower Tt proxy)
34X	6	100	105	315.40	330.20	0.50	330.45	0.69	C4An(0.94)	9.01	±0.01	259.17	15 LO <i>Bolboforma metzmacheri</i> s.s. (upper occurrence interval)
36X	1	60	64	326.50	341.30	-0.50	341.05	1.00	C4Ar.2r(0.11)	9.34	±0.02	271.83	16 HO <i>Bolboforma metzmacheri</i> s.s. (lower occurrence interval)
36X	2	10	14	327.50	342.30	-0.50	342.05	0.50	C4Ar.2r(0.41)	9.42	±0.02	269.07	17* Top Gc-1123/B coiling zone >20% Dex (= top TCZ)
36X	2	10	14	327.50	342.30	±0.50	342.30	1.00	C4Ar.2r(0.48)	9.44	±0.04	274.72	18 <i>Bolboforma metzmacheri</i> s.s. abundance spike (lower occurrence interval)
36X	2	110	114	328.50	343.30	0.50	343.55	1.00	C4Ar.2r(0.86)	9.54	±0.02	276.82	19 LO <i>Bolboforma metzmacheri</i> s.s. (lower occurrence interval)
36X	5	10	14	332.00	346.80	-0.50	346.55	0.67	C4Ar.2n(0.51)	9.61	±0.00	278.61	20 HO <i>Bolboforma gracilireticulata</i> s.l.
36X	5	60	64	332.50	347.30	0.50	347.55	0.50	C4Ar.2n(0.71)	9.62	±0.00	270.82	21* Base Gc-1123/B coiling zone >20% Dex (= base TCZ)
37X	1	50	54	336.00	350.80	0.50	351.05	0.67	base C4Ar.3r	9.75	±0.02	284.62	22 LO <i>Bolboforma gracilireticulata</i> s.l.
37X	6	50	54	343.50	358.30	-0.50	358.05	0.75	C5n.2n(0.16)	10.08	±0.01	287.18	23 HO <i>Bolboforma pentaspinosa</i> (excludes Site 1123 outlier)
38X	1	10	14	345.20	360.00	-0.70	359.65	1.00	C5n.2n(0.21)	10.13	±0.01	289.62	24 HO <i>Bolboforma capsula</i>
38X	1	10	14	345.20	360.00	0.40	360.20	0.75	C5n.2n(0.22)	10.15	±0.01	290.42	25 LO <i>Bolboforma pentaspinosa</i>
38X	2	0	4	346.60	361.40	0.50	361.65	1.00	C5n.2n(0.27)	10.20	±0.01	293.61	26 LO <i>Bolboforma capsula</i>
38X	4	50	54	350.10	364.90	-0.50	364.65	0.89	C5n.2n(0.38)	10.31	±0.01	295.22	27 HO <i>Bolboforma gruetzmacheri</i>
38X	7	0	4	354.10	368.90	0.60	369.20	0.89	C5n.2n(0.53)	10.46	±0.01	299.02	28 LO <i>Bolboforma gruetzmacheri</i>
39X	1	100	104	355.70	370.50	-0.50	370.25	1.00	C5n.2n(0.56)	10.50	±0.01	304.57	29 HO <i>Bolboforma subfragoris</i> s.l. (top occurrence interval BBs-1123/D)
39X	4	50	53	359.70	374.50	±0.50	374.50	1.00	C5n.2n(0.71)	10.61	±0.02	306.86	30 <i>Bolboforma subfragoris</i> s.l. abundance spike (occurrence interval BBs-1123/D)
40X	1	50	53	364.90	379.70	-0.40	379.50	1.00	C5n.2n(0.87)	10.82	±0.01	309.05	31 Top Gc-1123/A coiling zone >20% Dex (= top KCZ)
40X	3	0	3	367.40	382.50	0.50	382.45	1.00	C5n.2n(0.97)	10.92	±0.01	315.24	32 Base Gc-1123/A coiling zone >20% Dex (= base KCZ) Tt/Sw boundary
41X	6	0	5	381.60	398.42	0.04	398.44	0.60	C5r.2r(0.55)	11.56	±0.00	334.65	33 LO <i>Bolboforma subfragoris</i> s.l. (base occurrence interval BBs-1123/A)

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