THE PALAEONTOLOGY OF BERING SEA FORAMINIFERA FROM THE LATE QUATERNARY

Thesis submitted for the degree of

Doctor of Philosophy

at the University of Leicester

by

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2015

Abstract

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ABSTRACT

The taxonomy of benthic foraminifera recovered from 160 core samples over depth 20.59 m and representing the past ~597 Kyr (sedimentary deposit of the Tarantian and Ionian stages) at Bowers Ridge, Bering Sea IODP site U1342, includes some 52 species from 41 genera and 22 families: these species are given formal taxonomic treatment with detailed illustration. A further 16 species are discussed in open nomenclature. Foraminifer assemblages are dominated by species of *Takayanagia delicata, Uvigerina bifurcata, Islandiella norcrossi* and *Alabaminella weddellensis* accounting for more than 58 % of all specimens recovered. In addition to their taxonomic identification, this study interrogates the relationship between benthic foraminifera and interpreted changes in oxygen concentration and productivity during a series of late Quaternary glacial–interglacial cycles at site U1342. In particular, the species *Bolivina spissa* (Cushman) – thought to record changes in seabed oxygen level, shows no correlation between test pore density and interpreted bottom water oxygen level (BW-O_2), suggesting that oxygen is not the sole driver influencing the distribution and morphology of this species. Further assessment of the total foraminiferal assemblages at site U1342 - using the sedimentological context and the proportion of deep infaunal species as a proxy for low oxygen conditions at the seabed, and shallow infaunal species as a proxy for a well-oxygenated seabed, identify eight broadly defined temporally successive benthic foraminiferal intervals through the sampled core. Three of these intervals, between depths 0 - ~5.40, ~ 6.50 - 9.00 and ~16.90 - 18.67 m-CCSF, signal a well-oxygenated sea bed, whilst the other five intervals suggest increased phytodetritus flux to the seabed, coupled with variations in seabed oxygen level. In general, there is no clear connexion between these intervals and the glacial-interglacial oscillation at the site during the past ~597 ka, suggesting that ecological influences on foraminiferal distribution at Bowers are complex.

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Chapter 1

An introduction to the Bering Sea and its benthic foraminifera

Chapter 1: An introduction to the Bering Sea and its benthic foraminifera

1 Introduction

This thesis examines the foraminiferal signature of a sedimentary core at Integrated Ocean Drilling Program (IODP) site U1342 on Bowers Ridge in the Bering Sea (Fig. 1.1), focussing on the upper 20.59 m of the core that equates to the past ~597,000 years (age calibration based on oxygen isotope stratigraphy from Knudson and Ravelo: in review). The core contains a diverse assemblage of benthic foraminifera whose taxonomic signature is given detailed appraisal (Chapter 2). The thesis also examines the environmental signature of the species *Bolivina spissa* (Chapter 3) vis-à-vis its distribution and morphology, and also the overall down core pattern of the 68 foraminiferal species identified, relative to interpreted palaeoenvironmental conditions (Chapter 4). This opening chapter provides the geographic and oceanographic context of the Bering Sea, the description of the methods utilised for studying its seabed microfauna, and presents summaries of the chapters as they appear in the thesis.

1.1 Bering Sea geography

The Bering Sea is a semi-enclosed, high-latitude sea in the Arctic that is bounded to the north and west by Russia and the Kamchatka Peninsula, to the east by Alaska (Fig. 1.1), and to the south by the Aleutian Islands (Stabeno et al. 1999). The Bering Sea is the third largest marginal Sea in the world after the Mediterranean and South China seas with a surface area of 2.29 x 10^6 km^2 and a volume of 3.75 x 10^6 km^3 (Hood, 1983; Takahashi 2005). It has shallow water connections to the Arctic Ocean and deep water connections to the North Pacific Ocean. It is divided almost equally between a deep basin (maximum depth 4,000 m) and continental shelves (<200 m); the broad shelf (width greater than 500 km) in the east contrasts with the narrow shelf (less than 100 km) in the west (Stabeno et al. 1999). The depth of the Bering Strait on the continental shelf is ~50 m; this region was aerially exposed and the marine passage was completely closed during the last glacial maximum (LGM). Okada et al. (2005) considers that global ocean circulation patterns and/or intensity are influenced by variation of the Bering Strait water depth.
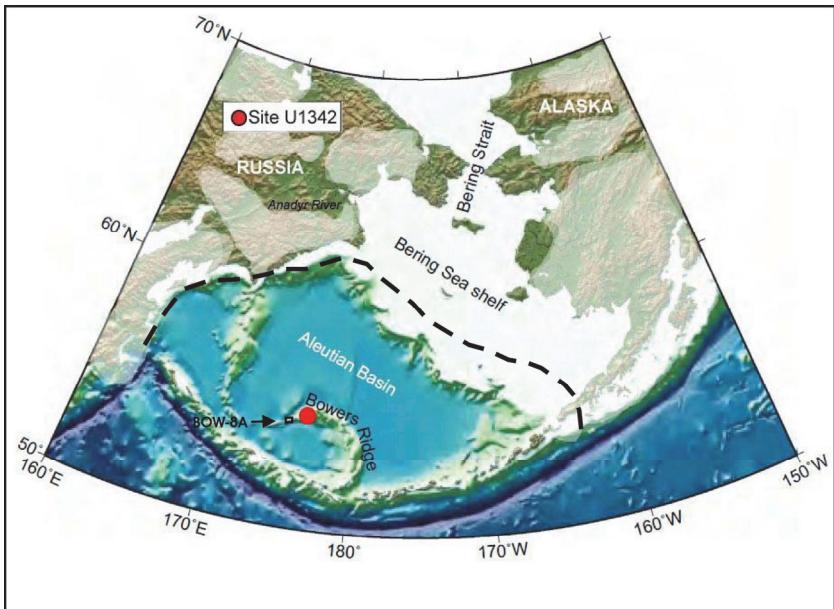
Figure 1.1 Location of Site U1342 (red dot) on the Bowers Ridge, Southern Bering Sea (figure adapted from Expedition 323 Scientists, 2011). The northern continental shelf, including the area between the Bering Sea Shelf and the Aleutian arc, are covered seasonally by sea ice (i.e. north of black dashed line); only a little ice is presently being formed over the deep southwest areas of the Bering Sea (Niebauer et al. 1999; Kender and Kaminski, in press).

1.2 Bering Sea oceanography

Surface water circulation in the Bering Sea is dominated by an anti-clockwise gyre (the Bering Sea Gyre) partly along the Bering Sea Slope, contributing to the main flow of the Bering Slope Current (Stabeno et al. 1999). Most Bering Sea deep water is sourced from the low-oxygen North Pacific Deep Water (NPDW), while a very minor component of deep water is formed within the Bering Sea itself, probably from sea ice brine rejection (Warner and Roden 1995). The Bering Sea is one of the most highly biologically productive regions in the world, exporting about 687,000 tons of carbon per year (Sambrotto et al. 1984; Stabeno et al. 1999). Deep-water connections to the Bering Sea are limited to the Aleutian Island passes (Fig. 1.2), with water depth <4000 m (Hood 1983; Stabeno et al. 1999). Water from the North Pacific extends to form the Bering slope current, flows into the Bering Sea through the Amtchitka Pass, the Buldir Pass and the Near Strait; whilst North Pacific water flows out through the Kamchatka Strait (Kinney and Maslowski 2012).

Relatively warm (6-7°C), high salinity (>33‰) Alaskan Stream surface water (Fig. 1.2) affects the southern Bering Sea and the Bowers Ridge. Nutrient-rich intermediate water up wells over Bowers Ridge, producing high primary productivity

and this is associated with a strong organic carbon flux to the sea floor (Stabeno et al. 1999; Takahashi 2005); there is also significant slope-shelf water exchange along the Pacific side of the ridge bringing nutrients from the slope (Stabeno et al. 1999).

At present, seasonally sea-ice covered areas of the Bering Sea (Fig. 1.1) are found mostly over the northern continental shelf (Niebauer et al. 1999; Kender and Kaminski, in press). The inception and culmination of summer stratification, from solar warming of surface water, causes blooms of spring and autumn primary productivity (Niebauer et al. 1995) and also accompanying high phytodetrital flux to the sea floor. In the southern Bering Sea, the presence of seasonal stratification disrupting winter mixing causes seasonal blooms and high productivity (Niebauer et al. 1995). This high productivity, combined with the low oxygen North Pacific Deep Water (NPDW), which forms the majority of the Bering Sea deep water flowing over Bowers Ridge (Stabeno et al. 1999), causes low-oxygen conditions at ~818 m water depth.
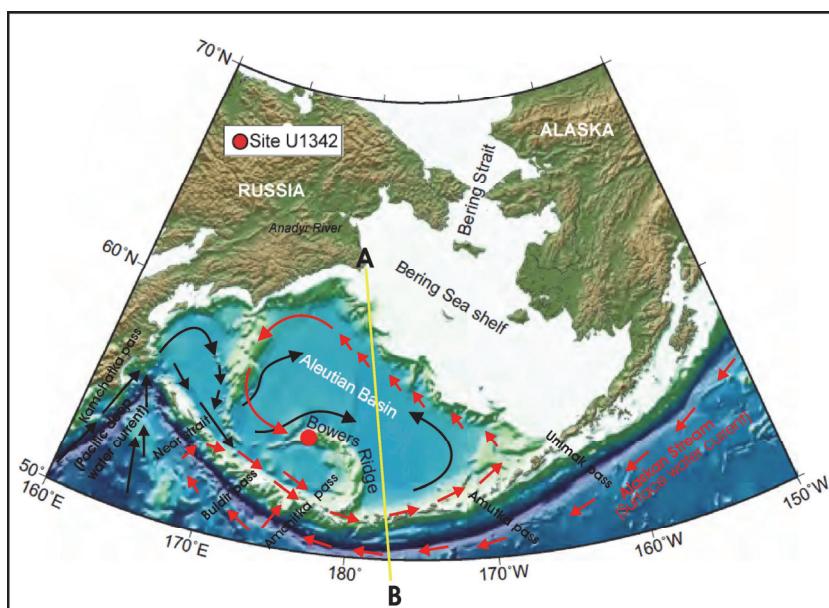
Figure 1.2 Bering Sea circulation: the Alaskan Stream surface water current (red arrows), and deep-water connections (black arrows) restricted to the Aleutian Island passes (<4000 m water depth; Hood 1983). Locus of cross-section (line A-B: yellow line) through the Bering Sea water column is shown in Figure 1.3

Because of its oceanography, the Bering Sea is thought to be one of the best regions to study environmental controls on benthic foraminifer distribution patterns, especially with relation to productivity and oxygenation.

Site U1342 is located on the north-western part of Bowers Ridge; an extinct arc system extending 300 km north from the Aleutian Island arc, within the modern oxygen minimum zone (OMZ) of ~0.6 ml/l (Conkright et al. 2002). This site is the shallowest site cored (see Fig. 1.3) during IODP Expedition 323 (Expedition 323 Scientists 2011).
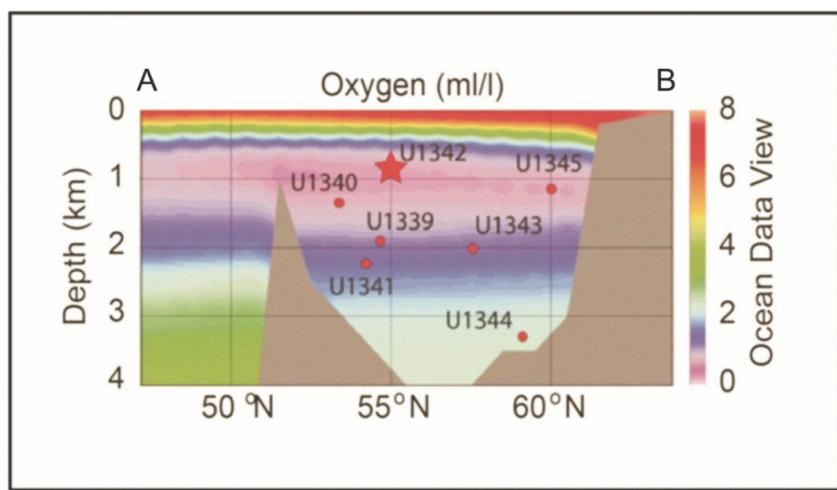
Figure 1.3 Cross-section through the water column of the modern Bering Sea, with IODP Expedition 323 sites (star = Site U1342: this study) showing the position of the oxygen minimum zone. Site U1342 is the shallowest seabed site cored during IODP Expedition 323. Image adapted from the Electronic atlas of World Ocean Circulation Experiment (WOCE) data: www.ewoce.org.

1.3 Bering Sea foraminifera

Relatively little has been published on the Late Quaternary foraminifera of the Bering Sea, (Anderson 1963; Gorbarenko et al. 2005; Okazaki et al. 2005; Kaminski et al. 2013; Setoyama and Kaminski (in press); Kender and Kaminski (in press)). The distribution of foraminifera along the North Pacific continental margins was compiled by Culver and Buzas (1985, 1987). Nevertheless, deep-sea benthic foraminifera are known to respond to changes in organic carbon flux and oxygen availability in modern settings (e.g. Corliss 1985; Kaiho 1994; Thomas and Gooday 1996; Jorissen et al. 2007), and have been shown to respond to environmental variability in the Bering Sea during the last glacial cycle (Gorbarenko et al. 2005; Okazaki et al. 2005). Anderson (1963) studied the distribution of foraminifera within the Bering Sea and concluded that water mass was of prime importance to the distribution of the assemblages. Site U1342 on the Bowers Ridge provides an important constraint on the influences of the oxygen

minimum zone (OMZ) within the Bering Sea (Expedition 323 Scientists 2011), and primary productivity and organic carbon flux perhaps linked to changes in surface productivity and the extent of sea ice cover. Thus, Late Pleistocene benthic foraminiferal records from a relatively high resolution sampling (~3 ka time steps) at this site, may reflect fluctuations in seabed oxygen conditions and surface water productivity at the Bowers Ridge for the past ~597 Kyr.

1.4 Sedimentological records at Site U1342

Mean sedimentation rates determined from a previous survey of the diatom-rich piston cores collected in the eastern Bering Sea range from 10 to 20 cm kyr^{-1} (Katsuki and Takahashi 2005). In contrast, the mean sedimentation rate of core BOW-8A (Fig. 1.1; in close proximity to Site U1342), from the western edge of the Bowers Ridge, is only 3 cm kyr^{-1} (Okada et al. 2005): a Pliocene age was reported for sedimentary deposits at the bottom of this sedimentary succession (Takahashi 2005). Core-sediments retrieved from Site U1342 display a relatively low sedimentation rate of an average 4.5 cm kyr^{-1} (Expedition 323 Scientists 2011). Sedimentary deposits comprise of: biogenic (diatom frustules with varying proportions of calcareous nannofossils, foraminifera, silicoflagellates and radiolarians), siliciclastic (mainly silt and very fine sand, and also isolated clasts of pebble to cobble size), and volcaniclastic materials (fine ash; Expedition 323 Scientists 2011). Grain size analysis shows that sediment at Bowers Ridge is generally coarser when compared with sediments from other Bering Sea slope sites; the average mean size being fine silt and sand-size particles: diatom ooze has been considered as the dominant lithology at the two other sites on the Bowers Ridge (Aiello and Ravelo 2012). Some of the siliciclastics on the ridge were likely derived from sea ice. Other accessory minerals include authigenic carbonates (dolomite and aragonite) and sulphide (Expedition 323 Scientists 2011).

The most prominent sedimentary features in the core from Site U1342 are decimetre to metre scale alternations of sediments that are parallel laminated, occasionally cross-laminated (Expedition 323 Scientists 2009). The sediments are also bioturbated at some intervals between 3.60 and 3.70 m; 5.00 and 5.20 m; 5.80 and 5.96 m; 8.90 and 9.20 m; 10.14 and 10.28 m.

1.5 Materials and methods

Benthic foraminiferal assemblages have been examined from 158 samples spaced at ~13 cm intervals from 20.59 m-CCSF (m-core composite below sea floor), being a subset of data from a core 41.35 m-CCSF recovered from Site U1342 (Fig. 1.1). This study analyses the benthic foraminifer through the past ~597 ka as calibrated by means of the oxygen isotope stratigraphy (Knudson and Ravelo: personal communication).

Samples were collected from the Kochi Core Centre, Japan, in 2010; freeze-dried and processed (wet-sieved to 62 μm fraction to liberate the microfossils) in Prof. Ravelo's laboratory at the University of California, Santa Cruz. Processed samples were stored in labelled vials. A total of 160 samples at ~13 cm intervals were picked for benthic foraminifera; there are no available samples for 2 horizons (7.44 m and 9.97 m-CCSF) out of the 160 horizon analysed, and these might have been missed during the original sample collection (by Kochi sampling staff). All foraminifera >62 μm were picked from each of the 158 samples or fraction and stored in cardboard reference slides. A micro hand-splitter was used to split samples where abundances were significantly higher than 300 specimens until a desired fraction was achieved. The samples were split into as many fractions as necessary (i.e. half, quarter, one-eighth sizes) to obtain an aliquot containing a population with a reasonable specimen density for benthic foraminiferal analysis. However, the final fraction of the sample (i.e. half, quarter, one-eighth sizes) represented by the aliquot was noted, and used for the Ice Rafted Debris (IRD) analysis. Specimens were sorted by species in micropalaeontological reference slides; all benthic foraminifer specimens picked into each slide were later identified and counted. The numbers of specimens of each benthic species were recorded as a percentage of the total benthic foraminiferal assemblage in the 158 samples; these data are presented in Appendix 1. A Hitachi S-3600N scanning electron microscope (SEM) in the Geology Department at Leicester University was used for imaging the benthic foraminifera. Selected foraminifera (typical of each species) were placed on aluminium stubs and coated with gold using an Emitech K500X sputter coater. Figured specimens are deposited in the collections of the British Geological Survey, Keyworth, Nottingham, for reference purposes.

For taxonomic analyses, species of benthic foraminifera identified were arranged in taxonomic order following the suprageneric classification of Loeblich and

Tappan (1987) for calcareous-walled taxa, with the aim of providing self-contained useful references for benthic foraminiferal faunas from the Bering Sea. Species identification has been based mainly on the taxonomic works of Kohl (1985), Van Morkhoven et al. (1986), Jones (1994), Gooday and Hughes (2002), Holbourn et al. (2013) and other authors whose work had focussed mainly on the Pacific Ocean. The classification is based mainly on test morphological characters, as well as additional information on evolutionary relationships. The features considered important are wall composition and microstructure of the test, mode of chamber and septal addition/coiling (including size) and apertural modification. Where applicable, the Ellis and Messina (1940) catalogue was consulted for the original description of type species.

1.6 Overarching aims of this study

This study aims to provide a detailed taxonomic and palaeoenvironmental analysis of the benthic foraminifera from Site U1342 on the western Bowers Ridge, Bering Sea, North Pacific, through the past ~597 kyr (early Holocene to middle Pleistocene: Tarantian and Ionian Stages; note that much of the Holocene was not recovered). The fauna are studied bearing in mind sedimentary and taphonomic processes that may have altered the primary structure of assemblages.

Key deliverables of this project are:

1. A detailed taxonomic appraisal of the late Quaternary benthic foraminifera from the Site U1342, Bowers Ridge, Bering Sea.

2. Assessment of the down core changes in morphology (especially test pore density) of *Bolivina spissa*. The dataset is used to test some existing models that this species can be used to track a relationship between foraminifer test morphology and seabed oxygen level (Kaiho 1994), and the relationship between seabed oxygen content and test pore density (Glock et al. 2011; Kuhnt et al. 2013).

3. Down core assessment of the total benthic foraminiferal faunal abundance and species diversity vis-à-vis the sedimentological (i.e. in conjunction with an examination of laminated/non-laminated intervals and the ice rafted debris) context of the foraminiferal assemblage structure, and to examine any possible links with productivity or seabed oxygen-level.

1.7 Chapter summaries

The thesis has 3 core science chapters, chapter 2 being taxonomic, whilst chapters 3 and 4 examine the possible environmental significance of benthic foraminifera.

1.7.1 Chapter 2 is a detailed taxonomic appraisal of the late Quaternary benthic foraminifera from the Bering Sea. For the systematic palaeontology, the synonymy lists are not exhaustive, most entries being based on comparison firstly with the original description of the type species and on key papers where such taxa are well illustrated, or are of direct comparative importance with the Bering Sea material. The fauna appraised includes 68 species, assigned to 41 genera from 22 families (of these, 52 species were identified to species level, while 16 species are discussed in open nomenclature).

1.7.2 Chapter 3 is a detailed assessment of changes in morphology (especially pore density, PD) in the species *Bolivina spissa* (Cushman). The dataset is used to test a model that equates species test morphology with seabed oxygen level (i.e. Kaiho 1994) and to test the relationship between pore density in *B. spissa* and seabed oxygen content (Glock et al. 2011; Kuhnt et al. 2013). However, there is no clear correlation between *Bolivina spissa* PD and interpreted bottom water oxygen level (BW-O_2) suggesting that oxygen may not be a primary or sole driver influencing the distribution and morphology of *B. spissa*.

1.7.3. Chapter 4 examines the down core structure of foraminiferal assemblages and evaluates their possible environmental signature. Assessment of the benthic foraminifera also utilises the sedimentological context of the fossils. Down core changes in the percentage abundance of key benthic foraminiferal species identify eight temporally discrete intervals from the ~20.59 m long core; these intervals appear to reflect broad changes in seabed oxygen levels and phytodetritus influx through time. No clear relationship with the glacial – interglacial oscillation at the site over the past ~597,000 years is identified.

1.7.4. Chapter 5 presents the overall conclusions from this thesis.

Chapter 2

Systematic palaeontology of late Quaternary Bering Sea benthic foraminifera

**Chapter 2: Systematic palaeontology of late Quaternary Bering Sea benthic
foraminifera**

Abstract

This chapter provides a detailed taxonomic appraisal of benthic foraminiferal
assemblages from 160 samples, analysed at ~13 cm intervals from a 20.59 m long
sediment core. The core was recovered from Site U1342 (Bowers Ridge) in the Bering
Sea, during Integrated Ocean Drilling Program (IODP) Expedition 323. This interval
represents the past ~597 Kyr calibrated by means of the oxygen isotope stratigraphy
spanning middle Pleistocene to Holocene (better part of Holocene were not covered). At
Site U1342 (~818 m water depth), sedimentation rates are relatively low, with an
average of ~4.5 cm/ka. Some 68 foraminiferal species (almost all being calcareous with
the exception of *Eggerella* sp. and *Martinotiella communis*) were identified and
described from 41 genera and 22 families. Of these, 52 species are identified to species
level, while 16 were identified only to generic level. In total, 52 of the 160 samples
contained counts that have greater than 300 benthic foraminifera from the > 62μm
fraction. The abundance of the foraminifer downhole varies, with species such as
Takayanagia delicata accounting for ~21% of the total abundance, while only 1
specimen each of *Moncharmontzeiana petaloskelts* and *Cushmanina striatopunctata*
was recorded. In all, most of the species recorded in the Bering Sea are dominated by
infaunal cosmopolitan species that are typical of water depths in the range from bathyal
to abyssal.

2 Introduction

The Bering Sea is a semi-closed marginal back-arc basin of the North Pacific, whose
water circulation is controlled by the Bering Sea Gyre (Nagata et al. 1992: see chapter
1). It is the third largest marginal Sea in the world (Takahashi 2005), bounded by
Alaska to the east and by Russia and the Kamchatka Peninsula on the western side, and
has shallow water connections to both the North Pacific Ocean and Arctic Ocean (Fig.
2.1). Presently, Pacific waters with a relatively low salinity flow northwards via the
Bering Sea, through the Bering Strait into the Arctic Ocean (Takahashi 2005). The
depth of the Bering Strait on the continental shelf is approximately 50 m (Fig. 2.1) and
this expanse was aerially exposed and the marine passageway was completely closed

during much of the last glacial including the last glacial maximum (LGM). Repeated opening and closing of the Strait has been caused by sea-level changes during the glacial-interglacial cycles of the Quaternary, and this caused significant changes in water-mass circulation in this region (Hopkins 1973).

Site U1342 (cored sediments from this site are used for this study; Fig. 2.1) is located on Bowers Ridge, an ancient volcanic arc extending 300 km northwards from the Aleutian Island arc, and is the shallowest material recovered during IODP Expedition 323 at a water depth of ~818 m (Expedition 323 Scientists 2011). The total composite core length extends through 41.35 m, spanning approximately the last ~1.2 Ma (middle Pleistocene to Holocene), although the majority of the Holocene was not recovered (Expedition 323 Scientists 2011). In this study, benthic foraminiferal assemblages from the top 20.59 m of the core were examined.

Benthic foraminifera have previously been reported from Pliocene to Recent deposits in the Bering Sea (Anderson 1963; Khusid et al. 2006; Expedition 323 Scientists 2011; Kender and Kaminski in press; Setoyama and Kaminski, in press). However, none has provided detailed taxonomic notes and illustrations of the benthic foraminifera from the late Quaternary (last 0.5 Myrs) succession in this area. This chapter therefore provides the first detailed taxonomic appraisal of late Quarternary benthic foraminifera from the Bering Sea.
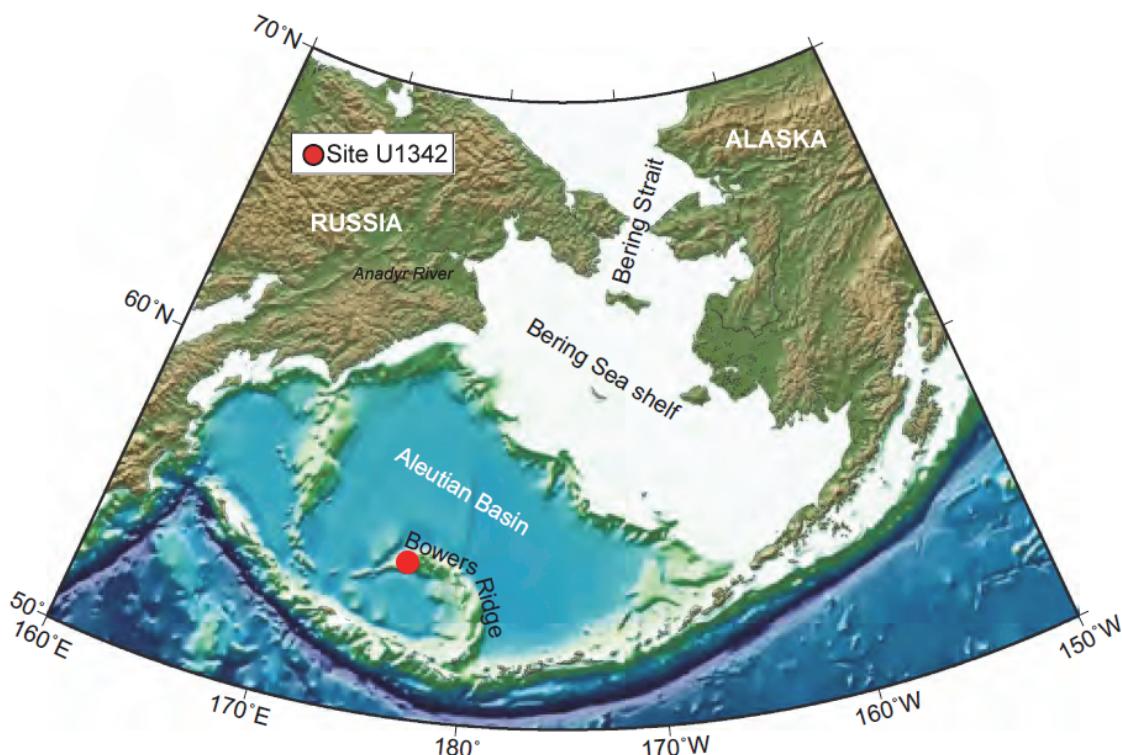
Figure 2.1 Bathymetric map of the Bering Sea showing the location of Site U1342 (red dot) on Bowers Ridge, southern Bering Sea (adapted from Expedition 323 Scientists, 2011)

2.1 Geological setting

Site U1342 is located within the modern Oxygen Minimum Zone (~0.6 ml/l, Conkright et al. 2002), and has the lowest sedimentation rates (4.5 cm/ka: Expedition 323 Scientists, 2009) out of the three drill sites explored in the Bowers Ridge region during IODP Expedition 323. Site U1342 comprises of a mixture of biogenic (mainly diatom frustules and foraminifera, with minor amounts of nannofossils, silicoflagellates, sponge spicules, and radiolarians), intermittent laminated intervals, volcaniclastic intervals (fine to coarse ash), and rare siliciclastic sediments that range from clay, to pebble-sized clasts (Expedition 323 Scientists 2011). The sediments are bioturbated at some intervals between 3.60 and 3.70 m; 5.00 and 5.13 m; 5.80 and 5.96 m; 8.90 and 9.20 m. Bioturbation is less obvious at other intervals. In general, the colour of the sediment ranges from very dark greenish grey and dark grey, to biogenic-rich olive grey to olive. Intermittent volcaniclastic ash layers are fine to coarse, dark grey to black or shades of light grey to white in colour.

2.2 Materials and methods

Samples were freeze-dried, washed through a 62 μm mesh screen to liberate the microfossils, and stored in labelled vials (in Christina Ravelo's laboratory at the University of California, Santa Cruz) before picking. This study focuses on the top 20.59 m (composite depth scale; m-CCSF). A total of 160 samples at ~13 cm intervals, were picked for benthic foraminifera; there are no available samples for 2 horizons (7.44 m and 9.97 m ccsf) out of the 160 horizon analysed, and this may have been missed during the original sample collection (by Kochi sampling staff), while 3 other samples (5.13, 15.29 and 15.44 m-CCSF) were barren of foraminifera. A minimum of 300 picked individuals of benthic foraminifera was targeted from each sample, although there were commonly fewer numbers available. In total, 52 of the 160 samples contained counts that have greater than 300 specimens from the > 62 μm fraction studied. A Hitachi S-3600N scanning electron microscope at the University of Leicester was used for imaging the fossils. Magnifications of up to 700 times have been used to image the test ultra-structure, for example in species of *Bolivina*. The SEM was also used to gauge the relative preservation condition of specimens, especially to determine incidences of abrasion. Foraminiferal specimens collected are deposited in the collections of the British Geological Survey, Keyworth-Nottingham.

2.3 Foraminiferal assemblages

A total of 35,465 benthic foraminiferal specimens were recovered from the sampled interval. In all, 68 benthic foraminiferal species, all calcareous with the exception of *Eggerella* sp. and *Martinotiella communis* which have agglutinated tests, were recorded from the top 20.59 m of Site U1342. 41 genera were identified; 52 species were identified to species level, while 16 species were identified only to generic level (Appendix 1). The diversity and abundance of the foraminiferal assemblages varied greatly throughout this interval. Most of the species are cosmopolitan, and are known mainly from the Pacific Ocean and its environs.

The species of benthic foraminifera in this study have been arranged in taxonomic order following the suprageneric classification of Loeblich and Tappan (1987) for calcareous-walled taxa. Species identification is based mainly on the taxonomic works

of McCulloch (1977); Kohl (1985); Van Morkhoven et al. (1986); Jones (1994); Gooday and Hughes (2002) and Holbourn et al. (2013), with reference made to other works where these are relevant. The classification is based mainly on test characters, as well as additional information on evolutionary relationships. Features considered of taxonomic importance include test composition and microstructure, mode of chamber and septal addition/coiling (including size), and apertural modification. Where applicable, the Ellis and Messina (1940) catalogue was consulted for the original description of type species. All photomicrographs (Plates 2.1-2.22) are based on specimens recovered from Site U1342 on Bowers Ridge, Bering Sea.

2.4 Systematic Palaeontology

The order of species presented below follows the suprageneric classification (Appendix 2) of Loeblich and Tappan (1988). Synonymy lists are not exhaustive, with most entries in the lists being selective, based on well illustrated material from the Pacific region (e.g, McCulloch 1977; Jones 1994; Kaiho 1992; Holbourn et al. 2013) or material considered to be of direct comparative importance (e.g. Finger 1990 and Abu-Zied 2008).

Family EGGERELLIDAE Cushman, 1937
Subfamily EGGERELLINAE Cushman, 1937
Genus *Eggerella* Cushman, 1935
Type species *Verneuilina bradyi* Cushman, 1911; designated by Cushman (1911), p. 54

***Eggerella* sp.**
Plate 2.1, Figures 1-5

Eggerella sp. 1 - KAMINSKI et al., 2013, p. 338, figs. 2A, Ha - Hb

Distribution in core: 10 specimens from 9 samples; highest occurrence at 0.63 m; then at 2.38, 8.72 m and intermittently down the core.

Description: Test trochospiral, conical or ovoid, slightly elongate, rapidly becoming triserial after a short biserial stage; overall shape is pyramidal. Wall finely agglutinated;

wall surface rough, containing ~ 40% cement. Test chambers compact, strongly overlapping. Chambers inflated and increasing in size as added; average number of chambers ranges from 9 to 13; sutures thin and slightly depressed. Length of the test ranges between 0.40 and 0.67 mm and the width between 0.26 and 0.32 mm; average width of the last chamber is 0.25 mm. The average length to width ratio is 1.7 (0.42/0.25). Aperture morphology varies; ranges from a simple slit-like to rounded opening, positioned centrally on a very short neck at the base of the final chamber; aperture surrounded by a thickened but narrow lip.

Remarks: This species is very similar to *Eggerella* sp. 1 described from the Bering Sea by Kaminski et al. (2013). *Eggerella* sp. possesses numerous pores thought to be an adaptation to survive low-oxygen conditions present in the deep Bering Sea. The type species was originally described from the Atlantic and Pacific Oceans (see Phleger et al. 1953 and the references therein). Brandy's (1884) material referred to *Verneuilina pygmea* (Egger) was recognised as *Eggerella bradyi* by Cushman (1937).

Eggerella sp. differs from *E. bradyi* which has a short biserial stage that might be confused with immature specimens of *Karreriella bradyi* (Phleger et al. 1953). However, *Karreriella bradyi* is biserial in its final chambers, and has a rounded aperture, clearly distinguishing mature specimens from *E. bradyi*. The specimens of *E. bradyi* from the Bering Sea differ from the type species of *E. bradyi* (Cushman) in being smaller, but in other aspects, are identical. In 7 out of the 10 specimens of *Eggerella* sp. from the Bering Sea, the aperture is narrow and slit-like, while in the other 3, it is round. However, there is no discernible trend in aperture type of specimens through the samples studied. In all cases the aperture is situated on a very short neck on the terminal chamber (Plate 2.1, Figs. 1-5).

Distribution: *Eggerella* sp. has only be recorded from the Bering Sea. *E. bradyi*, a morphologically close species is a cosmopolitan species, being typically recorded from the Arctic (Cushman 1937), Atlantic (Phleger et al. 1953; Belanger and Berggren 1986; Schmiedl et al. 1997; Austin and Evans 2000: Kender et al. 2008), Indian (Corliss 1979; Boltovskoy 1980; Sen Gupta 1994; Kurbjeweit et al. 2000; Schumacher et al. 2007), and Pacific Oceans (Brady 1884; Cushman 1911, 1922; Phleger et al. 1953; Keller 1980; Butt 1980; Schröder et al. 1988) and bordering seas (Fillon 1974; Wright 1978;

Keller 1980; Kaiho 1992; Sen Gupta et al. 2009; Wilson and Costelloe 2011; Kaminski et al. 2013). *E. bradyi* has a water depth range from 236 m in the 'Challenger stations' SW of Juan Fernandez Island (Jones 1994) to 5600 m in the Atlantic Ocean and China Sea (Corliss 1979; Belanger and Berggren 1986; Jian et al. 1999; Sen Gupta 1994; Kuhnt et al. 1999; Austin and Evans 2000; Sen Gupta et al. 2009). The stratigraphical range of *E. bradyi* is from the Late Eocene to Recent (Holbourn et al. 2013).

Genus Martinottiella Cushman, 1933
Martinottiella communis (d'Orbigny, 1846)
Type species *Clavulina communis* d'Orbigny 1826
Plate 2.1, Figures 6-9

Clavulina communis d'Orbigny 1826, p. 196, pl. 12, figs.1, 2
Martinottiella communis (d'Orbigny) - ASANO 1950, p. 3, figs. 16, 17; - BARKER, 1960, p.98, pl. 48, figs. 2, 3; - INGLE et al., 1980, p. 139, pl. 4, figs 14, 15; - KELLER, 1980, p. 855, pl. 1, fig. 12; - KOHL, 1985 p.33, pl. 4 fig. 2; - KATO 1992, p.389, pl. 1, fig. 5; - KAHIO 1992, p. 303, pl. 1, fig. 17; - JONES 1994, p. 52, pl. 48, figs. 1-2, 4-8, 3; - HANAGATA, 2006, pl. 2, figs. 5, 6; - KENDER et al., 2008, p. 546, pl. 12, figs. 8-10; - SZAREK, 2001, p. 189, pl. 8, figs. 9-10; - SEN GUPTA et al., 2009, p. A-10, pl. 14, figs.1-2; - HOLBOURN et al., 2013, p. 350.

Occurrence: 9 specimens, from depths 1.28, 9.40, 12.98, 13.99, 15.10 and 19.22 m

Emended diagnosis: (Modified from Asano 1950) Test early portion trochospiral, triserial, later becoming biserial and uniserial abruptly; aperture is circular, produced on a short tubular neck sometimes with a slight lip, and situated at the centre of the terminal chamber.

Description: Test is trochospiral; initially triserial, later reducing to biserial and uniserial, uniserial portion making up about ¾ of the test; test tends to be elongate, average dimensions is 1.35 mm in length and 0.15 mm in width; wall arenaceous, finely agglutinated with rough surface; chambers indistinct in the early portion; increasing gradually in size as added, sutures indistinct, slightly depressed; aperture is circular

(~0.05 mm diameter) and produced on a short tube-like neck, at the centre of the terminal chamber.

Remarks: D'Orbigny (1826) originally assigned his material to *Clavulina*, but this taxon is distinct from *Clavulina* by its initial trochospiral coiling, rather than triserial chamber arrangement. Some of the specimens are probably incomplete (broken).

Distribution: *M. communis* is cosmopolitan being recorded from the Miocene (Badenian) of the Vienna Basin (d'Orbigny 1846), Pacific coast of Japan (Kaiho and Hasegawa 1986), the Atlantic Ocean (Belanger and Berggren 1986; Charnork and Jones 1990), and other seas (Jian et al. 1999; Kender et al. 2008; Sen Gupta et al. 2009; Wilson and Costelloe 2011). *M. communis* has a water depth range from 385 m in the Pacific (Jones 1994) extending down to 714 m in the West Indies (Sen Gupta 2009), and to a deeper depth of 3477 m in the Atlantic Ocean (Jian et al. 1999). *M. communis* has a stratigraphical range from the Oligocene to Recent (Jones 1994).

Family HAUERINIDAE Schwager, 1876
Subfamily HAUERININAE Schwager, 1876
Genus *Quinqueloculina* d'Orbigny, 1826
Type species *Serpula seminulum* Linné, 1758; designated by Parker and Jones (1859), p. 480

Quinqueloculina sp.
Plate 2.1, Figures 10-12

Distribution in core: 7 specimens from 7 samples; intermittently at depths 0.63, 2.64, 6.20, 13.46, 14.88, 16.21 and 19.61 m respectively.

Description: Test ovate in outline, twice as long as broad, average dimensions: length 0.75 mm, width 0.32 mm and thickness 0.30 mm. Wall calcareous, slightly imperforate. The chamber arrangement is "quinqueloculine": four chambers are visible from one side and three from the other side, chamber margins are curved; aperture is not clearly seen,

but is located on a very short neck. Test surface is rough, ornamented with minute microstriae.

Remarks: These Bering Sea specimens are morphologically similar to *Quinqueloculina parvula* Schlumberger recorded by Milker and Schmiedl (2012) from the Holocene shelf of the western Mediterranean Sea, but differ by the morphology of the aperture, which is relatively wide and round in *Q. parvula* (Milker and Schmiedl 2012: fig. 15: 26 and 27). Though not clearly visible in the specimens of *Quinqueloculina* sp. from the Bering Sea, the aperture doesn't appear to be either wide or rounded, and is more triangular in outline.

Subfamily MILIOLINELLINAE Vella, 1957
Genus *Pyrgo* Defrance, 1824
Type species *Pyrgo laevis* Defrance, 1824

Pyrgo murrhina (Schwager, 1866)
Plate 2.1, Figures 13-16

Biloculina murrhina SCHWAGER, 1866, p. 203, pl. 4, figs. 15 a-c
Pyrgo murrhina CUSHMAN, 1929, p. 71, pl. 19, figs. 6, 7
Pyrgo murrhina (Schwager); - CUSHMAN, 1930, p. 357, pl. 32, figs. 7 a, b
Biloculina depressa, var. *murrhyna* Schwager.- BRADY, 1884, p. 146, pl. 2, figs. 10, 11, 15
Pyrgo murrhina (Schwager) – PHLEGER et al, 1953, p. 28-29, pl. 5, figs. 22-24; - BARKER, 1960, p. 4, pl. 2, figs. 10, 11, 15; - Le ROY, 1974, p. 439, pl. 7, figs. 4, 5; - SEJRUP et al., 1981, pl. 2, fig. 9; - MULLINEAUX and LOHMANN, 1981, p. 38, pl. 1, fig. 13 ; KAIHO and NISHIMURA, 1992, p. 312, pl. 3, fig. 2; - SEN GUPTA, 1994, p. 357, pl. 1, fig. 14; - DOWSETT and ISHMAN, 1995, p. 154, pl. 1, fig. 2; - OHKUSHI et al., 2000, p. 138, pl. 1, figs. 5a-c; - ABU-ZIED et al., 2008, p. 51, pl. 1, figs. 16-17; - HOLBOURN et al., 2013, p. 458.

Distribution in core: 8 specimens from 7 samples, at depths 1.03, 4.97, 5.26, 5.41, 5.74, 5.96 and 19.92 m respectively.

Diagnosis: (After Barker 1960) Test ovate, extended with carinate periphery, aperture nearly circular, tubular neck, with a bifid tooth attached to the apertural opening.

Description: Test ovate in outline, biconvex: one side more convex than the other; wall calcareous and smooth, imperforate and porcelaneous; two chambers making up the exterior, extended with a carinate periphery, somewhat longer than broad; maximum diameter of the test is 1.05 mm, thickness is up to 0.75 mm. Aperture nearly circular, at the end of a produced tubular neck, a small bifid tooth is attached to the apertural opening.

Remarks: Schwager (1866) originally assigned his material to *Biloculina. Pyrgo murrhina* from the Bering Sea is morphologically similar to specimens illustrated by Abu-Zied et al. (2008: pl. 1, fig. 16 and 17) from the Mediterranean Sea, and differs from specimens illustrated from the Choctawhatchee Formation of Florida by Cushman (1930) which have a larger bifid tooth associated with the aperture, partially filling the nearly circular apertural opening.

Distribution: *Pyrgo murrhina* is cosmopolitan in deeper waters, it has a geographical distribution in the Pacific (Kaiho and Nishimura 1992; Ohkushi et al. 2000; Bubenshchikova et al., 2010), and Indian Oceans (Corliss 1979; Sen Gupta 1994), the Gulf of Mexico (Le-Roy 1974; Sen Gupta et al. 2009), the Red Sea (Sen Gupta 1994) and other seas (Le-Roy 1974; Abu-Zied et al. 2008; Sen Gupta et al. 2009; Wilson and Costelloe 2011). *Pyrgo murrhina* has a water depth range extending from 181 to 839 m in the Okhotsk Sea (Bubenshchikova et al. 2010), down to 4600 m in the southeast Indian Ocean (Corliss 1979). *P. murrhina* was considered an indicator of oxic seabed conditions by Kaiho (1994) and Matul et al. (2013). Bubenshchikova et al. (2010) classified *P. murrhina* as a suboxic and epifaunal species. Its stratigraphical range is from the Miocene to Recent (Jones 1994).

Genus *Triloculina* d'Orbigny, 1826
Type species *Miliolites trigonula* Lamarck, 1804, designated by Cushman (1917), p. 65

Triloculina frigida Lagoe, 1977

Plate 2.2, Figures 1-3

Triloculina frigida Lagoe, 1977, p. 120, pl.1, figs 12, 17, 18; - SEJRUP et al., 1981, p. 292, pl. 2, fig. 11; MURRAY, 1983, pl. 3, figs. 12-14; - MACKENSEN, et al., 1990, p. 254, pl. 1, fig. 6; - ISHMAN and FOLEY, 1996, p. pl. 2, fig. 8; - WOLLENBURG and MACKENSEN, 1998, p. 179, pl. 3, figs. 2, 3; - OHKUSHI et al., 2000; - GOODAY and HUGHES, 2002, p. 97, pl. 1, fig. g

Distribution in core: 22 specimens in 14 samples; the highest occurrence is at 2.78 m, other intermittent occurrences down core from this level.

Emended diagnosis: (Based on the illustrations of Lagoe 1977; Murray 1983; Gooday and Hughes 2002 and the material from the Bering Sea) Test quinqueloculine, triangular in cross-section, three chambers visible from the exterior; aperture sub-rounded with a distinct tooth.

Description: Test with early chambers quinqueloculine, test triangular in cross-section, ovate in lateral outline, somewhat tubular; test has an equilateral triangular shape from apertural view, twice as long as broad, average dimensions being 0.37 mm in length and 0.12 mm in width. Wall calcareous, porcelaneous, imperforate; chambers added in the plane of the last preceding, covering it so that the exterior of the test is composed of about three visible chambers; aperture sub-rounded with a tiny tooth (on the flat side of the aperture) on a short but distinct neck at the end of the final chamber.

Remarks: *T. frigida* differs from the similar *Quinqueloculina lamarckiana* d'Orbigny, which has 5 visible chambers and an ovate aperture. The material from the Bering Sea compares well with the illustrations of *T. frigida* in Mackensen et al. (1990: pl. 2, fig. 6) from the Weddell Sea. The apertural tooth in *T. frigida* from the Bering Sea is tiny, and it is similar to specimens illustrated from the NE Atlantic by Gooday and Hughes (2002; pl. 1, fig. g). *T. frigida* has been described as being associated with phytodetritus-rich samples from the NE Atlantic (Gooday and Hughes 2002), and this

may signal this species to be opportunistic in nature, responding to seasonally high influx of organic detritus.

Distribution: *T. frigida* has a geographical distribution in the Atlantic and Arctic Oceans (Wollenburg and Mackensen 1998; Gross 2001; Gooday and Hughes 2002), and from bordering seas (Sejrup et al. 1981; Mackensen et al. 1995). Its water depth ranges from 1388 m to 1920 m in the north Atlantic (Gooday and Hughes 2002), extending to between 2500 and 3600 m in the Weddell Sea (Mackensen et al. 1990) and deeper to 4427 m in the Arctic Ocean (Wollenburg and Mackensen 1998). *T. frigida* has a stratigraphical range from the Eocene to Recent (Murray 1983).

Family NODOSARIIDAE Ehrenberg, 1838
Subfamily NODOSARIINAE Ehrenberg, 1838
Genus *Dentalina* Risso, 1826
Type species *Nodosaria cuvieri* d'Orbigny, 1826, designated by Risso (1826), p. 255

Dentalina ittai Loeblich and Tappan, 1953
Plate 2.2, Figures 4-9

Nodosaria calomorpha Reuss - EARLAND, 1933, p. 117, pl. 4, fig. 19
Dentalina cf. *calomorpha* (Reuss). – CUSHMAN and BRONNIMANN, 1948, p. 44, pl. 5, figs. 4, 5.
Dentalina ittai LOEBLICH and TAPPAN, 1953, p. 56, pl. 10, figs. 10-12; FEYLING-HANSSEN, 1964, p. 273, pl. 9, figs. 1, 2; - DABBOUS and SCOTT, 2012, pg. 199, figs. 26, 3.

Distribution in core: 5 specimens in 5 samples; few occurrences between intervals 1.28, 2.38 and 2.54 m.

Description: Test elongate, uniserial, tubular, circular in cross-section, 2 mm in length; test wall calcareous, smooth. Chambers gradually increasing in size slightly inflated and curved, average chamber width is 0.20 mm, while length is 0.51 mm. There are 8 to 9 chambers, with the last chamber being largest; first chamber (proloculus) has a spine at

the end. The size of the last chamber reduces towards the aperture, forming a conical shape; sutures slightly depressed; aperture rounded and terminal at the conical end.

Remarks: *D. ittai* specimens examined comprised of broken specimens, but nonetheless can be differentiated from *Dentalina cuvieri* (d'Orbigny) which has longitudinal costae on its test and a radiate aperture (see Loeblich and Tappan, 1986 pl. 439, fig. 19). The Bering Sea material may be conspecific with *Dentalina* sp. 1 illustrated by Sen Gupta et al. (2009) from the Gulf of Mexico.

Distribution: *D. ittai* has been recorded from 21 - 50 m water depth at the Northern Melville Peninsula, Canadian Arctic; Quaternary deposits in Southwestern Sweden (Klingberg 1997); Lake Uppsalstjänet and Lake Östen, Southwestern Varmland, in southwestern Sweden (Wastegård 1995), between 50 - 100 m at Tail of the Grand Banks, western North Atlantic (Sen Gupta 1971) and from the Barents Sea, Arctic Ocean (Tarasov and Pogodina 2001).

Genus *Lotostomoides* Hayward and Kawagata in Hayward et al. 2012
Type species *Nodosaria asperula* Neugeboren, 1852

Lotostomoides calomorphus (Reuss, 1866)
Plate 2.2, Figures 10-11

Nodosaria (*Nodosaria*) *calomorpha* REUSS 1866, p. 129, pl. 1, figs. 15-19
Glandulonodosaria calomorpha (Reuss) - JONES 1994, p. 72, pl. 61, figs. 23–26?, 27, supplementary plate 1, figs 10-11
Lotostomoides calomorphus (Reuss) – HAYWARD et al., 2012, p. 125, pl. 6, figs 24-29; - SETOYAMA and KAMINSKI (in press) fig. 8, 22.

Distribution in core: 8 specimens in 8 samples, first occurrence at 0.10 m and other occurrences intermittently down the core to depth 20.59 m.

***Emended diagnosis*:** (After Hayward et al. 2012) Test elongate, uniserial, each chamber weakly inflated, unornamented; aperture coarsely reticulate, slightly domed to conical mesh, usually on a neck and often divided into pillars or tubes

***Description*:** Test elongate, uniserial with up to three chambers that are tubular and weakly inflated, test divided into pillars or tubes; wall calcareous, unornamented; depressed sutures, aperture not clearly seen, probably terminal on a short neck.

***Remarks*:** All specimens are fragmentary, consisting mostly of two chambers; only one specimen out of the eight examined has three chambers. Setoyama and Kaminski (in press: figs. 8, 22) referred to a morphologically close specimen from the Bering Sea as *Lotostomoides calomorphus*. Some of the fragments described here are similar to the specimens illustrated as '*Nodosaria* sp.' from surface sediments of the Weddell Sea in the Antarctica by Anderson (1975: pl. 4, fig. 11), which has two tubular and weakly inflated chambers, with depressed sutures and an aperture which is terminal. Another morphologically similar specimen illustrated from Northern Gulf of Mexico by Sen Gupta et al. (2009: pg. A-168) was referred to as *Siphonodosaria calomorpha* (Reuss).

***Distribution*:** *Lotostomoides calomorphus* has been reported by Setoyama and Kaminski (in review) from the Bering Sea at a water depth of ~2140 m. A similar specimen illustrated by Jones (1994) as *G. calomorpha* was recorded at a depth range between 11 and 4026 m in the South Atlantic.

Family VAGINULINIDAE Reuss, 1860
Subfamily LENTICULININAE Chapman, Parr, and Collins, 1934
Genus *Lenticulina* Lamarck 1804 (=*Lenticulites* Lamarck, 1804, objective synonym)
Type species: *Lenticulites rotulata* Lamarck, 1804, designated by Children (1823), p. 153

Lenticulina rotulata Lamarck, 1804
Plate 2.2, Figures 12-16

Lenticulites rotulatus LAMARCK, 1804, p. 188, pl. 62, fig. 11

Lenticulina rotulata CHILDREN, 1823, p. 153

Cristellaria rotulata (Lamarck) - CUSHMAN, 1926, p. 599, pl. 19, fig. 4; - PLUMMER, 1926, p. 91, pl. 7, fig. 8.

Lenticulina rotulata (Lamarck) – CUSHMAN, 1931, p. 37, pl. 5, fig. 1 - CUSHMAN 1946, p. 56, pl. 18, fig. 19; pl. 19, figs. 1-7.

Lenticulina comptoni (Sowerby) – HOFKER, 1956, p. 114, text-figs. 117, 118

Lenticulina rotulata (Lamarck) - DONDI and BARBIERI, 1982, pl. 10, figs. 6; - KAHIO, 1992, p. 304, pl. 2, figs. 14a, 14b; - PERYT and LAMOLDA, 1996, fig. 7, no. 7; - ORTIZ and THOMAS, 2006, p. 139 pl. 8, fig. 5; - FRENZEL 2000, pl. 14, fig. 1.

Lenticulina sp. - SETOYAMA and KAMINSKI (in press) figs. 7, 9a, b

Distribution in core: 32 specimens from 11 samples intermittently between depths 0.10 and 20.06 m; highest abundance between intervals 1.28 and 2.24 m.

Emended diagnosis: Based on Ortiz and Thomas (2006) and the Bering Sea material documented herein. Sub-circular in outline, weakly carinate with umbonal boss, last two chambers tend to flare, closed regular spire; aperture radiate and terminal.

Description: Sub-circular in outline, closely coiled and compressed chambers, periphery weakly carinate, test with umbonal boss. Test wall calcareous, hyaline, smooth except on the sutures; broad chambers increasing slowly in size as added, forming a closed spire in overall morphology. Specimens are relatively large, average dimension of the longer diameter is 1.50 mm, 1.40 mm at the shorter diameter and thickness of 0.62 mm. About 9 to 12 chambers are visible in the final whorl (~90% of the specimens have 10 chambers), the last two chambers tend to flare; sutures distinct, non-depressed, radial to oblique, straight to curved, gently tangential to the slightly elevated umbo; aperture radiate and terminal.

Remarks: Frenzel (2000) considered *Lenticulina comptoni* (Sowerby, 1817) to be a junior subjective synonym of *L. rotulata*. *L. rotulata* possess an umbonal boss, which is absent from *L. gibba* (d'Orbigny): for other differences see 'remarks' for *L. gibba* below. The presence of the umbonal boss in *L. rotulata* makes this species similar to *L. convergens* (Bornemann) and *L. iota* (Cushman); however, there are more chambers in

L. iota than in *L. rotulata,* while *L. convergens* has oblique sutures fusing into a relatively large umbilical boss. *L. muensteri* (Roemer) recorded from the Oxford Clay in England by Holbourn et al. (2013; p. 338, figs. 1 and 2) is morphologically similar to *L. rotulata,* but is differentiated by its wide apertural form. Holbourn et al. (2013) described the test as radiate and terminal: this species is also older than the youngest (Eocene) occurrence of *L. rotulata*. *L. rotulata* recorded from the Bering Sea is morphologically similar to *Lenticulina* sp. recorded from the same area by Setoyama and Kaminski (in press).

Bartenstein and Bolli (1986) highlighted difficulties in separating *L. rotulata* (Lamarck), *L. muensteri* (Roemer), *L. roemeri* (Reuss), *L. macrodisca* (Reuss) and *L. subalata* (Reuss) due to transitional forms. However, *L. rotulata* specimens examined show intraspecific variation in the test outline down core: about 60% of the specimens have their test outline almost circular, while others are slightly angled. There appears to be no stratigraphical pattern in the distribution of these morphologies.

Distribution: *Lenticulina rotulata* is a cosmopolitan species that has a geographical distribution in the North American Atlantic Coast (Culver and Buzas 1980); Japan Sea (Kaiho 1992), Tyrrhenian Sea (Panieri et al. 2005), and the Caribbean Sea (Wilson and Costelloe 2011), also from the Betic Cordillera, southeastern Spain (Ortiz and Thomas 2006). *L. rotulata* has been recorded at water depths extending from ~60 to ~300 m in the Tyrrhenian Sea (Panieri et al. 2005), between 7 - 1,054 m at the Bay of Biscay and Celtic Sea, down to a depth of 2300 m in the Pacific (Kaiho 1992). *Lenticulina* spp. was classified as indicators of sub-oxic conditions by Kaiho (1994). It is present in dissolved oxygen range between 0.16 - 4.59 ml/l (Hayward 2014). The stratigraphical range of *L. rotulata* is from Eocene to Recent (Kaiho 1992).

Lenticulina gibba (d'Orbigny 1826)

Plate 2.2, Figures 17-18; Plate 2.3, Figures 1-7

Cristellaria gibba d'Orbigny, 1826, p. 292, no. 17; - BRADY, 1884, p. 546, pl. 69, figs. 8, 9; - CUSHMAN, 1923, p. 105-106, pl. 25, fig. 4

Robulus oblongata - CORYELL and RIVERO, 1940, p. 332, pl. 43, figs. 7, 12

Robulus gibba (d'Orbigny) - BERMÚDEZ, 1949, p. 126, p. 7, figs. 53, 54

Lenticulina gibba (d'Orbigny) - BARKER, 1960, p. 144, pl. 69, figs. 8-9; - DENNE, 1990, pl. 8, fig. 6; - JONES, 1994, p. 81, pl. 69, figs. 8-9; - ROBERTSON, 1998, p. 66. pl. 22, fig. 4; - KAMINSKI et al, 2002, p. 172, pl. 2, fig. 6; - SEN GUPTA et al., 2009, p. A-100, pl. 98, figs. 1- 2; - CHENDEŞ et al., 2004, p. 77, pl. 1, fig. 13; - HOLBOURN et al., 2013, p. 334, figs. 1, 2.

Distribution in core: 7 specimens in 6 samples at 0.88, 3.09 and between depths 15.95-16.65 m and 18.55-18.65 m.

Emended Diagnosis: (Based on Holbourn et al. 2013 and Jones 1994) Later chambers are narrower, uncoiled and involute; suture flush with chambers; aperture is radiate and terminal.

Description: Test planispiral, elongate in outline, involute, weakly biconvex in cross section, with keeled, sub-acute periphery; wall calcareous, smooth, and finely perforate; the later chambers are narrower, approximately twice as wide as long. Some six to nine chambers in the final whorl, tending to uncoil as added; average dimension of the test is 0.45 mm in length, 0.25 mm in width at the widest diameter and 0.12 mm in thickness; sutures flush with chambers; primary aperture in form of radial slits, terminal on the narrow later chamber.

Remarks: D'Orbigny (1826) first described his material as *Cristellaria gibba;* this was later accepted as a synonym of *Lenticulina gibba* (d'Orbigny 1826): see Gross (2001). *L. gibba* is differentiated from *L. rotulata* (Lamarck), *L. convergens* (Bornemann), *L. iota* (Cushman) and *L. muensteri* (Roemer) by its more elongated outline, and by its keel becoming narrower in later uncoiled chambers. *L. iota* has more chambers (13 to 15) in its final whorl. *L. convergens* (Bornemann) has numerous inflated chambers, increasing gradually in size, and these are separated by flush, oblique sutures that fuse into a large umbilical boss. *L. anaglypta* (Loeblich and Tappan) differs from *L. gibba* by having depressed sutures with ornamented, numerous and prominent raised costae. However, the primary apertures of these species are similar to that of *L. gibba*, being radiate and terminal. *L. gibba* from Site U1342 is morphologically similar to the specimen illustrated from the Mediterranean Sea by Kaminski et al. (2002: p. 2, fig. 6)

as *L. gibba*, having its aperture as radial slits. Specimens illustrated by Chendeş et al. (2004: pl. 1, fig. 13) from the southern shelf of the Marmara Sea as *L. gibba* d'Orbigny differ from the studied specimens in that the aperture is somewhat oval in shape. Whether this represents intraspecific variation, or this material represents a different species, is unclear.

Distribution: *L. gibba* is cosmopolitan, being typically recorded from the Gulf of Mexico (Sen Gupta et al. 2009; Sen Gupta and Smith 2010), Caribbean Sea (Wilson and Costelloe, 2011) and at the 'Challenger' stations in the West Indies (Jones, 1994). *L. gibba* has a depth range from 15 to 350 m in the shelf of Marmara Sea (Chendeş et al. 2004) to 714 m in the West Indies (Jones 1994) and 2918 m in the Gulf of Mexico (Sen Gupta et al. 2009; Gupta and Smith 2010). Jones (1994) classified *Lenticulina* spp. as indicators of sub-oxic seabed conditions. The stratigraphical range of *L. gibba* is Early Miocene to Recent (Holbourn et al. 2013).

Family LAGENIDAE Reuss, 1862
Subfamily LAGENINAE Brady, 1881
Genus *Lagena* Walker and Jacob, 1798
Type species *Serpula* (*Lagena*) *sulcata* Walker and Jacob, 1798; designated by Parker and Jones (1859), p. 337

Lagena hispida Reuss, 1858
Plate 2.3, Figures 8-15.

Lagena hispida Reuss, 1858, p. 335, pl. 6, figs. 77-79
Lagena hispida Reuss - BRADY, 1884, p. 459, pl. 57, figs. 1, 2; - CUSHMAN, 1923, p. 26-27, pl. 4, figs. 7, 8; - CUSHMAN, 1946, pl. 39, fig. 13; - BARKER, 1960, p. 116, pl. 57, figs. 1, 2; - JONES, 1994, p. 63, pl. 57, figs. 1, 2; - SEN GUPTA et al., 2009, p. A-9, pl. 89, fig. 1.

Distribution in core: 12 specimens in 8 samples at depths 2.38, 2.60, 8.60, 9.00, 9.25, 16.88, 15.69 and 17.09 m.

Emended Diagnosis: (Modified slightly from Barker 1960) Test is unilocular, flask shaped to globular, elongated apertural neck; hispids are distributed over the test and the neck, aperture rounded, terminal on a thin, elongate neck with a lip.

Description: Test is unilocular, ovate in outline, flask shaped to globular, circular in cross section. Wall calcareous, hispids are distributed over the test, longer and greater number of hispids around the base of an elongated apertural neck; average dimension of the test is between 0.40 mm and 0.50 mm in length; and between 0.25 mm and 0.33 mm in width/thickness (at the widest diameter). Aperture rounded, terminal at the end of the apertural neck, margin of the aperture possesses a lip; neck varies in length from 0.05 to 0.01 mm.

Remarks: Some of the *L. hispida* recorded in the samples differ from those illustrated by Jones (1994: pl. 57, figs. 1 and 2) in being more elongate (flask-shaped) than globular. This variation in shape is considered intraspecific in accordance with the observation of Cushman (1946) that "under *Lagena hispida*, are included a wide range of forms with somewhat differing shapes"; all the Bering Sea specimens have finely spinose surfaces. Setoyama and Kaminski (in press: fig. 8; 29) illustrated a similar specimen with less densely distributed hispids as *Lagena hispidula* Cushman from the Bering Sea; this is slightly different from our material which has more hispids that are densely distributed on the test, and more at the base of the neck. *L. hispida* is uniquely different from other species of *Lagena* because of the hispids distributed uniformly on its test. In the Bering Sea material, 8 of the specimens have elongated chambers that are flask shaped, ovate in outline, while the rest are globular. Variation in the length of the apertural neck is likely to be related to maturity; smaller specimens have shorter apertural necks.

Distribution: *L. hispida* is recorded from the South Atlantic and North Pacific Oceans (Jones 1994), the Gulf of Mexico (Sen Gupta et al. 2009), and the Caribbean Sea (Wilson and Costelloe 2011). Its water depth ranges from 632 m in the North Pacific to between 1061 and 2918 m in the Gulf of Mexico (Sen Gupta et al. 2009; Sen Gupta and Smith 2010; Wilson and Costelloe 2011) to 3477 m in the South Atlantic (Jones 1994). The stratigraphical age of *L. hispida* is not known beyond the Recent (Hesemann 2013).

Lagena sulcata Walker and Jacob, 1798

Plate 2.3, Figures 16-18

Lagena sulcata Walker and Jacob, 1798 - BAGG, 1912, p. 122, pl. XIV, figs. 10, 11, 12 a, b; - MICHEAL, 1967, p. 76, pl. 4, fig. 36; - NEAGU, 1975, pl. 69, figs. 18-19; - LEOBLICH and TAPPAN, 1988, p. 415, pl. 455, figs 12-13; - WEIDICH, 1990, p. 122, pl. 40, figs. 25-26; pl. 45, figs. 6, 14; - JONES, 1994, p. 64, pl. 57, figs. 23, 25-27, 33-34; p. 65, pl. 58, figs. 5-6, 18.

Distribution in core: 35 specimens in 20 samples; highest occurrence at depth 1.38 m, low but consistent occurrence from 18.55 to 19.44 m.

Diagnosis: Test with prominent longitudinal costae on the chambers; aperture terminal, rounded, at the end of a thin elongate neck which has hexagonal ornament.

Description: Test is unilocular, globular, ovate in outline, circular in cross-section; wall is calcareous, prominent and with longitudinal costae which run from the apertural neck to the bottom of the chamber. Test is 0.63 mm in length, 0.33 mm diameter (at its widest diameter); aperture terminal, rounded, at the end of a thin, elongate neck which may be long or short, with hexagonal ornament on the neck.

Remarks: About 60% of the *L. sulcata* examined here are ovate in outline, while the others are rounder. *Lagena sulcata* from the Bering Sea is more elongate than the specimens of this species illustrated in Jones (1994: pl. 54, figs. 1, 2) from the North and Central Pacific and Southern Japan Sea. *L. sulcata* is differentiated from *Lagena striata* (d'Orbigny) by the hexagonal ornament on the elongate neck of the aperture (see Jones 1994, pl. 57, figs. 23, 25-27 and 33-34): both of these species have longitudinal costae as ornamentation on their tests (Jones 1994: pl. 57, figs. 23; 25-27, 33-34 and figs. 22, 24), but the costae are more prominent, delicate (Bagg 1912) and fewer on *L. sulcata* than on *L. striata* (d'Orbigny).

   L. acuticosta (Reuss) differs from *L. sulcata* by having only a few sharp costae, extending over the entire chamber; the species is usually stout and larger. *L. striata*

(d'Orbigny) illustrated by Setoyama and Kaminski (in press) from the Bering Sea is morphologically similar to *L. sulcata* from core U1342 (also from Bering Sea) by possessing a neck that is ornamented, and by having costae that run from the apertural neck to the bottom of the chamber.

Distribution: *Lagena sulcata* is a cosmopolitan species with a geographical distribution in the Pacific and Indian Oceans (Jones 1994; Holbourn and Kaminski 1997). *L. sulcata* has a bathymetric range from neritic to bathyal. Its water depth ranges from 37 to 4300 m at the 'Challenger' stations in the Pacific Ocean (Jones 1994). *L. sulcata* is an indicator of sub-oxic conditions (Jones 1994; Bubenshchikova et al. 2010) and a shallow infaunal species (~ 0-2 cm; Bubenshchikova et al. 2010). The stratigraphical range of *L. sulcata* is recorded as Early Cretaceous to Recent (Neagu 1975; Weidich 1990; Holbourn and Kaminski 1997); however, a stratigraphical range of Miocene to Recent was assigned by Jones (1994).

Lagena nebulosa Cushman, 1923
Plate 2.3, Figure 19

Lagena leavis (Montagu 1803) var. *nebulosa* - CUSHMAN 1923, p. 29, pl. 5, figs. 4, 5. *Lagena nebulosa* Cushman, 1923; - BARKER, 1960, pl. 56, fig. 12; - JARKE, 1960, pl. 5, fig. 6; VILKS, 1969, p. 55, pl. 2, fig. 21; - FAGERLIN, 1971, p. 54, pl. 3, fig. 16. - ANDERSON, 1975, p. 83, pl. 5, fig. 12; - BOLTOVSKOY and KAHN, 1983, p. 305, pl. 1, figs. 16-17; - JONES, 1994, pl. 56, fig. 12

Distribution in core: 4 specimens in 3 samples at depths 0.51, 9.11 and 15.95 m

Emended Diagnosis: (Based on material from Anderson 1975; O'Niell 1981; Boltovskoy and Kahn 1983, and the Bering Sea specimens) Test globular to rounded, finely perforate, aperture terminal, produced on a long or short tubular neck; aperture may have a phialine lip.

Description: Test unilocular, globular to rounded, circular in cross section, widest at the middle of the chamber, average dimension of 0.70 mm in length (including the neck),

0.53 mm diameter. Wall calcareous, finely perforate and smooth; aperture is rounded, diameter is ~0.05 mm, terminal, produced on a long neck.

Remarks: Based on published illustrations, this species is variable in shape from elongate to round, globular to cylindrical (Boltovskoy and Kahn 1983). The 4 Bering Sea specimens are more rounded and globular.

Distribution: *Lagena nebulosa* has a geographical range in the Atlantic, Pacific and Arctic Oceans (Boltovskoy and Kahn 1983; Jones 1994; Gross 2001) and the 'Challenger' Station 279C French Polynesia off the French territories (Jones 1994; Vilks 1969). Its water depth ranges from 1133 m at the aforementioned the 'Challenger' Station (Jones 1994) to 5014 m in the Pacific (Jones 1994). *Lagena* may be an indicator of sub-oxic conditions and has been designated an infaunal species (Kahio 1994; Bubenshchikova et al. 2008). The stratigraphical range is not known beyond the Recent (Jones 1994).

Lagena sp. 1
Plate 2.3, Figures 20-22; Plate 2.4, Figures 1-4

Distribution in core: 4 specimens at depths 13.30, 13.71, 14.28 and 14.88 m.

Description: Test unilocular, globular to ovate in outline, circular in cross-section; walls calcareous, ornamented with about 16-18 longitudinal costae in the form of concentric ridges (with 6-7 prominent longer costae), with alternation of long and short prominent longitudinal costae on the test (about 8 each); the longer costae reach to the apertural end, while the shorter costae terminate before getting to the base of the neck. Test size is twice as long as broad, average dimension of 0.58 mm in length, 0.26 mm in diameter at the widest part of the chamber. Aperture is terminal, rounded at the end of a produced neck.

Remarks: *Lagena* sp. 1 differs from *Lagena strumosa* Reuss illustrated by Milker and Schmiedl (2012; figs. 18, 34) from the Western Mediterranean Sea, which has a crown-like aperture on a long neck that is covered by concentric ridges. *L. multicostata*

Copeland (reproduced in Ellis and Messina 1940) from the Eocene and Miocene of North Carolina is differentiated from *Lagena* sp.1 by its smaller size and the slightly tapering neck with horizontal annulations. Jones (1994) illustrated *Cushmanina desmophora* (Jones 1872) as a morphologically similar species from the 'Challenger' Station in the North Pacific and the Atlantic Oceans, but this differs from *Lagena* sp. 1 by the hollow that is present on the pronounced longitudinal costae.

***Lagena* sp. 2**
Plate 2.4, Figures 5, 6

***Distribution in core*:** 1 specimen at depth 15.23 m

***Description*:** Test unilocular, globular, ovate in outline, circular in cross-section; wall is calcareous, ornamented with 6-7 high longitudinal costae which later bifurcate towards the base of the neck about one-fourth the distance along the chamber, and then merge again, forming raised polygonal ridges arranged in a honey-comb pattern around the base of the apertural neck in the form of a collar. This species is 0.50 mm in length, 0.25 mm in diameter at the widest part of the chamber. Aperture is terminal, round, at the end of a short, well-differentiated, smooth neck.

***Remarks*:** *Lagena* sp. 2 resembles *Oolina acuticosta* (Ruess) recorded from the Champlain Sea, New York, Quebec (Cronin 1977; pl. 2, fig. 15) and *Oolina emaciata* (Reuss 1862), but differs by having raised polygonal ridges in the form of a honey-comb pattern around the base of the neck. *Oolina emaciata* (Reuss 1862) has a more broad apertural neck, which is not pitted. *Lagena* sp. 2 is similar to *Lagena bifurcata* LeRoy illustrated in Ellis and Messina (1940), which has a smaller test and is more globose. *Lagena recticulocervix* Poag recorded from the Lower Miocene of Alabama and Mississippi reproduced in the Ellis and Messina Catalogue (1940) differs from this species by having a neck that is ornamented by a reticulate network to which the longitudinal costae are attached, with no distinct aperture.

***Lagena* sp. 3**
Plate 2.4, Figures 7-11

***Distribution in core*:** 1 specimen at depth 16.21 m

***Description*:** Test unilocular, globular, ovate in outline, circular in cross-section; wall is calcareous, ornamented with 7-8 prominent (thick) longitudinal costate, about 8 less pronounced horizontal short costae lie in a row separating the longitudinal costae, but do not dissect the longitudinal costae themselves, forming a sort of 'square' structure with a conspicuous pore at the centre of each of the 'square' structures. The test of this species is 0.50 mm in length, 0.25 mm in diameter at the widest part of the chamber. Primary aperture is terminal, rounded at the end of a non-distinct, relatively short neck.

***Remarks*:** *Lagena* sp. 3 is similar in size and shape to *Lagena* sp. 2, but differs by having thin horizontal costae in between the pronounced longitudinal costae with pores, and by lacking bifurcate ornament on the apertural neck.

Genus *Procerolagena* Puri, 1954
Type species *Lagena gracilis* Williamson, 1848; designated by Puri (1954), p. 104

Procerolagena gracilis (Williamson, 1848)
Plate 2.4, Figures 12-13

Lagena gracilis WILLIAMSON, - 1848, p. 13, pl. 1, fig. 5 ; - BRADY, 1884, p. 464, pl. 58, figs. 19, 22-24; - p. 24, pl. 8, figs. 5, 6; - VILKS, 1969, p. 55, pl. 2, fig. 17; - ANDERSON, 1975, p. 86, pl. 5, fig. 7; - BOLTOVSKOY and de KAHN, 1983, pl. 1, figs. 12-13.
Procerolagena gracilis (Williamson, 1848); - CLARK and PATTERSON, 1993, figs. 2, 4; - JONES, 1994, p. 65, pl. 58, figs. 9?, 11-15; - PATTERSON et al., 1998, p. 9, pl. 6, fig. 1
Procerolagena distoma (Parker and Jones) - IGARASHI et al., 2001, pl. 7, fig. 12
Procerolagena gracilis (Williamson, 1848) - RIVEIROS and PATTERSON, 2007, figs. 6, 7.

***Distribution in core*:** 6 specimens in 5 samples at depths 0.63, 6.37, 9.40, 16.21 and 19.22 m.

Emended Diagnosis: Test hyaline, unilocular and elongated into narrow 'neck-like' extensions at both test extremities, some 16 to 20 longitudinal costae extend from the base of one neck to the other; aperture terminal at the two ends.

***Description*:** Test unilocular, elongated into neck-like extensions at both ends of the chambers, average length of test is 0. 85 mm and diameter of 0.16 mm, circular in cross-section, widest near middle of the chambers; wall calcareous, hyaline; 16 to 20 longitudinal costae extend from the base of one neck to the other, in some specimens the costae unite to form an elongate process in the terminal regions; small and circular aperture at the termination of both necks.

Remarks: There is intraspecific variation in the thickness of the longitudinal costae on the chambers among the few specimens studied: 3 out of the 5 specimens have more pronounced costae. *Procerolagena gracilis* is differentiated from *P. gracillima* above. *P. gracilis* differs from *Procerolagena mollis* (Cushman 1944) by being more bulbous (Riveiros and Patterson 2007).

Distribution: *Procerolagena gracilis* is typically recorded from the Atlantic, Pacific and Southern Oceans (Cushman 1923; Anderson 1975; Jones 1994), and bordering seas (Vilks 1969; Boltovskoy and de Kahn 1983 and Jones 1994). *P. gracilis* ranges from 117 and 137 m depth in the North Atlantic (Jones 1994) to 300 m in waters of the Canadian Arctic (Vilks 1969), to 631 m in the East Pacific (Jones 1994). The stratigraphical range of *P. gracilis* is from Holocene to Recent (Hesemann 2014)

Procerolagena gracillima (Seguenza 1862)
Plate 2.4, Figures 14-15

Amphorina gracillima Seguenza 1862, p. 51, pl. I, fig. 39
Lagena sulcata var. *Distoma polifa* PARKER and JONES, 1865, p. 357, pl. XIII, fig. 21; pl. XIII, fig. 8

Lagena gracillima (Seguenza) BRANDY 1884, p. 456, pl. LVI, figs. 19-28; - BAGG, 1912, pl. XIII, fig. 3; - LOEBLICH and TAPPAN, 1953, p. 60, pl. 11, figs. 1-4; - CRESPIN, 1960, pl. 1, fig. 14; - COLE and FERGUSON, 1975, pl. 5, fig. 12.

Hyalinonetrion gracillimum (Seguenza); CIMERMAN and LANGER, 1991 p. 52, pl. 55, figs.1, 2

Hyalinonetrion gracillis (Costa); HOTTINGER, et al., 1993, p. 78, pl. 90, figs. 7, 8

Procerolagena gracillima (Seguenza) - JONES, 1994. p. 62, pl. 56, figs. 19-22, 24-29 [cop. Brady, 1884, figs. 19-22, 24-29]

Hyalinonetrion gracillimum (Costa) - MILKER and SCHMIEDL, 2012, p. 74, figs. 18, 30

Distribution in core: 6 specimens in 5 samples at depths 1.03, 8.86, 16.21, 18.26 and 19.44 m respectively.

Emended diagnosis: Test elongate, consists of a long attenuated tube drawn into constricted aperture at each extremity; test surface nearly smooth, tube typically straight and has its widest diameter at the centre.

Description: Test elongate, slender and tubular, wall calcareous, hyaline and smooth; test straight and slightly bulbous at the middle of the test, widest diameter at the centre of the test; the best preserved specimen has an average length of 0.65 mm and diameter of 0.21 mm; test typically straight, long tapering extension at each end of the test. Aperture is terminal and rounded, on a long, tapering neck at both ends.

Remarks: *Procerolagena gracillima* (Seguenza) is similar to *Lagena elongata* (Ehrenberg) except that the test of *L. elongata* is less bulbous and more attenuated, with a relatively short taper at the ends (see Jones 1994; pl. 56, fig. 29); while *Lagena dentaliformis* Bagg is also similar to *P. gracillima* (Seguenza) but more bulbous at the centre of the test. *P. gracillima* is differentiated from *P. gracilis* by its smooth test surface; *P. gracilis* has 16-20 longitudinal costae that extend from the base of one neck to the other.

Distribution: *P. gracillima* has been reported from South Pacific and North Atlantic Oceans (Parr 1950; Jones 1994; Hayward et al. 2012), Southern Ocean (Jones, 1994), Norway (Bagg 1912) and North Alaska (Loeblich and Tappan 1953). *P. gracillima* (Seguenza) has a depth range extending from about 25 m water in the Adriatic Sea (Panieri 2006), to between 45 and 1958 m at the 'Challenger' stations in the Pacific (Jones 1994), to 4758 m in the Southern Ocean (Jones 1994). The stratigraphical range of *P. gracillima* is Holocene through Quaternary (Hesemann 2014).

Genus REUSSOOLINA Colom, 1956

Type species *Oolina apiculata* Reuss, 1851, p, 22; original designation

Reussoolina apiculata (Reuss, 1851)

Plate 2.4, Figures 16-19

Oolina apiculata Reuss, 1851: p. 22, pl. 2, fig. 1.

Reussoolina apiculata (Reuss 1851) - CLARK and PATTERSON, 1993, fig. 2.7. - SETOYAMA and KAMINSKI (in review) fig. 7. 11

Reussoolina cf. R. *apiculata* (Reuss 1851) - FINGER, 2013, p. 424, p. 11, fig. 26

Distribution in core: 8 specimens in 8 samples; the highest occurrence is at 0.10 m, intermittent occurrences down core from this level to 20.59 m depth.

Diagnosis: Test globose to ovate, unornamented, single chambered, aperture radiate and terminal on a less distinct neck.

Description: Test unilocular, elongate, globular to ovate, test twice as long as wide, average length of 0.63 mm and 0.33 mm at the maximum diameter; wall calcareous, perforate, surface smooth; aperture terminal, radiate or rounded, bordered by radiating grooves, produced on the tip of the chamber on an indistinct apertural neck.

Remarks: *Reussoolina apiculata* specimens from Bering Sea are morphologically similar to one another, having the same form of aperture, and almost the same size.

Aboral spine is present in the specimen illustrated by Setoyama and Kaminski (in press: fig. 7.11), *Glandulina laevigata* has close resemblance with *R. apiculata*, but it is characterised by more than one chamber. Most of our specimens are not as well preserved.

Distribution: *R. apiculata* occurs in the SW Pacific Ocean (Clark 1990), the NW Atlantic Ocean (Friedrich and Hemleben 2006) and the Bering Sea (Setoyama and Kaminski in press) at depth of ~2139 m. The stratigraphical range of *R. apiculata* is from Lower Jurassic to Recent (Loeblich and Tappan 1988).

Family ELLIPSOLAGENIDAE Silvestri, 1923
Subfamily OOLININAE Loeblich and Tappan, 1961
Genus *Cushmanina* R.W. Jones, 1984
Type species *Lagena vulgaris* Williamson var. *desmophora* Rymer Jones, (1872), p. 54

Cushmanina striatopunctata (Parker and Jones 1865)
Plate 2.4, Figure 20

Lagena sulcata Williamson var. *striatopunctata* - PARKER and JONES, 1865, p. 350, pl. 13, figs. 25-27.
Cushmanina striatopunctata (Parker and Jones, 1865) - CLARK and PATTERSON, 1993, pl. 4, fig. 19; - PATTERSON and RICHARDSON, 1987, pl. 1, 2 - 6; - WILCOX and TURPIN, 2009, p. 11, pl. 4, fig. 5

Distribution in core: 1 specimen at depth 14.88 m

Emended diagnosis: (Revised from Patterson and Richardson 1987) Few prominent longitudinal costae that may continue to the base of the neck, each costa bearing one or two rows of large circular perforations (punctae) that are chain-like in appearance; aperture bordered by a thickened collar on a distinct narrow neck.

Description: Test unilocular, conical in outline, circular in cross-section; twice as long as broad; 0.60 mm in length, 0.28 mm in diameter at the widest part near the base of the chamber; wall calcareous, ornamented with 7-8 prominent (high) longitudinal costate, in which one out of three costae reaches the neck of the test; spaces between longitudinal costae roughened by granular shell growth, circular punctae in the form of chains at the base of costae where they merge with the roughened chamber surface. Aperture is rounded, terminal at the end of a distinct, funnel-shaped, narrow and short neck, bordered by thickened collar.

Remarks: *Cushmanina striatopunctata* from the Bering Sea is similar to *C. striatopunctata* illustrated from the southwest Pacific described by Clark and Patterson (1993: figs. 4, 19). *C. striatopunctata* differs from the superficially similar *Lagena* sp. 3 in having punctae associated with the longitudinal costae, and in the form of its neck which is funnel-shaped. The punctae associated with the longitudinal costae are the primary distinguishing character of this species.

Distribution: *Cushmanina striatopunctata* is a cosmopolitan species recorded from the Atlantic and Pacific Oceans (Loeblich and Tappan, 1988; Clark and Patterson 1993), the Mediterranean Sea (Zenetos et al., 2010; Pećarević et al. 2013), and the Gulf of Mexico (Sen Gupta and Smith 2010). Its stratigraphical range is from Pleistocene to Recent (Patterson and Richardson 1987).

Genus *Oolina* d'Orbigny, 1839
Type species *Oolina laevigata* d'Orbigny, 1839

Oolina hexagona (Williamson, 1848)
Plate 2.5, Figures 1-3

Entosolenia squamosa (Montagu) var. *hexagona* WILLIAMSON, 1848, p. 20, pl. 2, fig. 23
Lagena hexagona (Williamson). - BRADY, 1884, p. 472, pl. 58. fig. 33. - CUSHMAN and TODD, 1945, p.33, pl.5, fig.14.

Oolina hexagona (Williamson). - BARKER, 1960, pl. 58, fig. 33; - TODD and LOW, 1967, p. A 29, pl. 3, fig. 28; - VILKS, 1969, p. 55, pl. 2, fig. 28; - CRONIN, 1979, p. 795, pl. 3, figs. 7, 11; - HERMELIN and SCOTT, 1985, p. 214, pl. 2, fig. 10.

Favulina hexagona (Williamson). - PATTERSON and RICHARDSON 1988, p. 250, figs 32, 33; - LOEBLICH and TAPPAN,1988, p. 120, pl. 463, figs. 1, 2; - CIMERMAN and LANGER, 1991, p. 55, pl. 58, figs. 8, 9.

Oolina hexagona (Williamson) - HERMELIN, 1989, p. 56, pl. 10, fig. 5; - JONES, 1994, p. 66, pl. 58, fig. 33; - ROBERTSON, 1998, p. 100, pl. 37, fig. 2; RASMUSSEN, 2005, p. 76, pl. 8, fig. 10.

Favulina hexagona (Williamson) – CHENDEŞ et al., 2004, p. 76, pl. 1, fig. 16 - MILKER and SCHMIEDL, 2012, figs. 19, 4

Oolina hexagona (Williamson); - HOLBOURN et al., 2013, p. 382

Distribution in core: 3 specimens from depths 0.51, 18.55 and 18.67 m.

Emended diagnosis: (Revised from illustrations and descriptions of Hermelin 1989; Jones 1994; Holbourn et al. 2013 and the Bering Sea specimens) Test with hexagonal reticulae in the form of polygonal ridges, arranged in a honeycomb pattern; cross section of test is circular. Aperture is rounded, terminal on a short neck.

Description: Test is ovate and unilocular, cross-section circular. Wall calcareous, finely perforate, ornamented with raised polygonal ridges, arranged in a honeycomb pattern, giving rise to hexagonal reticulae pattern, 11-12 stout longitudinal costae together with continuous transverse costae forming numerous hexagonal pits on the test. Average length of the test is 0.60 mm and 0.48 mm at the widest diameter; test reticulae are arranged in slightly oblique rows. Aperture is rounded, terminal, produced on a short neck.

Remarks: *O. hexagona* from the Bering Sea shows distinctive hexagonal reticulation. *Oolina hexagona* (Williamson) differs from *Oolina melo* d'Orbigny by these hexagonal reticulae: *Oolina melo* d'Orbigny has quadrate reticulae. *O. hexagona* is superficially similar to *Favulina epibathra* described from the Pacific Ocean (by Patterson and Richardson 1988: p. 250, figs. 30, 31), but this has only 8-10 stout longitudinal costae,

which together with the discontinuous transverse costae form rectangular pits on the test. Todd and Low's (1967) specimens from Gulf of Alaska are similar to the Bering Sea specimens.

Distribution: *O. hexagona* (Williamson) is recorded from the Pacific and Arctic Oceans (Vilks 1969; Jones 1994) and the Caribbean (Robertson 1998). It has a bathymetric range from neritic to abyssal, from a water depth extending from 50 m in the Canadian Arctic (Vilks 1969) to ~4438 m in the 'Challenger' Station in the south Pacific (Jones 1994). Cronin (1979) noted that *O. hexagona* is common in Recent Arctic assemblages. The stratigraphic range of *O. hexagona* is Miocene to Recent (Holbourn et al. 2013).

Genus *Fissurina* Ruess 1850
Type species *Fissurina laevigata* Reuss, 1850

Fissurina crebra (Matthes, 1939)
Plate 2.5, Figures 4-11

Lagena crebra MATTHES 1939, p.72, pl. 5, figs. 66-70
Fissurina crebra (Matthes). - BARKER, 1960, p. 122, pl. 59, fig. 6; - BOLTOVSKOY and de KAHN 1983, p. 1, p. 305, figs. 1-2; - ANDERSON 1975, p. 85, pl. 6, fig. 5; - MAJEWSKI, 2005, p. 202, fig. 21, 8; - MILKER and SCHMIEDL, 2012, fig. 19, 7

Distribution in core: 29 specimens in 12 samples; highest occurrence at 1.13 m, intermittent but low abundance from 5.25 to 18.95 m, highest abundance at 19.22 m.

Emended diagnosis: Smooth unilocular test that is ovate in outline, with a keeled periphery; aperture a terminal curved slit.

Description: Test unilocular, ovate in outline, biconvex in cross-section, extended keeled periphery; average length of test is 0.60 mm, and diameter is 0.50 mm at the middle of the test, with thickness of 0.15 mm. Wall calcareous, hyaline, finely perforate and smooth; early part of the chambers sometimes with non-distinct aboral projection

(basal spine). Aperture is a curved terminal slit, within a slightly depressed fissure at the test apex.

Remarks: Boltovskoy and Kahn (1983) report that some specimens from the South Atlantic show weak ornament on the aboral part of the test, but this is not present in the Bering Sea specimens. In some of the Bering Sea specimens the keeled periphery is poorly developed.

Distribution: *Fissurina crebra* is found in the Atlantic, Arctic, and Indian Oceans (Boltovskoy and de Kahn 1983; Anderson 1975; Majewski 2005), Japan Sea (Sharma and Takayanagi 1982) and other regions (Corliss 1979; Gaby and Sen Gupta 1985; Milker and Schmiedl 2012). Its water depth ranges from 235 m in the Japan Sea (Sharma and Takayanagi 1982) extending to 982 m and 4,600 m in the Indian and Atlantic Oceans respectively (Corliss 1979; Boltovskoy and de Kahn 1983; Majewski 2005; Wilson and Costelloe 2011; Milker and Schmiedl 2012). The stratigraphical range of *F. crebra* is from Oligocene to Recent (Boltovskoy and Kahn 1983).

Fissurina minima Aoki, 1964
Plate 2.5, Figures 12-15

Fissurina minima Aoki, 1964, pl. 25, figs., 1a, b

Distribution in core: 8 specimens from 6 samples; absent in the top 14.87 m of the core, intermittent occurrence down core to a depth of 20.44 m.

Emended diagnosis: (Revised from Aoki 1964 and including analysis of the Bering Sea material) Unilocular; length 0.15 mm, width 0.14 mm, thickness 0.09 m (Holotype). Test compressed; aperture a short terminal slit on the periphery.

Description: Test small, unilocular, average length 0.175 mm, width 0.15 mm, thickness 0.10 mm, compressed, almost circular in side view, slightly longer than broad, lenticulinar in apertural view, rounded to ovate in outline, oval to biconvex in cross-section, thickness about two-thirds of the test, periphery acute, rounded, not keeled.

Wall calcareous, finely perforate; aperture a short ovate to lens-shaped terminal slit at the test apex.

Remarks: *Fissurina minima* are morphologically similar to specimens illustrated from the Boso Peninsula, Japan, by Aoki (1964). It is different from *Fissurina* sp. illustrated by Jones (1994: pl. 59. figs. 5 a-c) from the 'Challenger' station 241, North Pacific, by its ovate to lens-shaped aperture. It also differs from the similar species illustrated as *Parafissurina caledoniana* McCulloch from the Bering Sea (Setoyama and Kaminski, in press: figs. 8, 32), which has unequal sides of the curved and more elongated aperture. One of the illustrated specimens of *Fissurina minima* reproduced in the Ellis and Messina catalogue (1940) has close resemblance with the Bering Sea material by having its periphery not keeled.

Distribution: *Fissurina minima* have been reported in the Japan Sea (Aoki 1964). The holotype was reported from Upper Miocene Sasa River exposure, Boso Peninsula (Aoki 1964).

Subfamily SIPHOLAGENINAE Patterson and Richardson, 1987

Genus *Moncharmontzeiana* Patterson, 2010

Non Pytine Fortey, 1975 (= Trilobite)

Pytine Zei and Sgarrella, 1978

Type species *Pytine parthenopeia* Moncharmont Zei and Sgarrella, 1978

Moncharmontzeiana petaloskeltsa (Patterson and Richardson, 1988)

Plate 2.5, Figure 16

Pytine petaloskelts PATTERSON AND RICHARDSON, 1988, p. 252, figs. 37-39

Moncharmontzeiana Patterson, 2010 p. 2, figs. 1-5

Distribution in core: 3 specimens in 3 specimens from 0.38, 1.13 and 19.44 m.

Emended diagnosis: (Modified from Patterson and Richardson 1988) Test ornament consists of 12-13 broad, flattened longitudinal ribs; aperture is small, round, terminal, at the end of a long narrow tubular neck.

Description: Test unilocular, flask shaped, ovate, circular in cross-section; twice as long as broad; 0.55 mm in length (including the neck), 0.27 mm in diameter at the widest part of the chamber; wall is calcareous, translucent, ornamented with 12-13 broad, flattened longitudinal ribs (from the side view) with narrow hollow between each costae; connected together and forming a smooth surface just below the base of the neck; aperture is a small, round opening on a long, narrow terminal tubular neck which makes up about one-third of the length of the test.

Remarks: Patterson (2010) noted that the genus name of the foraminifera *Pytine* Moncharmont Zei and Sgarrella (1978; p. 2), which has its type species as *Pytine parthenopeia* Moncharmont Zei and Sgarrella (1978), is preoccupied by the trilobite genus name *Pytine* Fortey 1975 (type species *Pytine graia*, Fortey 1975), and therefore proposed *Moncharmontzeiana* as a replacement.

Distribution: *M. petaloskeltsa* has been recorded from the Quaternary sediments of western Philippine Basin, in the western Pacific Ocean (Patterson and Richardson 1988).

Family EPISTOMINIDAE Wedekind, 1937
Genus *Hoeglundina* Brotzen, 1948
Type Species *Hoeglundina elegans* (d'Orbigny, 1826)

Hoeglundina elegans (d'Orbigny, 1826)
Plate 2.6, Figures 1, 2

Rotalia (*Turbinulina*) *elegans* d'Orbigny, 1826, p. 276.
Rotalia partschiana d'Orbigny, 1846, p. 153, pl. 7, fi gs. 28 - 30; pl. 8, fi gs. 1-3.
Rotalia flosculiformis SCHWAGER, 1866, p. 262, pl. 7, fig. 109.

Rotalia (Turbinulina) *elegans* d'Orbigny, 1826, pl. 12, fig. 142.

Epistomina bradyi GALLOWAY and WISSLER, 1927, p. 60, pl. 10, fig. 1.

Epistomina flinti GALLOWAY and WISSLER, 1927, p. 61, pl. 9, fig. 16.

Epistomina elegans (d'Orbigny). - CUSHMAN and JARVIS, 1930, p. 365, pl. 34, figs. 1a - c; - LEROY, 1941, p. 40, pl. 1, figs. 5 - 7.

Hoeglundina elegans (d'Orbigny). - BERMÚDEZ, 1949, p. 250, pl. 17, figs. 34 - 36; - PHLEGER and PARKER, 1951, p. 22, pl. 12, figs. 1a, b; - BELFORD, 1966, p. 190, pl. 36, figs. 8-13; - WRIGHT et al, 1978, pg. 723, pl. 5, figs. 15, 16; - VAN MORKHOVEN et al., 1986 , p. 97, pl. 29, figs. 1a, b, 2a, b. - LOEBLICH and TAPPAN, 1988, p. 446, pl. 478, figs. 1-5; - JONES, 1994, p. 104, pl. 105, figs. 3 - 6; - BOLLI et al., 1994, p. 361, figs. 55; 6-8, 9a-e; - ROBERTSON, 1998 , p. 114, pl. 44, fig. 2; - SEN GUPTA et al. 2009, p. A-79, pl. 77, fig. 1-; - MILKER and SCHMIEDL, 2012 , p. 79, figs.15 -16; - HOLBOURN et al., 2013, p. 289, figs. 1-3;- FINGER, 2013, p. 430 , pl. 13, fig. 9.

Distribution in core: 6 specimens in 5 samples; highest occurrence at 2.44 m, intermittent occurrence down core from this level to 118.95 m.

Emended diagnosis: (After illustrations of Bolli et al. 1994 and Van Morkhoven et al. 1986) Test trochospiral, close coiled, suture coiled backwards at the periphery on the spiral side, straight and oblique on the umbilical side; aperture latero-marginal and slit-like, parallel to the peripheral keel.

Description: Test trochospiral, closely coiled, biconvex in cross section and sub-circular in outline, with a sub-acute and keeled periphery. Test medium to large, average dimension is 0.60 mm at the longer diameter, 0.42 mm at the shorter diameter, average thickness 0.30 mm. Chambers about seven to eight in the last whorl, increasing gradually in size, being separated by thick, slightly depressed or flush sutures, curved backwards at the periphery on the spiral side, may be straight and / or oblique on the umbilical side. Chamber walls are calcareous, smooth and finely perforate. Aperture is an elongate, arched latero-marginal slit, parallel to the peripheral keel and opening on the umbilical side.

Remarks: *H. elegans* specimens illustrated from the 'Challenger' station in the West Indies by Holbourn et al. (2013) are morphologically similar to the Bering Sea specimens. Holbourn et al. (2013) recognise two different apertures on their specimens: a primary and a supplementary aperture. However, it was noted that the primary aperture, which is small and interiomarginal, may be absent in some specimens. All specimens examined from the Site U1342, Bering Sea, do not have this aperture type, but do possess the supplementary aperture type, being an elongate latero-marginal slit, parallel to the peripheral keel and opening on the umbilical side. Kaiho (1994) described *H. elegans* as an indicator of sub-oxic conditions.

Distribution: *H. elegans* is a cosmopolitan species, except in the highest latitudes (Holbourn et al. 2013). Its bathymetric range is from neritic to bathyal (<2000 m; van Morkhoven et al. 1986). It has been recorded at a water depth between 182 to ~382 m in the Atlantic (Jones 1994), and the Pacific Oceans (Jones 1994), 245 m in the Northern Gulf of Mexico (Sen Gupta et al. 2009) and 709 m from the 'Challenger' station in the West Indies (Holbourn et al. 2013). *H. elegans* ranges from the Late Eocene to Recent.

Order BULIMINIDA

Superfamily BOLIVINACEA

Family BOLIVINIDAE Glaessner, 1937

Subfamily BOLIVININAE Glaessner, 1937

Genus *Bolivina* d'Orbigny, 1839

Type species *Bolivina plicata* d'Orbigny, 1839

Bolivina spissa (Cushman, 1926)

Plate 2.6, Figures 3-15

Brizalina spissa Cushman, 1926 - pl. 6, figs. 8a-b

Bolivina spissa Cushman - BANDY 1953, pl.24, figs. 5 a-b; - BERGEN and O'NEIL 1979, p. 1273, pl. 3, fig. 25; p.1275, pl. 4, figs. 30, 31; - INGLE et al, 1980, p. 137, pl. 3, figs 13, 14; - WHITTAKER 1988, p. 102, pl. 11, figs 17- 20. - MALMGREN and FUNNELL 1991, p. 157, pl. 1, fig. 9; - BERNHARD et al. 2001, p. 2243, fig. 4, M.

Distribution in core: 444 specimens in 55 samples; relative high occurrence at the top part of the core between depths 0-0.51 m, and moderately abundant between 18.43-19.22 m.

Emended diagnosis: Test is slender, elongate, initial chamber uniserial, later biserially arranged. Pores dominant in the centre of the chambers; an apical spine may be present; aperture is loop shaped with slight lip.

Description: Test elongate, slightly flattened, chambers initially uniserial, later biserially arranged forming alternate pairs, width broadened as new chambers are added, last two chambers weakly inflated, oval in cross-section, periphery is sub-acute; average test dimension is between 0.25 and 1.18 mm in length, 0.13 and 0.43 mm in width, 0.08 mm in thickness; while the average test length / width ratio is 2.7 (0.70/0.26). Wall is calcareous, perforate; striae on the early portion of the test runs longitudinally on the first and other early chambers. An apical spine is usually present, later part of the chambers smooth (near the aperture); pores are conspicuously absent near to, and on, the sutures. Chambers numerous (microspheric form has more chambers than the megalospheric form), six to eleven pairs in adult, last three pairs making up half of the test. Sutures slightly depressed, forming a groove towards the last chamber, often wide, curved and tangential to the edge of the chamber, making an angle of about 45 degrees with the edge of the test. Average proloculus diameter is 0.016-0.018 mm in microspheric form, 0.05-0.12 mm in megalospheric form. Aperture is a loop-shaped slit, bordered by a narrow lip. The species is strongly dimorphic: megalospheric form having a large proloculus with fewer numbers of chambers.

Remarks: *Bolivina seminuda* Cushman is differentiated from *B. spissa* by its slightly depressed and narrow sutures on the chambers that are almost normal to the median line (Scripps 1940); *B. seminuda* also has more pointed chambers in the initial part of the test. Pore density in *B. seminuda* is more than double that of *B. spissa,* with the pore diameter slightly smaller than that of *B. spissa* (Glock et al. 2011). Generally, the number of pores varies in *B. spissa* within a single test; there are more pores on the later chambers than on the earlier chamber. The pore-densities on the test vary from 0.0013

P/μm^2 to 0.0104 P/μm^2 (see Appendix 4b); while pore diameter varies randomly within a chamber and across the chambers with an average diameter of 4.11 μm.

About 85% of the specimens examined (n = 444) are megalospheric (the product of sexual reproduction), having a pronounced proloculus. The number of chambers increases with increase in length of the test (Appendix 3d; Fig. 2.2: R^2 = 0.7374). There is a wide range of intraspecific variation in the size of *B. spissa* within assemblages: the length varies randomly from 0.25 to 1.18 mm, while width ranges from 0.13 to 0.43 mm down core (Fig. 2.3: R^2 = 0.1886; no correlation). Assessment of *B. spissa* pore density shows random variation across intervals, which include horizons determined to signal different levels of water column oxygenation based on sedimentary characteristics (laminated and non-laminated intervals), and associated benthic foraminifera (deep infaunal species). With the very weak correlation in the size (length and width) and water column oxygenation, one interpretation is that this investigation does not support the benthic foraminiferal dissolved-oxygen index model of Kaiho (1994). Box and whisker plots (Fig. 2.4) statistically and visually shows the data spread for PD variation in *B. spissa* from 6 different intervals, these include laminated interval (shaded: 78.77%) and other non-laminated intervals. However, from the data spread, there is also no significant relationship between the PD and the sedimentology. An alternative interpretation would be that the average pore density of specimens within samples does not correlate with bottom water oxygenation (as is proposed in Chapter 3).
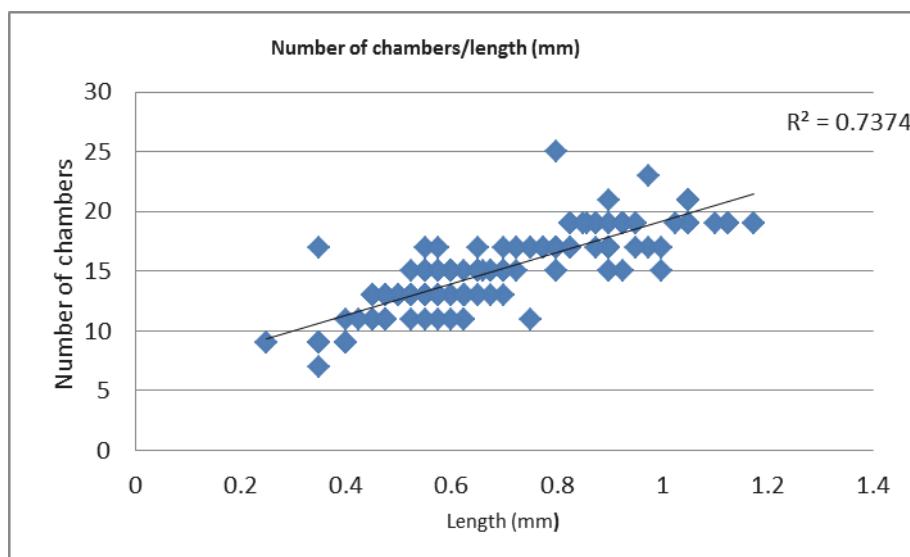
Figure 2.2 *B. spissa* **number of chambers plotted against lengths of test from laminated and non-laminated intervals. A total of 203 specimens were measured down core, being a subset of the total specimens in the samples.**
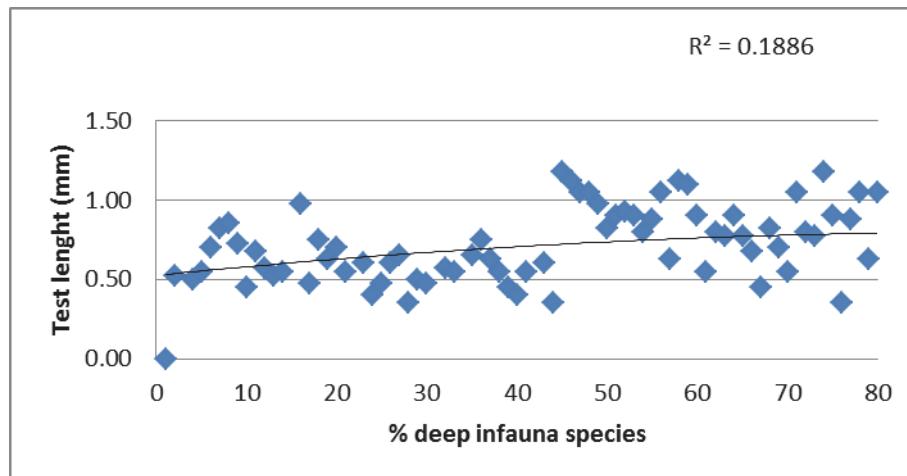
Figure 2.3 Correlation between *B. spissa* **test length and pre-determined oxygen level (% deep infauna is used as a proxy for dissolved oxygen content at various intervals). A total of 203 specimens were measured down core, being a subset of the total specimens in the samples. Horizontal axis shows the percentage of associated infaunal species based their microhabitats (Bubenschikova et al. 2010).**
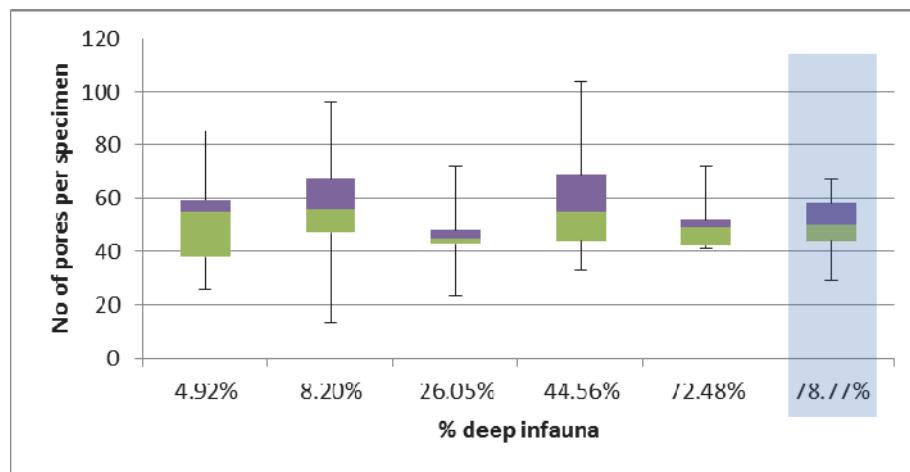
Figure 2.4 Box plot statistically and visually showing the data spread for PD variation in *B. spissa* **from 6 different intervals, these include laminated interval (shaded: 78.77%) and other non-laminated intervals. There is no significant**

relationship between the PD and the sedimentology at these intervals. Pores from 10,000 μm^2 on 121 specimens (being a subset of the total specimens in the samples: only megalospheric forms are used for this analysis) across laminated and non-laminated intervals were counted. The horizontal axis shows the percentage of associated infaunal species based on microhabitats (Kaiho 1994; Bubenschikova et al. 2010).

Distribution: *B. spissa* has a geographical distribution that extends from the Pacific Ocean (Bandy 1953; Kennett 1995; Joachim and Dorothee 1995; Bernhard et al. 2001; Ohkushi et al. 2003; Bubenshchikova et al. 2010), and to the Weddell and Japan Seas (Mackensen et al. 1990; Sharma and Takayanagai 1982; Kitazato and Ohga 1995; Nomaki et al. 2008; Noda et al. 2008) and other seas (Bergen and O'Neil 1979; Bergen 1979; Ingle et al. 1980; Bernhard et al 2001; Nomaki et al. 2008). Its water depth ranges from 135 m in Japanese waters (Sharma and Takayanagai 1982; Kitazato and Ohga 1995) to between 595 and 1174 m in the Gulf of Alaska (Ohkushi et al. 2003), to a greater water depth of 4500 m in the Pacific Ocean (Smith 1963; Bergen and O'Neil 1979; Ingle et al. 1980; Bernhard et al 2001; Ohkushi et al. 2003; Nomaki et al. 2008; Bubenshchikova et al. 2008; 2010). *B. spissa* is a deep infaunal species and has been considered an indicator of dysoxic conditions (Kaiho 1994; Ohkushi et al. 2003; Bubenshchikova et al. 2008; 2010). *B. spissa* has been recorded in the Pleistocene to Recent (Smith 1963).

Bolivina **sp. 1**
Plate 2.6, Figures 16-20; Plate 2.7, Figures 1-3

Distribution in core: 110 specimens in 15 samples: consistent occurrence at the top of the core between depth interval 0 and 0.25 m, highest abundance between depth 6.11 and 6.37 m, intermittent occurrence down core.

Description: Test small, elongated biserial, tapered, twice as long as wide, average length ranges between 0.20 and 0.32 mm, width 0.15 and 0.22 mm at the widest. Wall calcareous, slightly lobulate at the periphery, chambers indistinct, and typically between

8 to 10, increasing gradually in size as added; first chamber slightly rounded; surface rugose; sutures sinuous may be oblique and depressed; aperture a basal opening surrounded by a small lip; apertural face slants at about 45^0.

Remarks: *Bolivina* sp. 1 is similar to *Bolivina variabilis* (Williamson) recorded from the western Mediterranean Sea (see Milker and Schmiedl 2012: figs. 19, 25, 26), which has pronounced pores on the rugose test. *Bolivina lutea* Sliter, illustration reproduced in the Ellis and Messina catalogue (1940), has a rugose test surface and differs from this species in being smaller and less robust. *Bolivina subreticulata* Parr, illustrated from the Holocene of the Indian Ocean and the Red Sea by Sen Gupta (1994), is similar to *Bolivina* sp. 1 having a rugose test and an apertural face that slants at about 45^0, but differs with the suture being raised along the median line.

Morphologically similar *Bolivina substriatula* was described by Keller (1980) from the Japan Trench area, but can be differentiated from *Bolivina* sp. 1 by the prominent pores on the rugose surface of the chamber. About 20% of the specimens described here have a lobulate periphery, the degree of roughness in the ornamentation on the chambers varies; depressed areas are somewhat smooth in some specimens. There is intraspecific variation in the number of chambers on the specimens within the assemblage; the average number of chambers per specimen varies randomly from 8 to 10, this seems not related to different levels of water column oxygenation, based on the low percentage of associated species (i.e deep infaunal) recorded at these intervals and on absence or reduced sedimentary lamination.

Bolivina **sp. 2**
Plate 2.7, Figure 4

Distribution in core: 1 specimen from depth 1.38 m.

Description: Test small, elongate biserial, gradually tapering, average test length ranges between 0.22 and 0.37 mm, 0.15 and 0.30 mm at the widest in the last two chambers. Wall calcareous, slightly lobulate at the periphery; chambers number 10 to 12, having basal projections, adjacent to the depressed central axis of the test, becoming pronounced in the middle chambers. Chambers irregular, first chamber weakly rounded,

increasing gradually in size as added; surface rugose, sutures sinuous, not distinct, may be oblique and depressed; aperture a basal opening surrounded by a small lip; apertural face slants at about 45°.

Remarks: *Bolivina* sp. 2 is similar to *Bolivina* sp. 1 recovered from Site U1342, but differs in being longer in length, having more inflated chambers with a lobulate periphery; also differs from *Bolivina lutea* Sliter described from the Recent of Santa Monica Bay, California (reproduced in Ellis and Messina 1940) which has more chambers, and *Bolivina palantia* Poag from the continental shelf of Texas (Gulf of Mexico) which is coarsely perforate at the sides of the chambers, but non-perforate in the later chambers. Only one specimen of *Bolivina* sp. 2 is recorded, this is not enough for any meaningful identification

Bolivina sp. 3
Plate 2.7, Figures 5-16

Distribution in core: 25 specimens in 22 samples; highest occurrence at the top of the core 0 to 0.10 m, intermittent occurrence down core to 19.44 m.

Description: Test initially uniserial, rapidly becoming biserial, elongate, forming alternate pairs of chambers, weakly flattened, oval in cross-section; width broadened as new chambers are added; average dimension of *Bolivina* sp. 2 is between 0.22 and 0.92 mm in length, 0.13 and 0.37 mm in width, 0.08 mm in thickness; average length / width ratio of *Bolivina* sp. 2 is 2.8 (0.62/0.22). Wall calcareous, smooth, finely perforate (visible with high magnification on the SEM); two distinct striae on the early portion of the test, run longitudinally through the middle of the test at various lengths to later chambers of the specimens; chambers six to eight pairs in adults. Sutures slightly depressed, forming a groove towards the last chamber where longitudinal striae are weakly developed. Aperture a loop shaped slit on the last chamber.

Remarks: *Bolivina* sp. 3 is similar to *B. spissa* but differs by having striae on the early portion of the test, which run longitudinally through the middle of the test to the later

chambers at various lengths. Pores are conspicuously present on the chambers *of B. spissa*; this can only be spotted under a high magnification (i.e SEM) on *Bolivina* sp. 3. *Bolivina* sp. 3 has fewer chambers when compared with *B. spissa* described from the Pacific Ocean (Bergen and O'Neil 1979: p. 1273, pl. 3, fig. 25; p.1275, pl. 4, figs. 30 and 31; Ingle et al. 1980: p. 137, pl. 3). *Bolivina* sp. 3 differs from *Bolivina seminuda* Cushman illustrated by Glock et al. (2011) from the Pacific coast off Peru, which are conspicuously perforate. There is intraspecific variation in the number of chambers on the specimens, but circa 80% have seven to eight pairs of chambers, irrespective of the size.

Genus *Brizalina* Costa, 1856
Type species *Brizalina aenariensis* Costa, 1856

Brizalina earlandi Parr 1950
Plate 2.7, Figures 17-21

Brizalina earlandi Parr, 1950, pl. 12, figs. 16 a-c
Bolivina punctata d'Orbigny - BRADY 1884, pl. 52, figs. 18, 19; pl. II, fig. g
Brizalina earlandi Parr, 1950; - JONES, 1994, pl. 52, figs. 18-19; - HUGHES and GOODAY, 2004, pl. 2, fig. g; - ABU-ZIED, 2012, p. 7, pl. 4, fig. 14;

Distribution in core: 480 specimens in 35 samples; intermittent occurrence from the top of the core down to 20.18 m; highest abundance between depth intervals 0 to 0.38 m and at 10.87 m.

Emended diagnosis: (Based on the illustrations and descriptions of Jones, 1994, Hughes and Gooday 2004; Abu-Zeid 2012 and the Bering Sea specimens). Distinctly perforate, coarser pores more concentrated at the top of the sutures on each chamber; slit-like aperture extends up the apertural face, with bordering thick lip.

Description: Test elongate, biserial throughout, initial end of the test rounded in outline; wall calcareous, distinctly perforate, pores at the distal part of each chamber near the preceding, coarser pores concentrated at the top of the sutures, last chamber (near the

aperture) without pores. Ten to fourteen chambers which broaden slightly in the later stages, slightly inflated as added. Average length of the test ranges between 0.20 and 0.90 mm, width 0.22 and 0.30 mm, average length / width ratio is 1.75 (0.42/0.24); sutures oblique, slightly depressed; aperture a slit-like opening extending up the apertural face, bordered with a thick lip in the form of the letter 'U'.

Remarks: About 95% of specimens described here have their test rounded in shape, whilst others are slightly ovate. *B. earlandi* illustrated by Hughes and Gooday (2004: p. 1479, pl. II, fig. g) from the North Atlantic are more ovate to flattened in shape. The specimens from Site U1342 are very similar to those from the Red Sea (Abu-Zeid 2012: figs. 4, 14). Apart from slight variation in test shape, specimen morphology is very uniform in the Bering Sea assemblages.

Distribution: *B. earlandi* was originally described from the seas around Heard Island in the Southern Ocean (Jones, 1994). It is a cosmopolitan species, which has a geographical distribution in the Atlantic and Pacific Oceans (Jones, 1994; Hughes and Gooday 2004; Jorissen et al. 2009), the Red Sea (Abu Zeid 2012; Ramadan, 2012). Its water depth ranges from ~70 to 5087 m (Jones 1994; Hughes and Gooday 2004; Jorissen et al. 2009; Abu-Zeid 2012). The stratigraphical age of *B. earlandi* beyond the Quaternary is not known (this study).

Brizalina alata (Seguenza, 1862)
Plate 2.8, Figures 1-10

Vulvulina alata Seguenza, 1862, p. 115, pl. 2, figs. 5, 5a
Bolivina alata (Seguenza) - CUSHMAN, 1937, p. 106, pl. 13, figs. 3-11; - RENZ, 1948, p. 116, pl. 6, fig. 26; pl.12, fig 12; - INGLE et al., 1980, p. 137, pl. 2, fig. 12; - CIMERMAN and LANGER, 1991, p. 59, pl. 61, figs. 12–14; - BOLLI et al., 1994, p. 339, figs. 78, 4-5, 73; - MERIC et al., 1995, pl. 6, figs. 8a-c; - den DULK et al., 1998, pl. 2, fig. 6; - ABU-ZIED, 2008, p.51, pl. 1, fig. 25; - SEN GUPTA et al., 2009, p. A-16, pl. 14, figs.1- 3.
Brizalina alata (Seguenza, 1862); - BARKER, 1960, p. 108, pl. 53, figs. 2-4; - POAG, 1981, p. 43, 44, pl. 23, fig. 2, pl. 24, figs. 2a-c; - DENNE, 1990, pl. 2, fig. 2; - VAN

MARLE, 1991, P. 166, pl. 17, figs. 1-2; - JONES, 1994, p.58, pl. 53, figs. 2-4; - AKINMOTO 1994, p. 289, pl.2 figs. 1a, 1b; - CHENDEŞ et al., 2004, p. 78, pl. 2, fig. 1; - POPESCU and CRIHIAN, 2005, p. 391, pl. 1, figs.17, 18; - HOLBOURN et al., 2013, p. 76.

Distribution in core: 199 specimens in 30 samples; relatively abundant at the top of the core between depths 0 to 0.51 m, 10.78 to 11.63 m and at 19.22 m; intermittent occurrence down core at other levels to 19.22 m.

Emended diagnosis: (Based on the illustrations and descriptions of Jones 1994: p. 58, pl. 53, figs. 2-4; Akimoto 1994: p. 2 fig. 1; Chendeş et al. 2004; p. 2, fig. 1, and Holbourn et al. 2013: p. 76). Chambers perforate, weakly flattened, having a sharp, downwards pointing carina, early chambers compressed; aperture a lens-shaped opening.

Description: Test is biserial, flattened, sub-triangular and elongate in shape, lobulate in outline, elliptical in cross-section; average length ranges between 0.45 and 0.98 mm, width 0.22 and 0.40 mm, average length / width ratio is 2.3 (0.71/0.31), test periphery sharp, acute to carinate, serrate with an imperforate carina, extending into a spinose (relatively sharp downward-pointing) carina that merges into the peripheral keel projection at the edge of each chamber. Walls calcareous, finely perforate, imperforate around the early chambers and peri-apertural area; chambers distinct and perforate, arranged adjacent to each other, average of ten to thirteen, increasing broadly in size as added rather abruptly in early chambers, early chambers compressed, weakly inflated and separated by curved, slightly depressed sutures which are oblique and distinct; aperture an elongate, lens-shaped terminal opening with a bordering lip and an internal toothplate.

Remarks: The Bering Sea specimens are similar to specimens illustrated by Chendeş et al. (2004; p. 2, fig. 1) and Kaminski et al. (2002: pl. 2, fig. 12) from the Sea of Marmara in shape, size, number of chambers, and the form of perforations on chambers. Based on morphological comparison, *Brizalina alata* is likely to be the species reported from the Mediterranean Sea and Arabian Sea as *Bolivina alata* (Seguenza) by Abu-Zied (2008: p.

51, pl. 1, fig. 25); and den Dulk et al. (1998: pl. 2, fig. 6). Generally, *B. alata* differs from the superficially similar *Bolivina pisciformis* (Galoway and Morrey) and *Bolivina alazanensis* (Cushman) in possessing fewer chambers that are slightly more inflated, and by having a relatively sharp, downwards pointing carina; *B. alata* also differs from *Brizalina barbata* (Phleger and Parker) which has a wider carina that extends along the entire periphery of the final chamber, forming an apertural lip; *Brizalina spathulata* (Williamson) is morphologically similar, but differs by its more flattened shape. Despite the relatively low abundance of this species in the Bering Sea samples, intraspecies variation is noticed; about 12% of the specimens examined have their first few chambers compressed, while others are elongate.

Distribution: *Brizalina alata* is recorded from the Pacific Ocean (Jones, 1994), European waters and the Mediterranean Sea (Gross 2001; Kaminski 2002), the Gulf of Mexico (Sen Gupta et al. 2009), Arabian Sea (den Dulk et al, 2000) and other seas (Akimoto 1994; Kuhnt et al 2007; Jones, 1994; Popescu and Crihian 2005). *B. alata* occurs at depths extending from 91 m in the Pacific (Jones 1994) to 350 m in the Sea of Marmara (Chendeş et al. 2004); to between 1265 and 1470 m in the Arabian Sea (den Dulk et al 2000) and Okhotsk Sea (Bubenshchikova et al. 2010). *B. alata* is considered a deep infaunal species, characteristic of oxygen-depleted sediments (Kaiho 1994; den Dulk et al 2000; Bubenshchikova et al. 2010). The stratigraphical age of *B. alata* is from Early Miocene to Recent (Van Marle 1991; Jones 1994).

Superfamily CASSIDULINACEA
Family CASSIDULINIDAE d'Orbigny, 1839
Subfamily CASSIDULININAE d'Orbigny, 1839
Genus *Cassidulina* d'Orbigny, 1826
Type species *Cassidulina laevigata* d'Orbigny, 1826

Cassidulina teretis Tappan, 1951
Plate 2.8, Figures 11-15

Cassidulina teretis TAPPAN 1951, p. 7, figs. 30 a-c; - LOEBLICH AND TAPPAN 1953; p 121. - BARKER 1960, p. 110, pl. 54, fig. 1; - LAGOE, 1977, pl. 5, figs. 15,16;

-RODRIGUES et al., 1980, pl. 5, figs. 1, 4, 7; pl. 6, figs. 7, 10; - FEYLING-HANSSEN, 1980, p. 184, pl. 1, figs. 22. 9, 10; - MACKENSEN and HALD, 1988, p. 19, pl. 1, figs. 8-15; pl. 1, figs. 6-8; - GOODAY and LAMBSHEAD, 1989, figs. 1H, I, pl. 2, fig. e; - SEIDENKRANTZ, 1995, pl. 1, figs. 12-13, pl. 2, figs. 15-18; - JONES, 1994, p. 59, pl. 54, fig. 1; - WOLLENBURG and MACKENSEN, 1998, p. 3, figs. 12, 13; - GOODAY and HUGHES, 2002. pl. 2, fig. E; - HOLBOURN et al., 2013, p. 138.

Distribution in core: 363 specimens in 52 samples; consistent occurrence at intervals between 0 to 2.78 m, followed by intermittent occurrence down core from this interval; highest abundance between intervals 15.69 to 17.09 m.

Emended diagnosis: (based on illustrations and descriptions of Rodrigues et al. 1980: pl. 5, figs. 1, 4, 7; Seidenkrantz 1995: pl. 1, figs. 12-13, pl. 2, figs. 15-18, Wollenburg and Mackensen 1998: p. 3, figs. 12 and 13; Holbourn et al. 2013: p. 138). Test shows pronounced umbilical boss on both sides; chambers extend from the umbilical boss on one side, across the peripheral keel and approximately halfway to the umbilical boss of the opposite side.

Description: Lenticular, planispiral test that is biconvex in cross-section, with an average diameter between 0.25 and 0.75 mm and thickness between 0.10 and 0.25 mm; the test possesses a clear umbilical boss on each side, and an acute, keeled periphery. Wall is calcareous and perforate, surface smooth, composed of clear calcareous material; sutures weakly developed on the surface, gently curved. Chambers are coiled and biserially arranged, alternating on the two sides of the peripheral keel, about eight to ten weakly inflated chambers, oval to sub-triangular shaped. Aperture is narrow, elongate, slit-like, extending from the base of the final chamber to the peripheral keel.

Remarks: This species was originally described from the Gubik Formation (Pleistocene) of Alaska by Tappan (1951). *C. teretis* is morphologically close to *C. laevigata* (Mackensen and Hald 1988). In the Bering Sea material, *C. teretis* is differentiated from *C. laevigata* by its larger size; *C. laevigata* is between 0.20 and 0.45 mm in diameter, 0.10 and 0.15 mm in thickness, while *C. teretis* is between 0.25 and 0.75 mm diameter; 0.10 and 0.25 mm thickness. *C. laevigata* has well developed pores

and a ridge near the aperture, while this is absent in *C. teretis* (Mackensen and Hald 1988, pl. 1 figs. 1-15). The major difference between these two species aside their size, is the possession of a boss-like umbilical structure on each side of the test of *C. laevigata*, which is absent in *C. teretis*. *C. teretis* has a peripheral edge which is not carinate, and an aperture that is not as elongated as in *C. laevigata*.

   C. teretis differs from *C. limbata* Cushman and Hughes by its wider chambers, which are more elongate in shape, and by its slit-like aperture. *C. teretis* differs from superficially similar *Islandiella helenae* on the basis of apertural features and the radial wall structure. *I. helenae* has a relatively short and broad apertural slit with a free apertural tongue, whereas *C. teretis* has a narrow apertural slit with a lip (Feyling-Hanssen and Buza 1976). *C. teretis* and *C. neoteretis* Seidenkrantz differ in the shape of their apertural lip, and by the smaller size of *C. neoteretis* (see Seidenkrantz 1995: pl. 1, figs. 12-13; pl. 2, figs. 15-18).

Distribution: The geographical distribution of *C. teretis* ranges through the Atlantic, Arctic and Pacific Oceans (Butt 1980; Jones 1994; Seidenkrantz 1995; Wollenburg and Mackensen 1998; Gooday and Hughes 2002; Hughes and Gooday 2004) and other seas (Mackensen and Hald 1988; Gross 2001). *C. teretis* has a water depth from 50 m and 2000 m in the Arctic Ocean (Seidenkrantz 1995) to 2982 m in the North Atlantic (Jones 1994). *C. teretis* may be an indicator of sub-oxic conditions (Kaiho 1994), and has been shown to increase in abundance after phytoplankton blooms (Gooday and Lambshead, 1989). The known stratigraphical range of *C. teretis* is Pliocene to Recent (Jones 1994).

Cassidulina laevigata d'Orbigny, 1826
Plate 2.8, Figures 16-19; Plate 2.9, Figure 1

Cassidulina laevigata d'Orbigny, 1826, p. 282, no. 1 pl. 15, figs. 4, 5; - BRADY 1884, p. 428, pl. 54, figs. 1-3
Cassidulina laevigata carinata Cushman; - COLOM, 1952, pl. 4, figs. 25, 26
Cassidulina carinata Silvestri; - MURRAY, 1971, pl. 7; - RODRIGUES et al., 1980, pl. 5, figs. 3, 6, 9
Cassidulina neocarinata Thalmann; - RODRIGUES et al., 1980, pl. 5, figs. 2, 5, 8

Cassidulina laevigata d'Orbigny, - FEYLING-HANSSEN et al., 1976, pl. 7, figs. 20-21; pl. 18, fig. 12; - SEJRUP et al., 1981, p. 291, pl.1, fig. 5; - SCOTT, 1987, p. 327, pl. 2, fig. 10; - MACKENSEN and HALD, 1988, pl. 1, figs. 1-7; - JONES, 1994, pl. 54, figs. 2, 3; - POPESCU and CRIHAN, 2005, p. 391, pl. 3, figs. 6-9; - MENDES et al., 2012, fig. 3, nos. 4a and 4b.

Distribution in core: 1353 specimens in 35 samples; first occurrence at 1.98 m, consistent occurrence between 5.26 and 6.52 m; highest abundance between depths 5.41 and 5.74 m.

Emended diagnosis: (After Mackensen and Hald 1998) Sub-triangular chambers, a distinct non-perforate umbilical region consisting of clear shell material, without displaying chambers of preceding whorl; apertural face parallel to the peripheral margin.

Description: Small lenticular and flattened test, ovoid to nearly circular in lateral shape, with acute periphery; average test dimensions are between 0.20 mm and 0.45 mm in diameter, 0.10 mm and 0.15 mm in thickness. Test wall calcareous, perforate, surface smooth; chambers sub-triangular, biserially arranged, tend to become strongly carinate; sutures pronounced and depressed, radial to oblique, straight to curved in some specimens, acute periphery which is variable, may become strongly carinate, chambers taper towards the umbilicus, distinct non-perforate, umbilical region consisting of clear test material. Aperture is an elongate slit-like opening with a lip or a flap formed by the infolded chamber walls, situated at the base of the apertural face, almost parallel to the peripheral margin.

Remark: Differences between *C. laevigata* and *C. teretis* have been described above (see 'Remarks' for *Cassidulina teretis*).

The Bering Sea material is very similar to Middle Miocene *C. laevigata* illustrated from Romania by Popescu and Crihian (2005: pl. 3, figs. 6-9), and Sejrup et al. (1981: p. 291, pl.1, fig. 5), in having depressed sutures, pronounced pores and an elongate slit-like aperture at the apertural face which is parallel to the peripheral margin. The Bering Sea specimens are similar to those from the northern North Sea (Mackensen and Hald

1988: pl. 1, figs. 1-7). No significant intraspecies variation is noticed in the Bering Sea assemblages.

Distribution: *C. laevigata* is cosmopolitan, being recorded from the Atlantic, Pacific and Indian Oceans (Keller 1980; Ingle et al. 1980; Joachim and Dorothee 1995; Bubenshchikova et al. 2010; Lutze 1980; Mackensen, et al. 1985; Lévy et al. 1998; Austin and Evans 2000; Asteman and Nordberg, 2013; Mazumder, et al. 2003; Jian et al. 1999; Corliss 1979), the North Sea (Mackensen and Hald 1988), and other seas (Kurbjeweit et al. 2000; Kuhnt et al. 2007; Wilson and Costelloe 2011; Mendes, et al. 2012; Erbs-Hansen et al. 2012). *C. laevigata* is found mostly in boreal environments (Phleger et al. 1953; Murray 1971; Lutze and Coulbourn 1984).

C. *laevigata* has a depth range extending from 270 to 3300 m in the Atlantic (Sejrup et al. 1981; Mackensen et al. 1985; Lévy et al. 1998; Jian et al. 1999; Bubenshchikova et al. 2010), to 5600 m in the Indian Ocean (Mazumder et al. 2003; Corliss 1979). *C. laevigata* is described as an indicator of suboxic conditions and as a shallow infaunal species (Kaiho 1994; Bubenshchikova et al. 2010; Asteman and Nordberg 2013). The stratigraphical range of *C. laevigata* is from Middle Pleistocene to Recent (Bergamaschi 2012).

Cassidulina reniforme Nørvang 1945
Plate 2.9, Figures 6-14

Cassidulina crassa d'Orbigny var. *reniforme* Nørvang, 1945, p. 41, figs. 6 c-h
Cassidulina crassa d'orbigny; - KNUDSEN 1971, pl. 1, figs. 5-6
Cassidulina barbara Buzas; – Buzas, 1965: 25-26, pl. 25, figs 2a, b, 3.
Cassidulina reniforme Nørvang; - SEJRUP and GUILBAULT, 1980, p. 79, figs. 2 F-K; - FEYLING-HANSSEN 1980, p. 184, pl. 1, figs. 9, 10; - RODRIGUES et al., 1980, p. 58, pl. 2, figs. 2, 4, 6; pl. 3, figs. 3, 6, 9, 11, 12; pl. 5, figs. 10-12; - SEJRUP et al., 1981, p. 291, pl. 1, fig. 7; - VILKS et al., 1982, p. 227, figs. 22a, 22b; - SCOTT, 1987, p. 327, pl. 2, figs. 11-12; - WOLLENBURG and MACKENSEN, 1998, p.179, pl. 3, figs. 14, 15; GUSTAFSSON and NORDBERG, 2001, pl. 1, fig. 8; - PATTERSON and KUMAR, 2002, p. 122, pl. 2, figs. 12, 18; - POLYAK et al., 2002, p. 261, pl. 2, fig. 12.

Distribution in core: 2063 specimens in 188 samples; relatively consistent occurrences down core to 20.59 m, highest abundance at depths 1.58 m and 5.87 m.

***Emended diagnosis*:** Test sub-globular and large, chambers inflated and biserially arranged; aperture an elongate to round opening, situated in a depression on the apertural face, surrounded by a lip on the outer margin.

Description: Test sub-globular, average dimension of between 0.37 and 0.92 mm at the maximum diameter, 0.35 and 0.62 mm thickness (~80% of the specimens have average dimension of their test diameter between 0.60 and 0.92 mm); rounded in cross-section, thick and rounded periphery. Wall calcareous with fine pores; opaque-white, chambers indistinct, inflated and biserially connected; number of chambers is between 4 and 6 with sutural lines that are nearly flush with the chambers and sometimes not visible; peripheral edge shows no lobulation. Aperture is an elongate to fairly wide, curved, slit-like opening, situated in a depression on the apertural face, having a flap attached to the upper edge of the apertural opening, surrounded by a lip on the outer margin.

***Remarks*:** *Cassidulina reniforme* is distinguished from the closely related species *C. obtusa* (Williamson) by the position of its apertural face. *C. obtusa* has a characteristic depression, or fold, which may develop in the apertural face, perpendicular to the aperture itself (Sejrup and Guilbault 1980). The Bering Sea material is morphologically similar to *C. reniforme* from the Norwegian continental margin described by Sejrup et al. (1981: p. 291, pl.1, fig. 7), Sejrup and Guilbault (1980: p. 79, figs. 2F-K) in having nearly flush sutural lines, and an elongated to fairly wide slit-like opening, situated in a depression on the apertural face that is surrounded by a lip on the outer margin. The Bering Sea specimens differ from those illustrated by Gustafsson and Nordberg (2001: pl. fig. 8) and Davidsson et al (2013: pl. 1, fig. 10) as *C. reniforme* from the Swedish Baltic coast, which has pronounced pores on the test. Most of the materials recovered from the Bering Sea are well preserved (probably because they are thick-walled) except near the aperture in some specimens, where parts of the tests are broken. Circa 80% of the specimens have average dimension of their test diameter between 0.60 and 0.92 mm.

Morphological assessment of *C. reniforme* specimens recovered from Bering Sea Site U1342 (the top 20.59 m), which incorporates horizons determined to signal different levels of water column oxygenation (based on sedimentary characteristics and associated benthic foraminifera), show slight but random variations in the test sizes: this variation seems to be related to maturity rather than ecological factors.

Distribution: *Cassidulina reniforme* has a geographical range from the North Atlantic, Pacific and Arctic Oceans (Rodrigues et al. 1980, Vilks et al. 1982; Scott and Vilks 1991; Wollenburg and Mackensen 1998; Polyak et al. 2002; Ohkushi et al. 2003, Khusid et al. 2005; Rasmussen et al. 2007; Ovsepyan et al. 2013), the Gulf of Mexico (Konradi 1996; Sen Gupta and Smith 2010) and other seas (Konradi 1996; Patterson and Kumar 2002). *C. reniforme* has a water depth range from 40 m on the Labrador Shelf, Canada (Vilks et al. 1982) down to 4427 m in the Arctic Ocean (Rodrigues et al. 1980; Wollenburg and Mackensen 1998; Sejrup et al. 1981; Vilks et al. 1982; Scott and Vilks 1991; Polyak et al 2002; Ohkushi et al. 2003; Khusid et al. 2005; Rasmussen et al. 2007). This species has been reported as abundant in cold-water areas (temperatures below 2°C) with seasonal sea-ice cover; it is common in glaciated Fjords (Sejrup and Guilbault 1980). The stratigraphic range of *C. reniforme* is Quaternary to Recent (Hesemann 2013).

Genus *Cassidulinoides* Cushman, 1927
Type species *Cassidulina parkeriana* Brady 1881

Cassidulinoides parkerianus (Brady, 1881)
Plate 2.9, Figures 2 - 5

Cassidulina parkeriana Brady, 1881, p. 432, pl. 54, figs. 11-16
Cassidulinoides parvus (Earland); - Nomura, 1984, p. 498, pl. 90, fig. 10, pl. 91, figs. 1-5; - IGARASHI et al., 2001, p. 156, pl. 10, fig. 12.
Cassidulinoides parkerianus (Brady); - Parr, 1950, p. 344, pl. 12, fig. 25; - FILLON 1974, p. 146, pl. 4, fig. 5; - KELLER, 1980, pl. 2, fig. 13; - WEBB and ANDREASEJN, 1986, p. 117; - ISHMAN and WEBB, 1988, p. 534, pl. 6, fig. 1; - HIRVAS et al., 1993, pl. 1, fig. 7; - GAZDZICKI and WEBB, 1996, p. 161, pl. 35, figs. 4 - 6; - MAJEWSKI,

2005, p. 204, fig. 23, 1 - 2; - QUILTY, 2010, p. 198, fig. 3, no. 13; - HOLBOURN et al., 2013, p. 140.

Distribution in core: 156 specimens in 38 samples; highest occurrence at 2.94 m, consistent down core occurrence, relative abundance increases at 9.65, 10.98, 17.09 and 19.76 m.

Emended Diagnosis: Early chambers coiled, robust and slightly compressed in outline; aperture loop-shaped with small folded toothplate, situated on the lateral face of the terminal segment, near its apex.

Description: Test elongate, coiled in early stage, cylindrical in cross-section, later chambers uncoiling, initially planispiral, becoming straight through the later chambers; somewhat compressed in outline, size typically between 0.42 mm and 1.05 mm in length, 0.18 mm and 0.20 mm in widest diameter, test robust, weakly inflated, periphery cylindrical. Wall calcareous, radial, slightly perforate; chambers not quite distinct, about 3 to 4 pairs of biserial chambers in adults; sutures slightly depressed, forming simple zigzag pattern on the inner and outer area of uncoiled biserial section; rounded periphery. Aperture is sub-terminal, loop-shaped to ovate opening with small folded toothplate.

Remarks: The direction of coiling in the early stage of the test of *C. parkerianus* specimens examined varies; about 85% of the specimens have their early chambers coiled towards the right side, when viewed from the apertural face, others are either straight, or coiled slightly towards the left. The specimens are similar to specimens illustrated from the Japan Trench by Keller (1980: pl. 2, fig. 13), from Recent sediments in the Indian Ocean (Nomura 1995), and from east Antarctica (Igarashi et al. 2001: specimens illustrated as *C. parvus* Earland). *C. parkerianus* differs from *C. bradyi* Norman which has a wider aperture surrounded by thick lip. Our specimens differ from those illustrated by Majewski (2005: figs. 23, 1-2) as *C. parkerianus* both in coiling style and sutures. Some of the Bering Sea specimens are delicate, with a smaller diameter than *Cassidulinoides porrectus* (Heron-Allen and Earland). Generally, the Bering Sea material has more chambers in the later portion, which is uncoiled.

Morphological assessment of *C. parkerianus* specimens recovered from Bering Sea Site U1342 (top 20.59 m), which incorporates horizons determined to signal different levels of water column oxygenation (based on sedimentary characteristics and associated benthic foraminifera), show no significant relationship between specimens with coiled early chambers and the sediment type (i.e. laminated / non-laminated intervals).

Distribution: *C. parkerianus* is cosmopolitan, recorded from low to high latitudes (Holbourn et al. 2013); having a geographical distribution extending through the Pacific and the Atlantic Oceans (Keller 1980; Jones 1994; Lévy et al 1975), the Gulf of Mexico (Sen Gupta and Smith, 2010) and the Antarctic (Fillon 1974; Anderson 1975; Majewski, 2005; Quilty 2010). Its depth range is from 82 to 520 m in Pacific (Fillon 1975; Keller 1980; Jones 1994) and Antarctic waters (Majewski 2005). The stratigraphical range of *C. parkerianus* is from the Late Miocene to Recent (Holbourn et al. 2013).

Genus *Globocassidulina* Voloshinova, 1960
Type species *Cassidulina globosa* Hantken, 1876

Globocassidulina subglobosa (Brady 1881)
Plate 2.9, Figures 15-17; Plate 2.10, Figure 1

Cassidulina subglobosa Brady; - BRADY 1881, p. 60; – BRADY, 1884, p. 430, pl. 54, fig.17; - CUSHMAN, 1911, p. 98, text-fig. 152; - CUSHMAN and TODD, 1945, p. 61. 10, fig. 8; - RENZ, 1948, p. 125, pl. 9, figs. 11-12; - PHLEGER, et al., 1953, p. 45, pl. 10, fig. 4; - BARKER, 1960, p. 112, pl. 54, fig.17.
Globocassidulina subglobosa (Brady); - BELFORD, 1966, p.149, pl. 25, figs. 11-16; - LeROY and LEVINSON, 1974, p. 14, pl. 7, fig. 8; - CORLISS, 1979, p. 14, pl. 3, figs. 12-13; - BOLTOVSKOY, 1980, p. 165, pl. 1, fig. 8; - POAG, 1981, p. 70-71, pl. 17, fig. 3; pl. 18, figs. 3a-c; - MURRY, 1983, pl. 2, figs. 3, 4; - KAHIO, 1992, p. 305, pl. 3, figs. 11-15; - JONES, 1994, pl. 54, figs. 17a-c; - SEN GUPTA, 1994, p. 359, pl. 2, figs. 17, 18; - SCHÖNFELD, 1995, p. 221, pl. 2, fig. 15; - RASMUSSEN, 2005, p. 84, pl. 10, fig. 11;- HAYWARD et al. 2007, p. 156, pl. 1, fig. 10; - SEN GUPTA et al., 2009,

p. A-70, pl. 68, figs. 1- 4; - MILKER AND SCHMIEDL, 2012, figs. 20, 13, 14;- HOLBOURN et al., 2013, p. 264.

Distribution in core: 761 specimens in 104 samples; consistent occurrence down core, highest abundance at depths 15.69 and 15.79 m.

Emended diagnosis: (Based on the illustrations and description of Schönfeld and Spiegler 1995; Milker and Schmiedl 2012; Holbourn et al. 2013). Test sub-globular, finely perforate, the ventral side is less convex; aperture a sub-elliptical opening in a depression on the apertural face, surrounded by a lip on the outer margin.

Description: Test sub-globular and ovate with a rounded periphery, rounded in cross-section; chambers indistinct, inflated and biserially connected, four to five pairs of chambers, increasing gradually in size, weakly inflated, average diameter of the test is between 0.30 and 0.45 mm; average thickness 0.20 and 0.32 mm. Wall calcareous, surface smooth and finely perforate, sutures are oblique and slightly depressed; aperture sub-elliptical, elongate to rounded opening in a depression on the apertural face, surrounded by a lip on the outer margin.

Remarks: Corliss (1979) noted that *G. subglobosa* exhibits a range of test sizes; and that small test sizes are found in water depths generally greater than 3500 m, with both small and large tests found in water depths generally less than 3500 m. The latter is true of the assemblages recovered from the interval studied in the Bering Sea Site U1342. This material is similar to specimens illustrated by Milker and Schmiedl (2012: figs. 20; 13, 14) from the western Mediterranean Sea, Schönfeld (1995: p. 221, pl. 2, fig. 15) and Kaiho (1992: pl. 3, figs. 11-15), in having an aperture that is elongate to rounded, situated in a depression on the apertural face, and surrounded by a lip on the outer margin. *G. obtusa,* a morphologically similar species to *G. subglobosa,* is differentiated by its densely perforate test, distinct sutures and by being planispirally enrolled (Milker and Schmiedl 2012: figs. 20; 10, 11)*. G. subglobosa* has been observed to increase in abundance following seasonal pulses of phytodetritus (Gooday 1988; 1993). Despite the relatively large number of specimens of this species, there is no significant intraspecific variation in the assemblage studied from Site U1342 at horizons determined to indicate

different levels of water column oxygenation (based on sedimentary characteristics and associated benthic foraminifera); all major morphological features, including number of chambers and form of aperture, are quite similar.

Distribution: *G. subglobosa* is recorded from the Atlantic, sub-Arctic and Indian Oceans (Said 1950; Corliss 1979; Boltovskoy 1980; Peterson 1984; Weston and Murray 1985; Sen Gupta, 1994; Schmiedl et al. 1997; Sen Gupta and Smith 2010), Japan Sea (Kaiho 1992), the Gulf of Mexico (Hayward et al. 2007) and other seas (Cornelius and Gooday, 2004; Jorissen 1987; Schönfeld and Spiegler 1995; Wilson and Costelloe 2011). Its water depth range is 1061 to 4600 m (Corliss 1979; Kaiho 1992; Hayward et al. 2007; Sen Gupta et al. 2009). Hayward et al. (2007) put the dominant water depth range for *G. subglobosa* between 1500 to 4000 m in the Gulf of Mexico. *G. subglobosa* has been classified as an infaunal species and as an indicator of oxic conditions (Mackensen et al. 1990; Murray 1991; Gooday 1993; Schmiedl et al. 1997; Hayward et al. 2007). *G. subglobosa* has a stratigraphical range from the Oligocene to Recent (Katz and Miller, 1993).

Genus *Islandiella* Nørvang, 1959
Type species *Cassidulina islandica* Nørvang, 1945, designated by Nørvang, 1959, p. 26

Islandiella norcrossi (Cushman 1933)
Plate 2.10, Figures 2-6

Cassidulina norcrossi Cushman, 1933, p. 7, pl. 2, fig. 7; CUSHMAN and BRÖNNIMANN, 1948, p. 75. pl. 8 fig. 12; -LOEBLICH and TAPPAN, 1953, p. 120, pl. 24, fig. 2; - TODD and LOW, 1967, p. A37, pl. 5, fig. 11; - KELLER 1980, p. 856, pl. 2, figs. 8-9.
Cassidulina norcrossi-australis PHLEGER and PARKER, 1951, pl. 2, Fig. 11; - LESLIE, 1965, p. 158, pl. 10, fig. 3
Islandiella norcrossi (Cushman); - KNUDSEN, 1973b, p. 184, pl. 3, figs. 2-3, pl. 12, fig. 6; - CRONIN, 1979, p. 796, pl. 4, figs. 16, 17; - RODRIGUES et al., 1980, p. 55, pl. 4, figs. 1, 4, 7, 10; - pl. 6, figs. 8, 9; - PATTERSON and KUMAR, 2002. p. 122, pl. 2, fig. 6; - ISHIMURA et al., 2012, p. 4355, fig. 3, f.

Distribution in core: 3566 specimens in 112 samples, making ~10% of the total benthic foraminiferal assemblage in the study interval; consistent occurrence down core, highest abundance at depths 9.50 and 9.65 m.

Emended diagnosis: (Following Rodrigues et al. 1980 and Ishimura et al. 2012) Test radial, aperture an elongate marginal opening with internal toothplate, flat tongue is visible, with one edge of the tongue extending beyond the opening of the aperture to the anterior corner of the aperture in the preceding chamber.

Description: Test sub-globular, radial, slightly biconvex in cross-section, periphery rounded, sub-acute to carinate, thickness of the test is between 0.17 and 0.37 mm, average diameter between 0.30 and 0.70 mm, with the diameter perpendicular to the aperture slightly wider; wall calcareous, surface smooth and polished, translucent to hyaline. Chambers not distinct, about five pairs of broad chambers in the final whorl, sutures flush to slightly depressed; aperture an elongate marginal opening, with internal toothplate on the sides and a flat tongue, which extends slightly beyond the apertural opening.

Remarks: The flat tongue seen from the apertural opening differentiates *Islandiella norcrossi* from the species of *Islandiella* (i.e *I. helenae, I. californica* and *I. inflata*), which have curved tongues (Rodrigues et al. 1980). There is intraspecific variation in *I. norcrossi* test size, circa 70% of the species are more biconvex in cross-section than the others, whilst the tests of some of the specimens are perforated randomly down-core; these, however, do not amount to any significant variation in the assemblage. *I. norcrossi* is one of the most abundant (~10%) species recorded from Site U1342 in this study, and has a consistently high relative abundance.

Morphological assessment of *I. norcrossi* specimens from Bering Sea Site U1342, which includes horizons determined to indicate different levels of water column oxygenation (based on sedimentary characteristics and associated benthic foraminifera), show no significant intraspecific variation.

Distribution: *I. norcrossi* has a geographical distribution that includes the Atlantic, Pacific and Arctic Oceans (Cronin 1979; Rodrigues et al. 1980; Steinsund and Hald 1994; Bubenshchikova et al. 2010), Bering Sea (Ovsepyan et al. 2013), and Japan Sea (Keller 1980; Ishimura et al. 2012). *I. norcrossi* has a depth range from 839 to 1312 m in the Okhotsk Sea (Ishimura et al. 2012; Bubenshchikova et al. 2010). *I. norcrossi* has been considered to be an indicator of sub-oxic environments and a shallow infaunal species (Kaiho 1994; Bubenshchikova et al. 2010). *I. norcrossi* ranges from the late Pleistocene to Recent (Hesemann 2013).

Subfamily CASSIDULININAE d' Orbigny, 1839
Genus *Takayanagia* Nomura, 1983
Type species *Cassidulina delicata* Cushman, 1927

Takayanagia delicata (Cushman, 1927)
Plate 2.10, Figures 7-13

Cassidulina delicata Cushman - CUSHMAN, 1927*, p. 168, pl. 6, fig.5
Cassidulina delicata Cushman, 1927, p. 168, pl. 6, Fig. 5; - NOMURA, 1983, p. 53, pl. 1, figs. 3a-c; pl. 7, figs. 1-5; - ISHIMURA et al., 2012, p. 4355, figs. 2f, 3e.
Takayanagia delicata (Cushman); NOMURA, 1983, p. 53, pl. 1, figs. 3a-c; pl. 7, figs. 1–5; - ISHIMURA et al., 2012 figs. 2f, 3e

Distribution in core: 7503 specimens in 113 samples making ~20% of the benthic foraminiferal assemblage in the core; consistent abundant occurrences down core, highest abundance at depths 16.46, 18.80, 18.95 and 19.31 m.

Emended diagnosis: (Based on the illustrations of Nomura 1983, Ishimura et al. 2012 and the Bering Sea specimens examined here). Test lenticular, periphery carinate; chambers biserially arranged, alternate chambers extending to the closed umbilicus on one side; aperture a curved long narrow interiomarginal slit.

Description: Test lenticular, circular in outline, compressed, average size of the test is 0.28 mm at the greatest diameter, 0.25 mm at the minimum diameter, 0.05 mm thick;

alternate chambers extend to the closed umbilicus. Wall calcareous, smooth, translucent, fragile, and hyaline; chambers are biserially arranged, alternate chambers extending to the closed umbilicus on one side, four pairs of chambers in the final whorl; periphery carinate; sutures curved and depressed. Aperture is a curved long interiomarginal slit, extending along the periphery of the penultimate chamber, bordered by a small carinate apertural lip.

Remarks: The Bering Sea material is very similar to the specimens illustrated from the Okhotsk Sea by Ishimura et al. (2012: fig. 3f) and Nomura (1983: p. 53, pl. 1, figs. 3a-c; pl. 7, figs. 1-5) in having alternate chambers that extend to the closed umbilicus, having four pairs of chambers on each side, and by the mode of apertural opening.

Morphological assessment of *T. delicata* specimens recovered from intervals which incorporate laminated and non-laminated horizons determined to indicate different levels of water column oxygenation (based on sedimentary characteristics and associated benthic foraminifera) from Bering Sea Site U1342, show no significant intraspecific variation in the assemblage studied and the sedimentology.

Distribution: *Takayanagia delicata* has a geographical distribution that includes the Pacific Ocean (Cushman 1927, Ohkushi et al. 2003, Bubenshchikova et al. 2010, Ishimura et al. 2012), Bering Sea (Ovsepyan et al. 2013), Japan Sea (Noda et al. 2008), and Arabian Gulf (Mazumder et al. 2003). *T. delicata* has a water depth that ranges between 150 and 480 m off Peru, down to between 1000-3500 m in the Pacific Ocean and Japan Sea (Ohkushi et al. 2003; Noda et al. 2008; Bubenshchikova et al. 2010; Ishimura et al. 2012). *T. delicata* may be an indicator of sub-oxic conditions and/or high organic carbon flux, and is a shallow infaunal species (Kaiho 1994; Bubenshchikova et al. 2010, 2008). Its stratigraphical range is from the Late Pliocene to Recent (Oveisi 2013).

Subfamily EHRENBERGININAE Cushman 1927

Genus *Ehrenbergina* Reuss, 1850

Type species *Ehrenbergina serrate* Reuss, 1850

Ehrenbergina sp.

Plate 2.10, Figures 14-16; Plate 2.11, Figures 1-10

Ehrenbergina sp. Butt 1980, pl. 8, fig. 5

Distribution in core: 1667 specimens in 86 samples; consistent occurrences down core with the exception of intervals between 3.24 to 4.58 m, and 14.14 to 18.26 m, where there are intermittent occurrences; highest abundances are at depths 0.74 m, 5.96 m, and between 18.67 and 19.07 m.

Diagnosis: (Based on the Bering Sea material and illustration by Butt 1980) Test densely perforate forms an elongate initial planispire, first few chambers coiled upwards in the form of a lobe, distinct convex dorsal margin, overlapping and depressed sutures; aperture elongate, narrow and curved slits with almost rounded edges at both ends of the aperture.

Description: Test biserial, sub-triangular in outline with fine peripheral spines, lens-shaped in cross-section, early chambers tends to uncoil, lenticulate in cross-section, shape is asymmetrically biserial, dorsal margin convex, with median ventral furrow and fine peripheral spines. Wall calcareous, densely and finely perforate, surface appears smooth; average test length is between 0.30 and 0.75 mm, width 0.27 and 0.50 mm, and thickness 0.145 mm. Chambers become broader as added, overlapping at the midline of the periphery, about 6 pairs of chambers visible on the dorsal side; dorsal sutures curved, overlapping about half their length, flush with the surface, first chamber in the form of a lobe, coiling upwards; distinct and depressed sutures. Aperture an elongate curved slit, positioned at the middle of the last chamber, nearly parallel to the peripheral margin, with almost rounded edges at both ends of the aperture; measuring up to 0.5 mm in length and 0.4 mm in width.

Remarks: *Ehrenbergina* sp. has an almost 'U'-shaped aperture, the rounded edges of the 'U' being conspicuously absent in *E. compressa* which is morphologically similar to *Ehrenbergina* sp. Whether the Bering Sea material simply represents a regional difference in this structure, or is diagnostic of a separate subspecies is not ascertainable with the available data. *E. hystrix* Brady differs from *Ehrenbergina* sp. by lacking

distinct spine-like projections at the edges of the chambers. Also, the sutures in *E. hystrix* are more raised than those of *Ehrenbergina* sp.; *Ehrenbergina* sp. can be differentiated from *E. bradyi* Cushman from the deep waters of the Pacific Ocean*,* as the latter species is flatter, lacks spines on the periphery, and has no ornamentation along the median line. *Ehrenbergina* sp. is similar to *Ehrenbergina* sp. from the Pacific Ocean (Butt 1980; pl. 8, fig. 5), and to *E. glabra* from the SE Pacific (Schönfeld 1995: pl. 1, fig. 8), which has its first chamber coiled upwards in the form of a lobe, but differs by lacking the overlapping depressed dorsal sutures and the distinctive apertural form that typify *Ehrenbergina* sp. *E. caribbea* Galloway and Hemingway from the Virgin Islands, (reproduced in Ellis and Messina, 1940) differs from *Ehrenbergina* sp. by lacking the first few chambers coiled in the form of a lobe.

More than 90% of the specimens studied from the Bering Sea have their first chamber obviously coiled upwards in form of a lobe.

Distribution: *Ehrenbergina* sp. is known only from the Bering Sea, with a similar *Ehrenbergina* sp. described from the Pacific Ocean (Butt 1980). In contrast, *E. compressa* (a morphologically similar species to *Ehrenbergina* sp.) has a geographical distribution in the Pacific Ocean (Takayanagi 1951; Scripps 1940; White 1956; Kern and Wincander 1974), and the Gulf of Alaska (Bergen and O'Neil 1979), where its water depth extends from 232 to 2623 m (Scripps 1940; Resig 1958; Bergen and O'Neil 1979). *Ehrenbergina* spp. has been classified as suboxic, and shallow infaunal (Kaiho 1994; Bubenshchikova et al. 2010). The stratigraphical range of *E. compressa* is Pliocene to Recent (Van Marle 1991), but the distinctive form described here is only known from the late Pleistocene of the Bering Sea and possibly the Pacific.

Family STAINFORTHIIDAE Reiss, 1963

Genus *Stainforthia* Hofker, 1956

Type species *Virgulina concava* Höglund, 1947

Stainforthia fusiformis (Williamson, 1858)

Plate 2.11, Figures 11-15

Bulimina pupoides var. fusiformis Williamson, 1858, p. 63, pl. 5, figs. 129-130

Bulimina fusiformis (Williamson); - HÖGLUND, 1947, p. 232-235, pl. 20, fig. 3; text-figs. 219-233

Virgulinella fusiformis (Williamson); - PARKER, 1952a, p. 417, pl. 6, figs. 2-3; - ATKINSON, 1970, p. 395

Fursenkoina fusiformis (Williamson). - MURRAY, 1971, p. 185, pl. 77, figs. 1-5

Cassidella fusiformis (Williamson). - LAGOE, 1977, p. 127, pl. 4, fig. 5

Stainforthia fusiformis (Williamson). - HAYNES, 1973, p. 124-125, pl. 5, figs. 7, 8; - ALVE, 1990, pl. 2, fig. 17; - BARMAWIDJAJA et al., 1992, pl. 3, figs. 1-4; - NORDBERG et al., 2000, fig. 3(9) 6.1.1; - GOODAY and ALVE, 2001, pl. 1, figs. H-L; pl. 3, figs. A-J, pl. II, fig. n; - DUIJNSTEE et al. 2004, pl. 1; - DIZ and FRANCES, 2008, pl. 2, figs. 11-12.

Distribution in core: 56 specimens in 9 samples; isolated occurrences at depth 0 m, and depth intervals 9.40 to 9.65 m, 15.69 to 15.79 m; few and intermittent occurrences down the core to 18.43 m.

Emended diagnosis: (Revised, based on the illustrations of Barmawidjaja et al. 1992; Duijnstee et al. 2004; Alve 1990 and descriptions of Gooday and Alve 2001; Alve 2003). Chambers elongate, fusiform, great degree of overlap between adjacent chambers; separated by steeply-angled sutures. Short epical spine often present on the first chamber. Aperture is ovate with serrated lip around the aperture.

Description: Test small, thin walled, triserial in the early stage, twisted biserial arrangement in later stage, tapering, fusiform, rounded in cross-section; wall calcareous, finely perforate; chambers elongate, stretched to near globular, obvious overlap between adjacent chambers. Average dimension of the test is 0.30 mm in length, and 0.18 mm in width (of the last chamber); sutures steeply angled, distinct and depressed, proloculus often with short apical spine, in the form of a blunt 'tail'. Aperture is ovate, wide and terminal, usually clearly defined and positioned away from the end of the chamber, in a spoon-shaped depression, becomes narrower and shallower distally with lip-like plate on its two sides; apertural lip is serrated, curved around aperture.

Remarks: *Stainforthia fusiformis* (Williamson) was first described by Williamson (1858) from samples collected around the British Isles. The Bering Sea specimens are similar to those from the Adriatic Sea (Barmawidjaja et al. 1992: pl. 3, figs. 1-5; Duijnstee et al. 2004: pl. 1) and NE Atlantic Ocean (Gooday and Alve 2001: pl. 3, A-J), but differ by being wider in the middle of the test. *S. fusiformis* differs from *Stainforthia* sp. described by Gooday and Alve (2001) from the N. Atlantic, which is smaller (0.04 - 0.15 mm in length), and has its aperture closer to the apex of the last chamber, with a non-serrated apertural lip which appears linear; *S. fusiformis* has its aperture located farther away from the apex of the last chamber, and the apertural lip is strongly serrated, and curved around the aperture. *S. fusiformis* changes aperture characteristics during growth (see Alve 2003; fig. 1).

S. fusiformis responds quickly to improved oxygen conditions and is the most successful re-colonizer of formerly anoxic environments; it has been designated as an opportunistic r-strategist that can withstand short periods of anoxic conditions (Alve, 1994). Approximately 10% of the specimens examined from the Bering Sea are biserial throughout and their chambers relatively shorter with less overlap.

Distribution: *S. fusiformis* is a cosmopolitan species; it is one of the most common benthic foraminiferal species in NW European marine waters (Alve 2003). It has been recorded from the continental shelf and coastal settings (intertidal to outer shelf), around NW Europe and North America (Alve 1994; Gooday and Alve 2001; Alve 2003), the Atlantic, Arctic and Indian Oceans (Wollenburg and Mackensen 1998; Gooday and Hughes 2002; Mazumder et al. 2003; Erbs-Hansen et al. 2012), the Japan Sea (Kato 1992), and other seas (Murray 1991; Barmawidjaja et al. 1992; Gooday and Alve 2001; Mazumder et al. 2003; Duijnstee et al. 2004). *S. fusiformis* has a depth range from 55 m in the Atlantic (Gooday and Alve 2001; Gooday and Hughes 2002; Erbs-Hansen et al. 2012) to between 1570 and 4217 m in the Arctic Ocean (Scott and Vilks 1991) and 3300 to 4850 m in the Indian Ocean (Mazumder et al. 2003). Its abundance was recorded at a depth of 4000 m in the North Atlantic Ocean (Alve 1994; Bubenshchikova et al. 2010). *S. fusiformis* is an infaunal species that flourishes in temperate, shelf and marginal marine environments independently of whether the sediments primarily consist of mud or fine sand; but it seems to require salinities >30‰ (Alve 1994). Its stratigraphical range is from Eocene to Recent (Loeblich and Tappan 1988).

Family BULIMINIDAE Jones 1875

Genus *Bulimina* d' Orbigny 1826

Type species *Bulimina marginata* d'Orbigny

Bulimina exilis Brady, 1884

Plate 2.11, Figures 16-22; Plate 2.12, Figure 1

Bulimina exilis Brady, 1884 (pl. 2 figs. 22, 23)

Bulimina elegans var. *exilis* Brady, 1884, p. 339, pl. 50, figs. 5, 6

Bulimina elegans var. *exilis* Brady; - CUSHMAN, 1911, p. 82, fig. 135

Bulimina elegans var. *exilis* Brady; - CUSHMAN, 1922, pl. 3, p. 106; pl.17, figs. 7-12; pl. 19, figs. 2,3.

Bulimina elegans var. *exilis* Brady; - CUSHMAN and PARKER, 1947, p. 123, pl. 28, figs. 27-28

Bulimina exilis Brady - LOEBLICH and TAPPAN, 1953, p. 110, pl. 20, figs. 4, 5

Bulimina exilis Brady – PHLEGER et al., 1953; - ASANO, 1958, p. 49, pl. 3, figs. 7a-7b; - PUJOS-LAMY, 1973, pl. 2, figs. 10.1, 10.2; - HAAKE 1980, pl. 2, fig. 23; - VAN MORKHOVEN et al. 1986, pl. 4, figs. 1-2; - OGGIONI and ZANDINI 1987, pl. 6, fig. 11; - CARALP, 1989, p. 40, figs. 1-2; - JANNINK et al., 1998, p. 1497, pl. 1, fig. 3; - LICARI and MACKENSEN, 2005, p. 213, pl. 1, figs. 17, 18; - SCHUMACHER et al., 2007, p. 62, pl. 1, fig. 15.

Eubuliminella exilis (Brady). – JONES 1994 p. 54, pl. 50, figs. 5.6

Distribution in core: 3222 specimens (~9% of the total count) in 119 samples; consistent occurrences down core, high abundances at depth 11.30 m, 17.57 m, and between intervals 15.97 and 16.10 m.

Emended diagnosis: (Diagnosis based on Van Morkhoven et al. 1986; Jannink et al. 1998; Hayward 2002 and the Bering Sea specimens examined here). Test elongate, nearly sub-globular, chambers predominantly triserially arranged; aperture loop shaped, situated in a depression.

Description: Test elongate, slender, nearly sub-globular, inflated; wall calcareous, finely perforate, surface smooth; chambers distinct, triserially arranged, test shows a tendency to become uniserial, average length of the test is 0.75 mm, width is 0.20 mm, and average length / width ratio is 4.3 (0.65 / 0.15); average number of chambers ranges from 8-12; sutures depressed, early chambers rounded at the periphery. Aperture is loop-shaped, situated in a depression, with a tiny tongue.

Remarks: *Bulimina exilis* is distinctive because of its slender, elongate and cylindrical test; the Bering Sea material is different from that illustrated from the northern Arabian Sea by den Dulk et al. (1998: pl. 2, fig. 5), which has an aboral spine with more elongated chambers, but it is morphologically similar to the specimens illustrated by Hayward (2002: pl. 3, fig. 1, 2) and from Trinidad and Venezuela by Morkhoven et al. (1986: pl. 4, figs. 1, 2) both from SW Pacific, and by Licari and Mackensen (2005: pl. 1, figs. 17, 18) from off the West Africa coast.

Intraspecific variation is noted in the assemblages from the Bering Sea: the degree of chamber inflation varies randomly across laminated / non-laminated horizons determined to indicate different levels of water column oxygenation (based on sedimentary characteristics and associated benthic foraminifera); about 75% of the specimens have their chambers more inflated, while others are weakly inflated and more enlongate; however, this does not relate significantly to different environments determined in the core. The number of chambers varies from 8 to 16, and there is variation in the size; circa 10 % of the specimens have more chambers (up to 14), but are shorter and smaller than some specimens with less chambers (i.e 10 chambers). One specimen shows evidence of mutation (Plate 2.12, Fig. 1), the test being significantly different in shape from other specimens of this species; the apertural opening and chamber form are the same as *B. exilis.*

Distribution: *Bulimina exilis* is a cosmopolitan species which has a geographical distribution from the Atlantic and Pacific Oceans (Lévy 1998; Rasmussen et al. 2002; Butt 1980, Khusid et al. 2005), Japan and Arabian seas (Asano 1958; Keller 1980; Schumacher et al. 2007 and Jannink et al. 1998), continental slope off SW Africa, (Schmiedl et al. 1997; Licari and Mackensen 2005) and other regions (Caralp 1984, 1989; Oggioni and Zandini 1987; Schmiedl et al. 1997; Jannink et al. 1998; Maas 2000;

Mazumder et al. 2003; Schumacher et al. 2007). *B. exilis* is known from upwelling and low oxygen environments, it has a water depth range from 136 m in the Arabian Sea (Schumacher et al. 2007) extending to 500 and 3300 m along the central west coast of India and northern Arabian Sea (Caralp 1984, 1989; Jannink et al. 1998; Mazumder et al. 2003). *B. exilis* is a dysoxic and deep infaunal species (Kaiho 1994; Jorissen 1999; den Dulk et al. 2000). *B. exilis* ranges from late Miocene to Recent (van Morkhoven et al. 1986; Gibson 1967).

Bulimina mexicana Cushman, 1922
Plate 2.12, Figures 2 - 6

Bulimina inflata Seguenza var. *mexicana* Cushman 1922, p. 95, pl. 21, fig. 2
Bulimina striata d'Orbigny var. *maxicana* Cushman; - CUSHMAN and PARKER 1940, p. 16, pl. 3, fig. 9
Bulimina striata mexicana Cushman; - PARKER 1954, p. 511, pl. 6, fig. 24; - KOHL, 1985, pl. 20, fig. 4; - ROBERTSON, 1998, p. 147, pl. 56, fig. 7.
Bulimina mexicana Cushman; - BELANGER and BERGGREN, 1986, p. 334, pl. 2, figs. 4a-5; - VAN MORKHOVEN et al. 1986, p. 61, pl. 19, figs. 1-4; JONES, 1994, pl. 51, figs. 10-13; - BERNHARD et al. 2001, p. 2243, fig. 4N; - LICARI and MACKENSEN, 2005, p. 213, pl. 1, figs. 12, 13; - KENDER et al., 2008b, p. 553, pl. 17, fig. 12; - SEN GUPTA et al., 2009, p. A-12, pl. 30, figs.1- 2.

Distribution in core: 25 specimens in 11 samples; most occurrences are within the upper part of the core between depths 0 and 0.88 m, then intermittently down core; most abundant at a depth of 15.19 m.

Emended diagnosis: (Based on Van Morkhoven et al. 1986; Jones 1994 and Holbourn et al. 2013). Test triserial, conical, initial end acute, ornamented with tooth-like crenulations which extend to sharp spines at the margins; aperture is loop-shaped opening surrounded by a lip, containing a tooth.

Description: Test triserial, conical, circular in cross-section, tapered in outline, twice as long as wide, average length of the test is 0.65 mm, width 0.15 mm; wall calcareous,

finely perforate and smooth; chambers slightly inflated towards the later chambers, initial end acute, increasing in size slowly, slightly overhanging the previous chambers, about five chambers in adult. Sutures depressed and well defined five to seven longitudinal costae on the lower half of each chamber, ending in narrow spines; chambers ornamented with tooth-like crenulations which often extend into short, sharp spines at the margins. Aperture is a loop-shaped opening, positioned near the apex of the last chamber, surrounded by a lip that merges with an internal toothplate in the form of a tooth.

Remarks: *B. mexicana* from the Bering Sea material is morphologically similar to specimens illustrated from the Atlantic by Belanger and Berggren (1986: pl. 2, figs. 4a-5), Antarctica by Holbourn et al. (2013: p.110, figs. 1, 2), Monterey Bay by Bernhard et al. (2001: fig. 4N) and from off the coast of West Africa (Licari and Mackensen 2005: pl. 1, figs. 12, 13); these specimens have sharp spines at the margins, between 5 to 7 longitudinal costae, and a loop-shaped aperture containing a tooth surrounded by a lip. The Bering Sea material differs from specimens recorded from the Pacific illustrated by Brady, 1884 (pl. 51, figs. 10-13), in that the triserial arrangement of the last chambers in the latter are distinct. *B. mexicana* differs from *B. rostrata* Brady illustrated from the 'Challenger' Station in the Central Pacific by Holbourn et al. (2013) which is elongate and fusiform, with indistinct sutures. All *B. mexicana* specimens studied across laminated / non-laminated horizons determined to indicate different levels of water column oxygenation based on sedimentary characteristics and associated benthic foraminifera (i.e: deep infaunal species) from different horizons in core U1342 reveals no fundamental change in the key morphological traits; they are morphologically similar.

Distribution: *B. mexicana* is cosmopolitan, being recorded from the Pacific (Keller 1980; Joachim and Dorothee 1995), and Atlantic Ocean (Jian et al. 1999; Schmiedl et al. 1997); offshore Angola West Africa (Kender et al. 2008b) and other regions (Molina-Cruz and Ayala-Lopez 1988; Jian et al. 1999; Licari and Mackensen 2005; Sen Gupta et al. 2009). *B. mexicana* extends from 900 m depth in Monterey Bay (Bernhard et al. 2001) to between 1200 and 2000 m off West Africa (Licari and Mackensen 2005; Kender et al. 2008b) to 3820 m in the Atlantic Ocean (Griggs et al. 1970). *B. mexicana*

is considered by some studies an indicator of sub-oxic conditions, and a shallow infaunal species (Kaiho 1994; Kender et al. 2008b). The stratigraphical range of *B. mexicana* is Early Miocene to Recent (Holbourn et al 2013).

Genus GLOBOBULIMINA Cushman, 1927

Type species *Globobulimina pacifica* Cushman, 1927

Globobulimina auriculata (Bailey, 1851)

Plate 2.12, Figures 7-11

Bulimina auriculata Bailey, 1851, p. 12, pl. 1, figs. 25-27; - KATO, 1992, pl. 2, figs. 9a-b; - HALD and KORSUN, 1997, p.1, fig. 20; - GUSTAFSSON and NORDBERG, 2001, pl. 1, fig. 8; - ISHIMURA et al., 2012, p. 4355, figs. 2b, 3g.

Distribution in core: 129 specimens in 42 samples; intermittent occurrences down core, highest abundance at depth 10.98 and 12.98 m.

Emended diagnosis: (Diagnosis based on original description in Ellis and Messina 1940; Hald and Korsun 1997; and Ishimura et al. 2012). Test fragile, inflated, usually widest towards the initial end, tends to be elongate; final chamber very large, almost encompassing the whole test.

Description: Test fragile, inflated, sub-globular in outline and circular in cross-section, widest towards the initial end, tends to be elongate, average dimension of the test is 0.62 – 0.75 mm in length, and 0.36 - 0.62 mm in width. Wall calcareous, thin, smooth, finely perforate and translucent; the maximum width is located in the middle portion of the test usually towards the early part; final chamber large, encompassing more than 80% of the whole test, with a fairly rounded proximal end; aperture is a loop with an internal tooth.

Remarks: *Globobulimina auriculata* was recorded from the upper Miocene - Pliocene Quinault Formation in the USA by Cushman et al. (1949). *G. auriculata* differs from *G. affinis* (d'Orbigny 1839) which has a rounded proximal end (Corliss 1985), and from *G.*

pacifica by possessing a more encompassing terminal chamber, which almost overlaps all of the other chambers. The Bering Sea specimens are similar to those illustrated by Hald and Korsun (1997: pl. 1, fig. 20) and Vilks et al. (1982) from the Labrador Sea, Canada. All specimens of *G. auriculata* studied across laminated / non-laminated horizons from the Bering Sea core U1342, are morphologically similar, except for slight variation noticed in their size, probably related to maturity.

Distribution: *G. auriculata* has a geographical range in the northern Atlantic (Asteman and Nordberg, 2013; Rasmussen et al. 2013), Pacific (Ohkushi et al. 2005; Ovsepyan et al. 2013), Southern Ocean **(**Husum and Hald 2004; Khusid et al 2005; Jennings et al. 2006), and Japan Sea (Noda et al. 2008). *G. auriculata* has a depth range from 425 m in the Atlantic (Rasmussen et al. 2013) to 3500 m in the Pacific (Ohkushi et al. 2005; Khusid et al. 2005; Noda et al. 2008; Bubenshchikova et al. 2008). *G. auriculata* has been classified as a dysoxic and deep infaunal species (Jones 1994; den Dulk 2000; Bubenshchikova et al. 2008). The stratigraphical range of *Globobulimina auriculata* is Miocene to Holocene (Kato 1992; Hald and Korsun 1997).

Globobulimina pacifica Cushman 1927

Plate 2.12, Figures 12-17; Plate 2.13, Figures 1 to 6

Bulimina pyrula d' Orbigny; - BRADY, 1884, p. 399, pl. 50, figs. 7-10; - POPESCU and CRIHIAN, 2005, pl. 6, fig. 10.

Globobulimina pacifica Cushman - CUSHMAN 1927, p. 67, pl. 14, fig. 12; CUSHMAN 1927 b, p. 153, pl. 3, fig. 1; - GALLOWAY and WISSLER, 1927, p. 74, pl. 11, fig. 18; - CUSHMAN, et al., 1930, p. 66, pl. 5, fig. 4; - CUSHMAN and MOYER, 1930, p. 57; - CUSHMAN and LAIMING, 1931, p. 108, pl. 1a-b; - BERMUDEZ, 1949, p. 185, pl. 12, fig. 14; - BARKER, 1960, pl. 50, figs. 7-10; - INGLE et al., 1980, p. 134, pl. 2, figs. 7, 8; - LOEBLICH and TAPPAN, 1987, p. 521, pl. 571, figs. 8-12; - JONES, 1994, p. 54, pl. 50, figs. 7-10; - SEN GUPTA, 1994, p. 36i, pl. 3, fig. 10; - ROBERSTON, 1998, p. 150, pl. 57, fig. 1; - ORTIZ and THOMAS, 2006, p. 118, pl. 6, figs. 8-11; - HOLBOURN et al., 2013, p. 260.

Distribution in core: 48 specimens in 20 samples; intermittent and low occurrence down core, highest abundance at depth 2.54 m; ~34% of its total occurrence is between depths 18.43 and 19.92 m.

Emended diagnosis: (Modified from Jones 1994 and Holbourn et al. 2013). Test is elongate, final chamber large, last three chambers making up the exterior by enclosing the preceding ones. Aperture loop-shaped, with folded tongue joined to the margin.

Description: Test elongate, triserial; sub-globular, ovate in outline, circular in cross-section, about one and a half times as long as wide, widest near the lower part of test. Average length of the test ranges between 0.70 - 0.92 mm, and width between 0.32 - 0.55 mm. Wall calcareous, fragile, finely perforate, very thin with smooth surface, translucent. Chambers distinct, inflated, rapidly enlarging and strongly overlapping; last 2-3 chambers may partially overlap the preceding ones, only 2-3 chambers visible. Sutures thin, slightly depressed, oblique, nearly parallel to the margins of the test; aperture loop-shaped, with a slight border and an internal toothplate joined to the margin of the opening.

Remarks: *G. pacifica* differs from *Globobulimina auriculata* (Bailey) in the arrangement of the chambers, and by the size of the final chamber that is much larger in *G. auriculata* and almost encompasses the whole test, while the proximal end is more pointed in *G. pacifica* relative to *G. auriculata.* The Bering Sea material is similar to specimens illustrated by Brady (1884: pl. 50, figs 7-10) from the Pacific and Atlantic Oceans, but differs from those recorded from SE Spain by Ortiz and Thomas (2006: pl. 6, figs. 8-11), with their sutures being more depressed and prominent. All specimens of *G. pacifica* studied from different horizons from core U1342 reveal no fundamental change in the key morphological traits, except slight variation noticed in their sizes; this may be related to maturity.

Distribution: *G. pacifica* has a geographical distribution that encompasses the Pacific (Ingle et al. 1980) and Indian Oceans (Sen Gupta 1994) and other regions (Cushman and Laiming 1931; Mazumder et al. 2003; Sen Gupta and Smith, 2010). It has a bathymetry from ~824 m at the 'Challenger' stations, off the Azores in the Atlantic

Ocean (Jones, 1994) to 2012 m in the Pacific (Ingle et al. 1980) and to 3300 m in the Arabian Sea (Mazumder et al. 2003). *G. pacifica* is a deep infaunal species characteristic of dysoxic settings (Jorissen et al. 1998; den Dulk et al. 2000). The stratigraphical range of *G. pacifica* is Miocene to Recent (Jones 1994).

Family UVIGERINIDAE Haekel, 1894

Subfamily UVIGERININAE Haekel, 1894

Genus *Uvigerina* d'Orbigny, 1826.

Type species *Uvigerina pygmaea* d'Orbigny

Uvigerina bifurcata d'Orbigny 1839

Plate 2.13, Figures 7-18; Plate 2.14, Figures 1-3

Uvigerina bifurcata d'Orbigny, 1839, p. 53, pl. 7, fig. 17

Uvigerina pygmae d'Orbigny BRADY 1884, 74, figs. 13 - 14

Uvigerina bifurcata d'Orbigny; - THALMANN 1932, p. 306, pl. 74, figs. 13–14; - Cushman 1947, p. 279, fig. 291; - BARKER, 1960, p.154, pl. 74, figs.13–14; - VAN DER ZWAAN et al. 1986, p. 226, pl. 16, figs. 4-6; pl. 17, figs. 1-4; - JONES, 1994, p. 86, pl. 74, figs. 13-14; - ABU-ZIED et al., 2008, p. 52, pl. 2, figs. 17-18.

Distribution in core: One of the dominant species, with 6103 specimens in 144 samples between depths of 0 and 29.59 m.

Emended diagnosis: (based on Van der Zwaan et al. 1986, Jones, 1994 and Abu-Zied et al. 2008). Non-spinose *Uvigerina* with slender, elongate test; relatively high lamellar costae, non-serrate; proloculus pointed; aperture often with a spiral tooth.

Description: Test loosely triserial, elongate, typically stout with dimensions between 0.30 to 1.05 mm for maximal length excluding apertural neck, and between 0.20 to 0.48 mm for maximum transverse diameter; average length / breadth ratio is 2 (0.63/0.32); wall calcareous, weakly perforate; initial part of the first chamber is pointed; chambers mostly inflated and robust, particularly the later chambers, number of chambers varies with maturity from 5 to 9. Costae is usually non-serrate with relatively high lamellar

forming a 'vault structure' on the test, number of heavy regular costae on the second to the last chamber varies from 4 and 9; costae sometimes end in spine-like projections at the base of the chamber, which might continue over the suture, the thickness of costae reduces on the last chambers towards the neck, proloculus pointed; aperture terminal with well-developed lip on a well-developed neck, having an inward projection of the inner portion of the neck wall into the aperture in the form of a spiral tooth, lip at the flattened side of the aperture. Arrangement of chambers tends to change from triserial to biserial in later stage of the test.

Remarks: A detailed morphological assessment was made of over 293 specimens of *U. bifurcata* between depths 0 and 0.51 m, from horizons determined to signal different levels of water column oxygenation (based on sedimentological and micropalaeontological characteristics in core U1342). Analyses reveal relatively longer specimens at intervals with higher oxygen levels (Fig. 2.5), but no significant change in other key morphological traits (test diameter, position of the neck, strength of costae, number of costae, chamber number). The number of chambers correlates with length and width (Appendix 3a; Fig. 2.6: $R^2 = 0.746$). The chambers are typically inflated, with the largest width above the middle of the test, often at the level of the second to last chamber. Proloculus shape and size varies in microspheric and megalospheric specimens.

U. bifurcata* is differentiated from other *Uvigerina* species by the differences in the development of spines and pustules (e.g. *U. senticosa*). *U. celtica* Schönfeld is differentiated from *U. bifurcata* by its numerous small spines between the costae and its less inflated chambers (Schönfeld 2006). The species correlates well with *U. bifurcata* d' Orbigny illustrated from Mediterranean Sea by Abu-Zied (2008: pl. 2, figs. 17-18) in having distinct longitudinal costae that are well spaced on the chambers. However, there are variations in the thickness of costae within the assemblage; ~ 70% of the specimens have relatively heavy regular costae through all the chambers, while the strength of costae reduces on the terminal chamber of others.
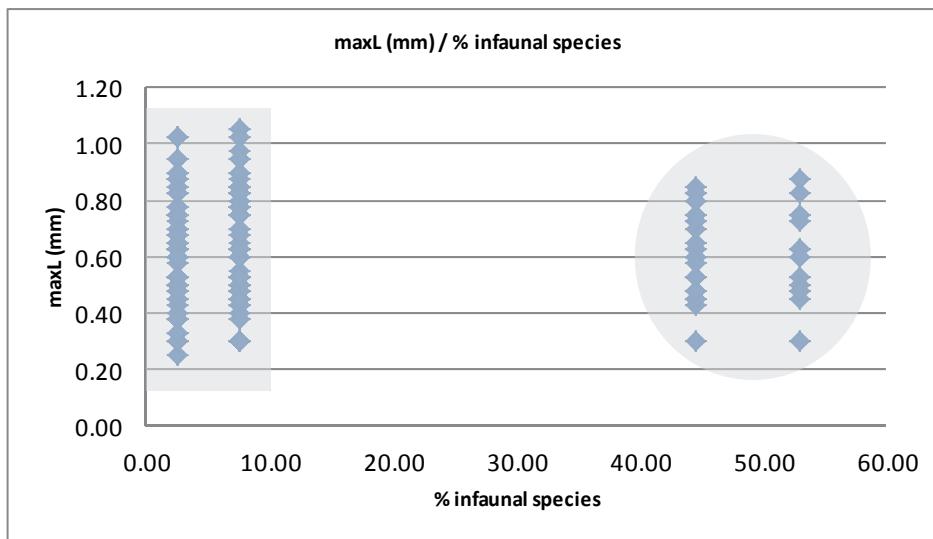
Figure 2.5 Length (in mm) of specimens of *U.bifurcata* from laminated (circular shape: average maxL value = 0.60 mm) and non-laminated intervals (rectangular shape: average maxL= 0.63 mm); *n* = 293, being a subset of the total specimens in the samples.
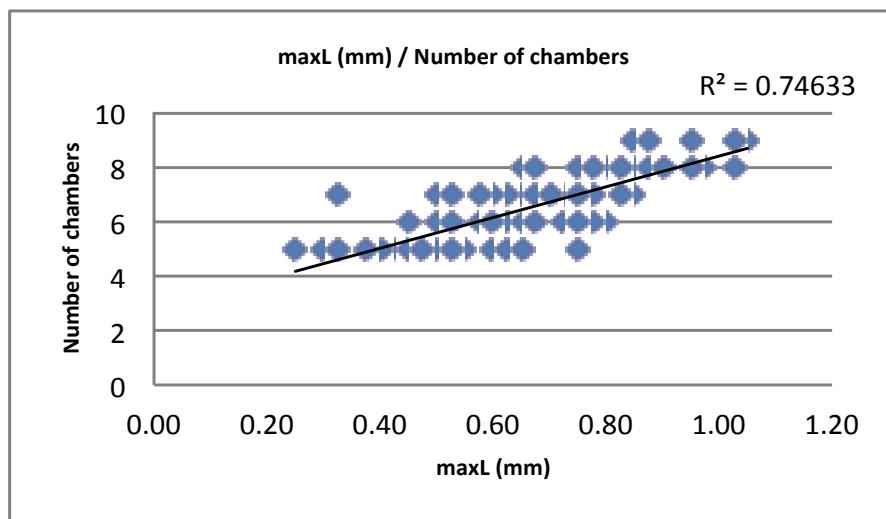
Figure 2.6 Number of chambers of *U. bifurcata* increases with increase in length; number of chambers correlate with length (R^2 = 0.746); *n* = 293, being a subset of the total specimens in the samples.

***Distribution*:** *U. bifurcata* is a cosmopolitan species that has a geographical distribution in the Pacific (Schönfeld and Spiegler 1994; Lutze 1986; Jones 1994); Southern Ocean (Anderson 1975) and Atlantic (Chiessi et al. 2008; Lutze 1986), and bordering seas (e.g.

Jones 1994; Burch and Burch 2007). This species has been recorded between 300 and 450 m water depth in the Atlantic Ocean (Lutze 1986). *U. bifurcata* is regarded as an infaunal species (Fontanier et al. 2002, 2006), and shallow infauna (see chapter 4); Kaiho (1994) classified *U. bifurcata* as suboxic (0.3-1.5 ml/l) based on empirical relations between the foraminiferal oxygen index and dissolved-oxygen levels in modern ocean. The stratigraphical range of *U. bifurcata* is from the Pleistocene to Recent (Jones 1994).

Uvigerina hispida Schwager, 1866
Plate 2.14, Figures 4-12

Uvigerina hispida Schwager, 1866 - BOERSMA, 1984, p. 76, pl. 1, figs. 1-4; - VAN MORKHOVEN et al., 1986, p. 62, pl. 20, figs. 1-4; - MILLER and KATZ, 1987, p. 140, pl. 2, fig. 2; - KATZ and MILLER, 1993, pl. 4, fig. 7; - ROBERTSON, 1998, p. 154, pl. 58, fig. 3; - KUHNT et al.; 2002, p. 158, pl. 14, figs. 5-7; - ORTIZ and THOMAS, 2006, p. 134, pl. 11, fig. 8: - KENDER et al., 2008b, pl. 18, figs. 6-8; - HOLBOURN et al., 2013, p. 592.

Distribution in core: 209 specimens from 34 samples; intermittent occurrence down the core, highest abundance at depths 7.85 and 15.79 m.

Emended diagnosis: (Revised based on Holbourn et al., 2013 and material from the Bering Sea) Elongate *Uvigerina* with chambers that are densely ornamented with well-defined hispids (spines) that range from blunt to sharp.

Description: Test is elongate, triserial, mostly sub-cylindrical in shape, fusiform, tapered at the periphery, circular cross-section; approximately two times as long as broad, average length ranges between 0.22 and 0.65 mm, width 0.18 and 0.25 mm; average length / width ratio is 2.3 (0.48 / 0.21), widest in the middle. Wall calcareous, perforate, ornamentation of densely spaced spines over each chamber, the spines varying from blunt to sharp in morphology; chambers mostly inflated and robust, particularly the later chambers, separated by distinctly depressed sutures; number of chambers varies on average with maturity from 5 to 7. Aperture is a terminal, round

opening at the end of a relatively short neck, bordered by a phialine lip, and an internal toothplate.

Remarks: Characters that are typical for, but not exclusive to, *U. hispida* include the stout test, compact, sub-cylindrical shape, fusiform, triserial coiling (that tends to become loose in the later chambers), and the number of chambers varying with maturity from 5 to 8 (in Bering Sea specimens, the maximum number of chambers is 7). The circular aperture is situated on a short neck and bordered by a phialine lip, and contains an internal toothplate which is another distinctive character of *U. hispida* (see also Boersma 1984; Van Morkhoven et al. 1986 and description of Holbourn et al. 2013).

Morphological assessment of specimens of *U. hispida* recovered from Bering Sea core U1342, which incorporates horizons determined to signal different levels of water column oxygenation (based on sedimentary characteristics and associated benthic foraminifera); show no significant change in number of chambers (Appendix 3c; Fig. 2.7), shape of chambers and position of the apertural neck. However, maximal length without apertural neck (maxL) and maximum transversal diameter (MTD) show a weak correlation with relative oxygen level. Relatively longer specimens characterise intervals interpreted to have higher oxygen (based on the low percentage of associated dysoxic species recorded at these intervals and on absence or reduced sedimentary lamination). Average measurement of *U. hispida* specimens recorded range from 0.22-0.45 mm (maxL), and 0.18-0.25 mm (MTD) in the laminated interval; while a range of 0.51-0.65 mm (maxL), and 0.24-0.35 mm (MTD) is obtained from intervals interpreted to have higher oxygen (Fig. 2.8). Out of 209 specimens recorded from 34 samples, only 4 specimens of *U. hispida* were recorded from the laminated intervals that signal dysoxic conditions. This is probably due to the low dissolved oxygen level; Kaiho (1991) interpreted *U. hispida* as a suboxic species (with oxygen levels between 0.3-1.5 ml/l) within the benthic foraminiferal oxygen index (BFOI). However, with only 4 specimens in laminated intervals, no meaningful statistical correlation can be ascertained.
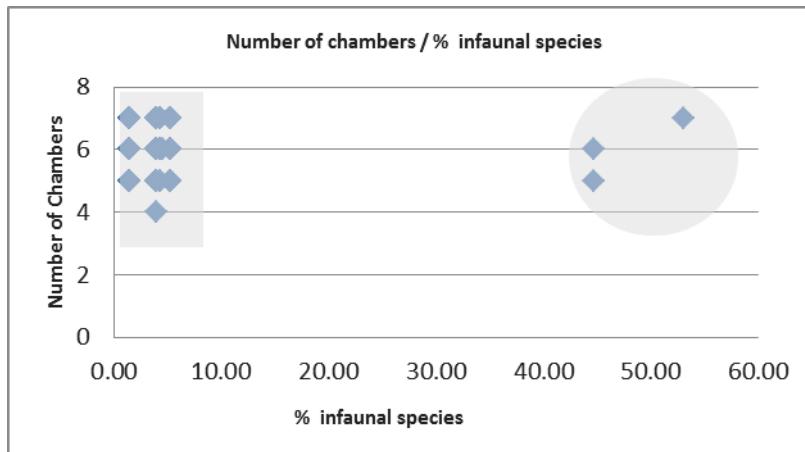
Figure 2.7 Number of chambers on *U. hispida* specimens from laminated intervals (in circle) and non-laminated intervals (in rectangle); *n* = 100, being a subset of the total specimens in the samples. Horizontal axis shows the percentage of associated infaunal species based on microhabitats in the Okhotsk Sea (Bubenschikova et al. 2010). Note that the number of chambers on some of the specimens overlap.
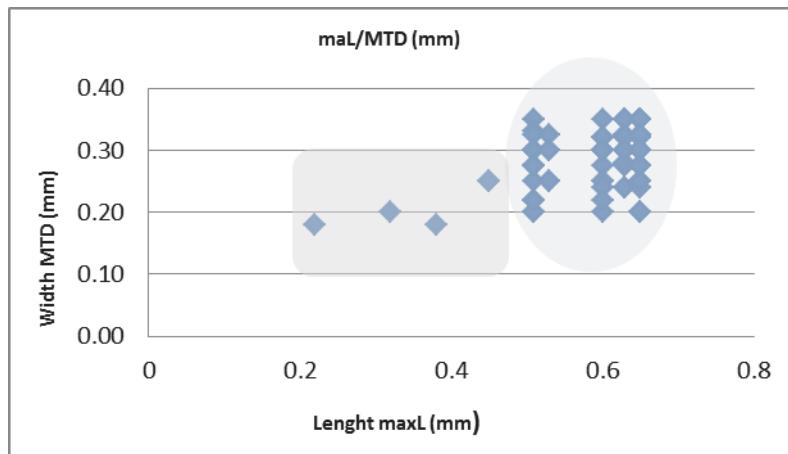
Figure 2.8 Dimensions of specimens of *U. hispida* from laminated intervals (in rectangle) and specimens from non-laminated intervals (in circle); *n* = 100, being a subset of the total specimens in the samples.

The Bering Sea material is very similar to specimens illustrated as *U. hispida* in the original description (reproduced in Ellis and Messina, 1940), having depressed and distinct sutures: the Bering Sea specimens are distinct from those illustrated from the Gulf of Mexico by Holbourn et al. (2013: p. 592), which have a basal spine on the first chamber, but no apertural neck. Circa 90% of the specimens in assemblages from the

Bering Sea are well preserved, but have no basal spine. Holbourn (2013) interpreted the absence of the latter to be due to preservation, but data from this study implies that the presence/absence of this character varies intraspecifically.

There is variation in the strength of spines on individual chambers (Plate 2.14, Figs. 4-14) and these ranges from dense and acicular (needle-shaped) to blunt and coarse ornamentations. *U. hispaniolana* Bermúdez is morphologically similar to *U. hispida* but differs by having its sutures not depressed as in *U. hispida*. The chambers in *U. senticosa* are more inflated than in *U. hispida,* while the spines are not as pronounced (sharp) and high as it is in *U. hispida*.

Distribution: *U. hispida* is a cosmopolitan species that has a geographical distribution in the Atlantic, Pacific and Indian Oceans, the Gulf of Mexico and the Mediterranean Sea (van Morkhoven et al. 1986; Kender et al. 2008; Holbourn et al. 2013) and other ocean regions (Holbourn et al. 2013). *U. hispida* has a bathymetric range that includes bathyal settings (Holbourn et al. 2013); its water depth ranges from 937 to 2539 m in the Gulf of Mexico, and 2489 to 3257 m in the Peru-Chile trench (LeRoy and Levinson 1974). *U. hispida* also occurs as a shallow infaunal species (Corliss and Emerson 1990; Fontanier et al. 2002; 2003; 2006)*,* and has been suggested as an indicator of sub-oxic conditions (0.3-1.5 ml/l) based on empirical relations between the BFOI and dissolved-oxygen levels in the modern ocean (Kaiho 1994). The stratigraphical range of *U. hispida* is from Early Miocene to Recent (Boersma 1984c; Holbourn et al. 2013).

Uvigerina senticosa Cushman 1927
Plate 2.14, Figures 13-17

Uvigerina senticosa CUSHMAN, 1927, p. 159, pl. 3, fig. 14; - CUSHMAN et al., 1930, p. 68, pl. 5, fig. 9; - CUSHMAN et al., 1949, p. 153, pl. 17, fig. 13; - BANDY, 1953, p. 177, pl. 25, fig. 12; - PIERCE, 1956, p. 1301, pl. 139, fig. 2; - SCHÖNFELD and SPIEGLER, 1993, pl. 1, figs 5 and 6.

Distribution in core: 50 specimens from 23 samples; intermittent occurrence between intervals 1.38 and 15.23 m, highest abundance at depths 8.60, 8.72 and 15.23 m.

Emended diagnosis*: Uvigerina* with chambers that are inflated and weakly hispid throughout; hispidity is low density and evenly distributed over the chambers, costae on the first chamber are divided into irregular hispids.

Description: Test robust, elongate, triserial, sub-cylindrical in shape, fusiform, circular cross-section, periphery lobate, approximately two and a half times as long as broad, average length ranges between 0.32 and 0.77 mm, width 0.20 and 0.30 mm; average length / width ratio is 1.9 (0.48 / 0.25), increasing in size, widest in the middle of the test. Wall calcareous, moderately hispid throughout, hispidity being evenly distributed over the chambers: hispids are not aligned and do not seem to follow any hidden costae (for example, as observed in more spinose forms of *U. peregrina*), except on the first chamber where the costae break into irregular hispids. Chambers are more inflated than most other *Uvigerina* species, and are evenly graduated in size from the almost rounded initial end to the broadest towards the apertural end. Sutures are straight, oblique and depressed; aperture terminal with well-developed lip, having an inward projection of (the inner portion of) the neck wall into the aperture in the form of a spiral tooth lip at the flattened side of the aperture.

Remarks: Morphological assessment of *U. senticosa* recovered from Bering Sea core U1342, which incorporates horizons determined to signal different levels of water column oxygenation (based on sedimentary characteristics and associated fauna), shows no significant change in key morphological features including maximal length without apertural neck (maxL) and maximum transversal diameter (MTD). Bering Sea material is morphologically similar to specimens recorded by Bandy (1953, pl. 25, figs. 12 a, b) from the California coast, and from the SE Pacific by Schönfeld and Spiegler (1993: pl.1, figs. 5, 6), by having the same number and arrangement of the chambers; *Uvigerina proboscidea* Schwager recorded from the California coast (Bandy 1953: pl. 25, figs. 11a, b), which has hispids, fairly elongated chambers and slightly straight sutural lines, is also morphologically similar to *U. senticosa,* but differs in having less inflated chambers. *Uvigerina auberiana* d'Orbigny is morphologically similar to *U. senticosa,* but is differentiated by its relatively broad cylindrical neck. Material from the Bering Sea shows intraspecific variation in the length of the apertural neck of specimens

in the assemblage; the average length of the neck ranges between 0.05 - 0.1 mm; about 60% of the specimens have longer necks.

Distribution: *U. senticosa* has a geographical distribution in the Pacific Ocean (Schönfeld and Spiegler 1993), the coasts of Australia and California (Bandy 1953; Lowry and Smith 2003), and the Gulf of Mexico (Sen Gupta et al. 2009). Its water depth ranges from 351 - 800 m in the SE Pacific Ocean (Schönfeld and Spiegler 1993), to 3488 m in the Pacific to the east of Australia (Lowry and Smith 2003), up to 3657 m in the NE Pacific (Bandy 1953) and 0-3850 m at the Gulf of Mexico (Sen Gupta et al. 2009). *U. senticosa* also occurs as a shallow infaunal species (Ovsepyan et al. 2013) and is considered by some an indicator of suboxic conditions (Kaiho 1994). The first record of *U. senticosa* is from the Recent of the eastern Pacific (Weldon 1970). It has since been recorded from the Miocene, Pliocene, and Pleistocene of California.

Uvigerina peregrina Cushman, 1923
Plate 2.15, Figures 1-16

Uvigerina peregrina Cushman, 1923, p. 166, pl. 42, figs. 7-10; - PHLEGER and PARKER, 1951, p. 18, pl. 8, figs. 22, 24-26; - PARKER, 1954, p. 521, pl. 8 fig. 5; - MILLER and LOHMANN 1982, pl. 1, figs. 11-12; - BOERSMA, 1984, p. 124, pl. 1, figs. 1-4; - LUTZE, 1986, p. 32, pl. 1, figs. 1-6; - TIMM, 1992, p.67, pl. 6, fig. 2; - VAN LEEUWEN 1986, p. 59, pl. 1, figs. 1-5. p. 67, pl. 6, fig. 2; - SCHÖNFELD, 2006, p. 1, fig. 21; - LÉVY et al. 1998 p. 610, pl. 1, fig. 10; - KOUWENHOVEN, 2000, p. 197, pl. 11, figs. 1-2; - SCHÖNFELD, 2006, p. 354, pl. 1, figs. 14-18.

Distribution in core: 502 specimens in 69 samples; consistent occurrences at depth intervals 0 to 3.24 m, 5.26 to 6.63 m; most abundant in the uppermost 3.24 m of Site U1342.

Emended diagnosis: (Modified from description reproduced in Ellis and Messina, 1940) Test elongate, chambers usually numerous (up to 11). Wall ornamented with longitudinal costate, which become divided into spinose or irregular short portions; the

wall between each costae is distinctly granular; aperture circular at the end of a distinct cylindrical neck, often spinose and with a phialine lip.

Description: Test elongate and stout, about 2 times as long as broad, widest in the middle, typically between 0.20 to 1.13 mm in maximum length (maxL) excluding neck; 0.15 to 0.45 mm maximum transverse diameter (MTD); average length / breadth ratio is 1.9 (0.62 / 0.32); later chambers inflated, more loosely triserial from side view, number of chambers varies with maturity from 4 to 11; sutures distinct and depressed. Longitudinal costae are distinct, and tend to become serrate and divide up into a series of plate-like spines or irregular short portions towards the younger chambers; wall calcareous, perforate, first and final chambers are mostly spinose, short series of pustules may be present between the costae, which may be coarse or fine. Aperture terminal, produced on a neck, which may be depressed at the base or not; aperture circular at the end of a distinct cylindrical / tubular and often spinose neck, aperture bordered with a lip having an internal projection like a toothplate at the flattened side of the aperture, with a phialine lip.

Remarks: *U. peregrina* was originally described by Cushman (1923) from a continental slope sample (~2100 m), off the northeastern United States. A detailed morphological assessment of 504 specimens of *U. peregrina* between depths 0 and 20.59 m, equating to ~597 ka, from core U1342, reveals no fundamental change in the key morphological traits of test diameter and length, or chamber number (Appendix 3b; Figs. 2.9 - 2.12). This is particularly important given that this interval is characterised by changes in seabed oxygen and nutrient levels (indicated from associated benthic faunas and occasional sediment laminations) that might have influenced subtle morphological changes in the test, as documented from other benthic foraminiferal assemblages (e.g. Kaiho 1994; Thomas and Gooday 1996; Kuhnt et al. 2013). In the assemblages, the length of the apertural neck varies randomly from 0.025 to 0.05 mm. The chambers are typically inflated, with the largest width often above the middle of the test. Costae vary from strong to weak on the chambers. The number of chambers correlates weakly with the length; length (maxL) and width (MTD) correlate such that greater width is associated with greater length while there is no significant correlation between number of chambers and width (Figs. 2.9 - 2.11). The final chambers are generally hispid in all

the assemblages, while the aperture is situated on an elongated neck, which may or may not be spinose.

The size of the test, shape of the chambers, length / width ratio, arrangement and morphology of costae are the main diagnostic features in differentiating this species from other *Uvigerina* species. *U. peregrina parva* Lutze is differentiated from *U. peregrina* by its smaller but uniform length, which ranges between 0.40 to 0.45 mm in adults (Schönfeld 2006), but resembles *Uvigerina peregrina* with its early and final chambers often being spinose. *U. dirupta* Todd has the same variation in test size and shape, but it is more slender with an average of 0.44 mm maximum transversal diameter (Van Leeuwen 1986). *U. pygmea* d' Orbigny (1826) has thin and low costae on the chambers, which may be partially serrate on the upper end of the lower chambers, and which are often smaller with few pustules between the costae. *U. peregrina* differs from *U. peregrina* var. *latalata* Stewart and Stewart in that the latter has fewer numbers of costae (usually 5 or 6) on fully grown chambers (Ellis and Messina 1940). The Bering Sea *U. peregrina* are similar to those from the Mediterranean Sea figured by Abu-Zied et al. (2008: pl. 2, figs. 19-20) and Schönfeld (2006: pl. 1, figs. 14-18), in having serrated costae, spines on the first chambers and prominently on the last chambers.

Distribution: *U. peregrina* has a geographical distribution from the Pacific (Joachim and Dorothee 1995; Keller 1980; Butt 1980), Atlantic (Lévy et al. 1998; Schönfeld 2006) and Indian Oceans (Kurbjeweit et al. 2000; Schumacher et al. 2007), the Mediterranean Sea (Fontainer et al. 2008) and other seas (e.g. Jorissen 1987). The characteristic water depth distribution of *U. peregrina* ranges from 900 to 3200 m (Haake 1980; Lutze 1980; Lutze and Coulbourn 1984). Its water depth range varies from 300 m in the Atlantic, having its shallowest reliable occurrences in the Gulf of Mexico (Pflum and Frerichs 1976), to 2496 m in the deep Guinea Basin (Timm 1992). A complete bathymetric succession of *Uvigerina* morphotypes from eastern North Atlantic has been described by Lutze (1986); *U. peregrina* is replaced progressively by another *Uvigerina* morphotype with spines between the costae and an entirely spinose last chamber (*U. hollicki* Thalmann) at 2000 m depth (Lutze 1986). Below 3000 m, *U. peregrina* is replaced by the spinose morphotype, *U.* hispida which became increasingly dominant (Van Leeuwen 1986).

The test morphology within the assemblage under review does not vary substantially, given that the water depth is relatively shallow (~800 m). *U. peregrina* has been described as a shallow infaunal species (Corliss and Emerson 1990; Fontanier et al. 2002, 2003a, 2006), and classified by Kaiho (1994) as a suboxic indicator. The stratigraphical range of *U. peregrina* is from Eocene to Recent (Jones 1994).
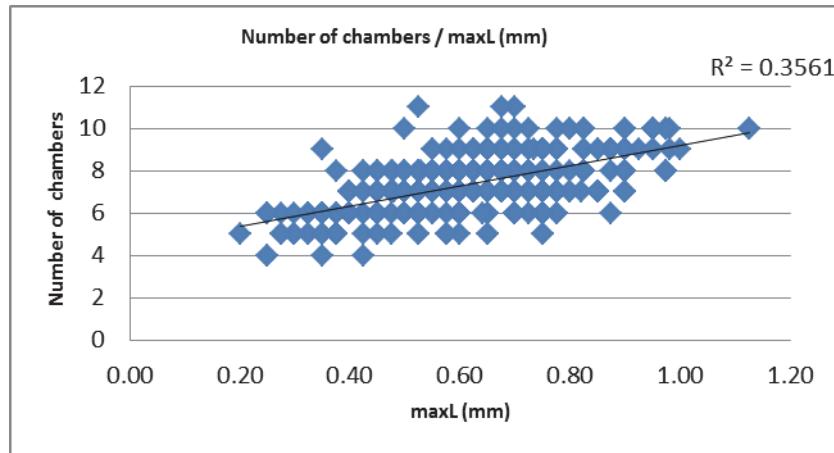
Figure 2.9 Number of chambers against length (maxL) for *U. peregrina*, across both laminated and non-laminated intervals, where *n* = 502.
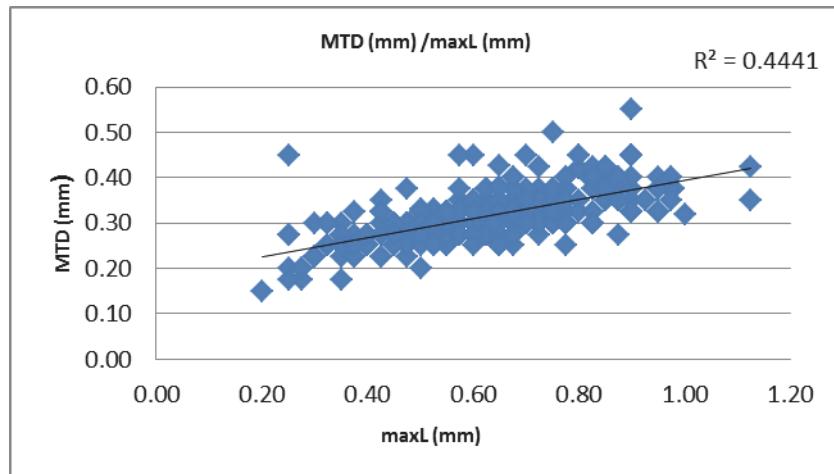
Figure 2.10 Length (maxL) against width (MTD) for *U. peregrina*; across both laminated and non-laminated intervals, where *n* = 502.
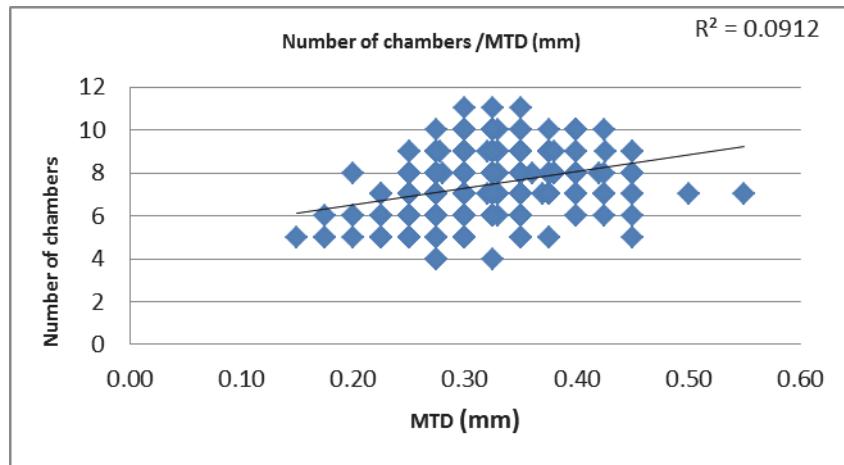
Figure 2.11 Number of chambers against width (MTD) for *U. peregrina*; across both laminated and non-laminated intervals, where *n* = 502.
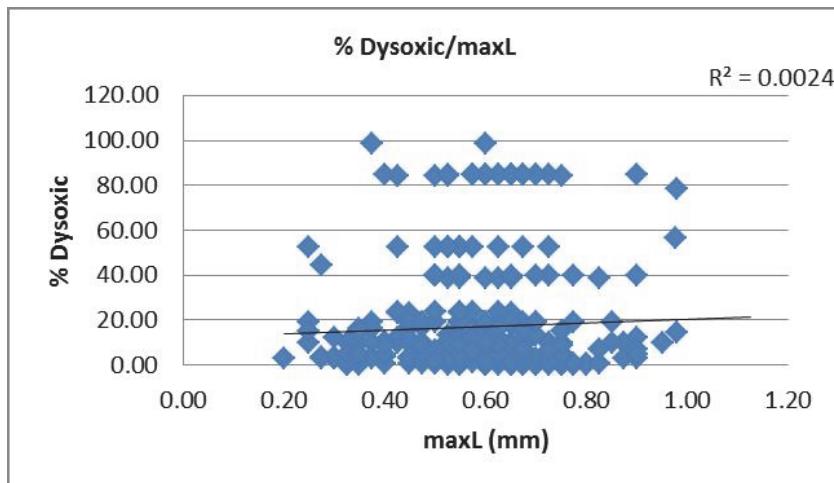
Figure 2.12 Length (maxL) against oxygen (percentage dysoxic) for *U. peregrina*; across both laminated and non-laminated intervals, where *n* = 502.

Uvigerina **sp.**

Plate 15, Figure 17; Plate 16, Figures 1-8

Distribution in core: 9 specimens from 7 samples; first occurrence at 0 m, intermittent occurrence down core to 20.06 m.

Description: Test small, robust, small terminal neck, broken surface carinate; average length of test 0.32 to 0.45 mm, and width 0.20 to 0.32 mm, rounded in cross-section; chamber outlines and sutures indistinct, 11 to 12 longitudinal coarse costae on the chambers, prominent costae stop abruptly before getting to the base of the apertural neck; wall coarsely calcareous, micro perforate; aperture a round opening at the end of a depressed neck bordered with a lip.

Remarks: *Uvigerina* sp. is superficially similar to juvenile *U. bifurcata* in shape, coaste and rounded aperture, but is differentiated by the wall structure which is coarsely calcareous, and its apertural opening without a spiral tooth.

Subfamily ANGULOGERININAE Galloway, 1933

Genus *Angulogerina* Cushman, 1927

Type species *Uvigerina angulosa* Williamson 1858; original designation by Williamson 1858, p. 67

Angulogerina angulosa (Williamson, 1858)

Plate 2.16, Figures 9-13

Uvigerina angulosa Williamson, 1858: p. 67, pl. 5, fig. 140; - CUSHMAN 1923, p. 170, pl. 41, figs. 17-20

Angulogerina angulosa (Williamson); - PARKER, 1958, p. 259, pl. 2, figs. 1, 2; - FEYLING-HANSSEN, 1980, p. 184, pl. 1, figs. 9, 10; - SEJRUP et al., 1981, p. 292, pl. 2, fig. 10; - LOEBLICH and TAPPAN, 1988, p. 151, pl. 574, figs. 5-9; - CIMERMAN and LANGER, 1991, p. 63, pl. 66, figs. 3, 4

Trifarina angulosa (Williamson); - SCHIEBEL, 1992, p. 56, pl. 3, fig. 1

Angulogerina angulosa (Williamson); - SGARRELLA and MONCHARMONT-ZEI, 1993, p. 215, pl. 16, fig. 8

Trifarina angulosa (Williamson); - MURRAY, 2003, p. 26, fig. 10, no. 5

Angulogerina angulosa (Williamson); - HROMIC and ZÚÑIGA, 2003, p. 69, fig 9, 1-3

Trifarina angulosa (Williamson); - RASMUSSEN, 2005, p. 89, pl. 12, fig. 1; - ABU-ZIED et al., 2008, p. 52, pl. 2, fig. 21; - MILKER et al., 2009, p. 218, pl. 3, fig. 2

Angulogerina angulosa (Williamson); - OBLAK, 2011, p. 52, pl. 2, fig. 5; - MILKER and SCHMIEDL, 2012, p. 91, pl. 21, figs. 2-4

Distribution in core: 363 specimens from 65 samples; species totally absent between depths 2.78 to 5.13 m and 10.51 to 12.24 m, intermittent occurrence down core, highest abundances are at depths 1.13 m, and 5.26 to 5.87 m.

Emended diagnosis: (Based on illustrations of Feyling-Hanssen 1980 and materials from the Bering Sea) Test is angled with three flat sides, triserial, triangular in cross-section; three angles of the test are carinate and are well developed, tending towards being uniserial in later arrangement; aperture terminal with a toothplate.

Description: Test elongate, angled with three flattened sides, triangular in shape and cross-section, triserial, slightly inflated, about two and a half times as long as broad, average length ranges between 0.22 and 0.85 mm, width 0.18 and 0.30 mm, average length / width ratio is 2.6 (0.57 / 0.22). Wall calcareous, finely perforate, surface ornamented with a few narrow high costae; chambers triserially arranged, later tending towards uniserial arrangement; sutures curved, oblique, and slightly depressed, the three angles of the test are carinate and well developed, longitudinal costae may not be continuous over some sutures in some specimens; aperture terminal with a toothplate, bordered by a narrow lip on a short neck.

Remarks: This taxon was originally assigned to *Uvigerina*, but placed within *Angulogerina* because of its triangular shape, cross-section and triserial arrangement of chambers, tending towards being uniserial at the later chambers (Loeblich and Tappan 1988). The material from the Bering Sea seems morphologically identical to *A. earlandi* Parr recorded from the SW Pacific Ocean by Kawagata (1999: figs. 5, 11a, b and 12a, b) in being elongate, having carinate angles, tapering at both ends and by having longitudinal costae that are not continuous over the sutures.

Morphological assessment of specimens of *A. angulosa* recovered from Bering Sea core U1342, which incorporates horizons determined to signal different levels of water column oxygenation and organic carbon flux (based on sedimentary characteristics and associated benthic foraminifera), show no significant change in

number of chambers, shape of chambers, strength of costae, and position of the neck. However, there is variation in the strength of costae on the chambers; circa 5% of the specimens have costae that are limited mostly to the early chambers.

Distribution: *A. angulosa* has a wide geographical distribution in the Pacific and Southern Oceans (Brady 1884; Dowsett and Ishman 1995; Bubenshchikova et al. 2010); Bering, Weddell and Mediterranean Seas (Anderson 1975; Mackensen et al. 1990; Gross 2001; Milker and Schmiedl 2012; Ovsepyan et al. 2013) and other regions (Bandy 1953; Culver and Buzas 1980; Asioli 1995; Wilson and Costelloe 2011). *A. angulosa* ranges from 10 to 250 m depth for the subtropical South American coast, off the California coast and in the Mediterranean Sea (Bandy 1953; Milker and Schmiedl 2012), down to deeper water depth from 839 to 1312 m in the Pacific Ocean and Bering Sea (Bubenshchikova et al. 2010; Ovsepyan et al. 2013). *A. angulosa* is also a shallow infaunal species (Bubenshchikova et al. 2010), and has previously been considered an indicator of sub-oxic conditions (Kaiho 1994). The stratigraphical range of *A. angulosa* is from Eocene to Recent (Loeblich and Tappan 1987).

Super family FURSENKOINACEA Loeblich and Tappan, 1961
Family FURSENKOINIDAE Loeblich and Tappan, 1961
Genus FURSENKOINA Loeblich and Tappan, 1961
Type species *Virgulina squamosa* d'Orbigny

Fursenkoina* aff. *texturata (Brady, 1884)
Plate 2.16, Figures14-18; Plate 2.17, Figures 1-3

Virgulina texturata Brady 1884, pl. 52, fig. 6
Virgulina subdepressa Brady, 1884, pl. 52, figs. 14-17; - BARKER, 1960, pl. 52, figs. 14-17
Fursenkoina texturata (Brady, 1884); - JONES, 1994, pl. 52, figs. 6, 14-17; HAYWARD, 2002, p. 290, pl. 3, figs. 4-5; - HAYWARD et al., 2004, p. 154, pl. 1, fig. 15; - HAYWARD and KAWAGATA, 2005, p. 173, pl. 1, figs. 5-9; - MOHAN et al., 2011, p. 54, pl. 4, figs. 19-20.
Virgulopsis sp. - KURIHARA and KENNETT, 1986, pl. 2, figs. 15-16

Distribution in core: 41 specimens from 4 samples; first occurrence at 0.10 m depth, other occurrences between 13.60 and 15.56 m; highest abundance at 14.28 m.

Description: Test narrow, elongate, round to ovate in cross-section, chambers high and narrow, weakly inflated and biserial, plane of biseriality twists about the test axis throughout; chamber number varies from 10 to 12, average length of test ranges between 0.55 and 0.85 mm, and width 0.18 and 0.37 mm; sutures oblique and depressed; wall calcareous, surface finely perforate and smooth; aperture oval to round, slightly elongate with apertural foramen in the form of a tongue.

Remarks: *Fursenkoina texturata* and *Virgulina subdepressa* are considered to be micro and macrospheric forms respectively (Jones 1994); *F. texturata* was listed in the Arabian Sea database under the older name *Virgulina texturata* Brady (see Heinz and Hemleben 2006). *F.* aff. *texturata* is morphologically similar to *F. texturata* (Brady 1884; Hayward and Kawagata 2005)*, the latter being biserial, with weakly inflated chambers having oblique sutures; and its plane of biseriality is twisted about the test axis *F.* aff. *texturata* can be differentiated from *F. texturata* by its apertural opening, which is more rounded (see Jones 1994; Pl. 52, figs. 6, 14-17). Whether this difference represents a subspecies, or is simply a function of regional variation, cannot as yet be defined. *F. fusiformis* (Williamson) also has its chambers more inflated than in *F.* aff. *texturata* (see Mohan et al. 2011; p. 53, pl. 4, figs. 17-18; 19-20).

Distribution: *F.* aff. *texturata* is only known from the Bering Sea. *F. texturata* has a geographical distribution in the SW Pacific Ocean (Hayward 2002; Hayward et al. 2004), the "Challenger station" in the South Pacific (see Brady 1884; Jones 1994) and the Arabian Sea (Heinz and Hemleben 2003; 2006). It has a water depth range from 200-4500 m in the South and Southwest Pacific Ocean (Jones 1994; Hayward 2002; Hayward et al. 2004), extending deeper than 4000 m in the NW Atlantic Ocean (Mohan et al. 2011). The stratigraphical range of *F. texturata* is from the Late Miocene to Holocene (Hayward 2002; Mohan et al. 2011).

Family BAGGINIDAE Cushman, 1927

Subfamily BAGGININAE Cushman, 1927

Genus *Valvulineria* Cushman, 1927

Type species *Valvulineria californica* Cushman, 1926

Valvulineria araucana (d' Orbigny, 1839)

Plate 2.17, Figures 4-12

Rosalina araucana d'Orbigny, 1839, 5, pl. 5, p. 44, pl. 6, figs. 16-18

Valvulineria araucana CUSHMAN, 1927, 1, p. 160, pl. 4, fig. 7,8; - KLEINPELL, 1938, p. 307; - CUSHMAN et al., 1947, p. 20, pl. 3, fig. 1; - CROUCH 1952, p. 834, pl. 4, figs. 7, 8.

Valvulineria araucana d' Orbigny; - WHITE, 1956, pl. 28, figs. 3a-b

Distribution in core: 833 specimens from 97 samples; consistent occurrence down core, high abundance at depths 10.78, 15.19, 19.07 and 19.44 m.

Emended diagnosis: (Revised based on Cushman 1927) Chambers densely perforate except at the umbilical region, sutures depressed and curved backward on the spiral side; aperture is an extraumbilical arch, with a large flap covering the umbilicus.

Description: Test rounded to elongate in outline, smooth, thin, hyaline, coarsely and densely perforate except at the umbilical region where pores are scarce; wall calcareous, chambers inflated, six chambers in the final whorl, gradually increasing in size as added; test average dimension is 0.38 mm in the longer diameter, 0.30 mm in the shorter diameter, two and a half whorls visible, spiral side slightly convex and flattened, trochospirally coiled, umbilical region involute and depressed with rounded periphery. Sutures are curved backward on the spiral side, depressed on both sides, tends towards being radial. Aperture an extraumbilical arch at the base of the final chamber provided with a large flap covering almost the entire umbilicus.

Remarks: *Valvulineria araucana* is similar in morphology to *V. complanata* (d' Orbigny) recorded by Milker and Schmiedl (2012) from the Holocene of the western Mediterranean Sea, except that *V. araucana* is slightly more elongate in outline with 6

to 8 chambers, while *V. complanata* is more rounded with 5 to 6 chambers (see Milker and Schmiedl 2012; figs. 16 and 17). Scripps (1940) considered that the specimens referred to as *V. inflata* (d'Orbigny) by Cushman (1927) are a variety of *V. araucana* (d'Orbigny) because of various morphological similarities, like the same number of chambers and the test outline which is elongate. Circa 80% of *V. araucana* from the Bering Sea have their test outline more elongated, while others tend towards being rounded in test outline; the extent of the apertural flap covering the umbilicus varies slightly, with the majority covering the whole apertural openings, while a few do not completely cover the openings (see Pl. 17, Figs. 7, 9, 11 and 12).

Distribution: *V. araucana* has a geographical distribution in the Atlantic and Pacific Oceans (Mackensen and Douglas 1989), Mediterranean Sea and the Gulf of Mexico (Molina-Cruz and Ayala-Lopez 1988; Gross 2001; Dorst and Schoenfeld 2013). *V. araucana* has a depth range from 500 m in the Pacific Ocean (Mackensen and Douglas 1989), 550 m in the Atlantic Ocean, extending to a deeper water depth range between 4,001 and 6,270 m in the West coast area offshore from Central America (Bandy and Arnal 1957; Kern and Wincander 1974; Culver and Buzas, 1980). *V. araucana* has been proposed to be an indicator of sub-oxic conditions (0.3 - 1.5 ml/l) based on empirical relations between the BFOI and dissolved oxygen levels in the modern ocean (Kaiho 1994). It has a stratigraphical range from the Miocene of Southern California USA (Kern and Wincander 1974).

Family EPONIDIDAE Hofker, 1951
Subfamily EPONIDINAE Hofker, 1951
Genus *Alabaminella* Saidova, 1975
Type species *Eponides weddellensis* Earland, 1936

Alabaminella weddellensis (Earland, 1936)
Plate 2.17, Figures 13-17

Eponides weddellensis Earland 1936, pl. 2, figs. 22 - 23; - SCOTT and LEGER, 1990, p. 206, pl. 1, figs. 12, 13.

Eponides pusillus Parr, 1950, pl. 14, figs. 16a-c

Alabaminella weddellensis (Earland) - EARLAND 1936, pl. 14, figs., 16 a - c; - RESIG and CHEONG, 1997, p. 436, pl. 2, figs. 1-6; - BARBIERI et al., 1999, p. 52, pl. 3, figs. 3-7; - AUSTIN and EVANS, 2000, p. 684, pl. 1, figs. p, q; - OHKUSHI, et al., 2000, p. 141, pl. 3, figs. 3a-c; - HAYWARD et al., 2002, pl. 1, figs. 25 - 27; - HAYWARD et al., 2007, p. 156, pl. 1, fig. 15.

Distribution in core: 3425 specimens from 63 samples; first occurrence at 2.78 m, consistent occurrences down core afterwards, high abundance at depth 16.10 m and also intervals 16.55 to 16.90 m and 19.22 to 19.92 m.

Emended diagnosis: (Revised from the illustrations and descriptions of Resig and Cheong 1997; Bergamaschi 2012 and materials from the Bering Sea: Test typically small in size, biconvex, umbilical side slightly depressed; perforate except at the rounded periphery, aperture a minute, slit-like extraumbilical and interiomarginal opening.

Description: Test is small, radial, average dimensions range from 0.075 mm to 0.175 mm in diameter. Wall calcareous, chambers are perforate except at the umbilicus, eight to ten chambers in the final whorl, biconvex, umbilical side slightly depressed, spiral side more convex, with broad low chambers, mostly five to six radial whorls, periphery rounded; sutures oblique, slightly depressed. Apertural face is prolonged on the test margin; aperture a slit-like extraumbilical and interiomarginal opening, offset from the centre toward the periphery, surrounded by a denticulated lip.

Remarks: *A. weddellensis* is differentiated from *Eponides weddellensis* Earland, which is morphologically similar but has a keeled periphery, smooth to slightly pustulose wall, and a broad aperture bordered by a narrow lip. *A. weddellensis* specimens described from the Bering Sea are more perforate than specimens described as *A. weddellensis* by Barbieri et al. (1999; pl. 3, fig. 4) from the Upper Pleistocene of the Ross Sea in Antarctica. *A. weddellensis* from the Pacific and Atlantic Oceans (Resig and Cheong 1997; Austin and Evans 2000; Gooday and Hughes 2002) are morphologically similar to the Bering Sea specimens in having perforate chambers, eight to ten chambers in the

final whorl, five to six radial whorls, a rounded periphery, and slightly oblique and depressed sutures.

A. weddellensis has been described as a phytodetritivore, which is an opportunistic species abundant when phytodetritus deposition increases, from for instance seasonal phytoplankton blooms in the surface water (Gooday 1993). The abundance of this species has been linked to pronounced seasonality of primary production in the Bering Sea (Okazaki et al. 2005). Despite being about 10% of the total assemblage recovered from the core, amounting to the second highest abundance in core U1342; no significant trends in intraspecific variation have been noticed in the assemblage down core.

Distribution: *A. weddellensis* has a geographical distribution in the Pacific and Atlantic Oceans (Resig and Cheong 1997; Austin and Evans 2000; Ohkushi and Natori 2001; Gooday and Hughes 2002; Khusid et al. 2005; Sun at al. 2006; Bubenshchikova et al. 2010), Antarctica (Barbieri et al. 1999; Igarashi et al. 2001; Hayward et al. 2007), Bering Sea (Ovsepyan et al. 2013), and other seas (Schmiedl et al. 1997; Cornelius and Gooday 2004; Murray and Pudsey 2004; Okazaki et al. 2005). *A. weddellensis* has a water depth range from 500 to 3354 m in different oceans and seas around the world (Ohkushi and Natori 2001; Gooday and Hughes 2002; Bubenshchikova et al. 2010; Ovsepyan et al. 2013). *A. weddellensis* is a shallow infaunal species (Bubenshchikova et al. 2010) and has been proposed to be an indicator of sub-oxic conditions (0.3-1.5 ml/l) based on empirical relations between the BFOI and dissolved-oxygen levels in modern oceans (Kaiho 1994; Hayward et al. 2007). The stratigraphical age of *A. weddellensis* is from the Pleistocene to Holocene (Resig and Cheong 1997; Bergamaschi 2012)

Family PARRELLOIDIDAE Hofker, 1956
Genus *Cibicidoides* Thalmann, 1939
Type species *Truncatulina mundula* Brady

***Cibicidoides* sp.**
Plate 2.18, Figures 1-5

Distribution in core: 35 specimens from 8 samples; first and lone occurrence at 6.37 m; lone occurrence at 8.86 m, other occurrences between 16.48 and 18. 80 m.

Description: Low trochospiral test, sub-rounded in outline, bi-umbonate, nearly biconvex in cross-section with an involute, slightly more convex umbilical side and an evolute spiral side; test average diameter is 0.45 mm, thickness is 0.15 mm; wall calcareous, coarsely perforate, periphery is imperforate; nine to twelve chambers in the last whorl, slightly inflated, increasing gradually in size, all chambers are visible on the spiral side, more perforate on the spiral side, separated by slightly curved sutures on the umbilical side, sparsely perforate on the umbilical side; sutures oblique and flush with the surface on the spiral side, aperture a narrow interiomarginal arch, bordered by a thin lip that extends onto the spiral suture.

Remark: *Cibicidoides* sp. recorded from Core U1342 is morphologically similar to *Cibicidoides mundulus* (Brady, Parker and Jones), but with a more pronounced convex umbo at the two sides, a fewer number of chambers (up to 9 in the final whorl). *C. mundulus* is a relatively common species in Neogene deep-sea sedimentary deposits; it was recorded from the Indian Ocean as *C. kullenbergi* (Parker) by Boltovskoy (1978: pl. 3, figs. 9-12). *Cibicidoides* sp. and *C. kullenbergi* (Parker) are characterised by considerable size variation, but no other essential morphological difference; *C. kullenburgi* is considered to be a junior synonym of *C. mundulus* (Van Morkhoven et al. 1986). Aside from the more pronounced convex umbo at the two sides, *Cibicidoides* sp. described from Core 1342, Bering Sea are morphologically similar to *Cibicidoides mundulus* from the Pacific and Indian Oceans, and the Red Sea (Hermelin 1989: pl. 17, figs. 9-11; Sen Gupta 1994: pl. 5, fig. 7).

Distribution: Most *Cibicidoides* species are cosmopolitan (Holbourn et al. 2013) with a geographical distribution in the Pacific, Atlantic and Indian Oceans (Brady 1884; Burke 1981; Resig 1981; Thomas 1985; Kurihara and Kennett 1986; Brady et al. 1888; Phleger et al. 1953; Boltovskoy 1978), Bering Sea (Ovsepyan et al. 2013), and offshore Angola (Kender et al. 2008b). The bathymetric range of *C. mundulus* is from bathyal to abyssal, from 751 to 2000 m (Lowell et al. 2007; Kender et al. 2008b; Ovsepyan et al. 2013). *C. mundulus* is an epifaunal species (Bubenshchikova et al. 2010), described by

Kaiho (1994) as sub-oxic B (1.5-6.0 ml/l) based on empirical relations between the foraminiferal oxygen index and dissolved-oxygen levels in the modern ocean. The stratigraphic range of *C. mundulus* is from late Oligocene to Holocene (Thomas 1985; Van Morkhoven et al. 1986; Kender et al. 2008b; Holbourn et al. 2013).

Superfamily PSEUDOPARRELLIDAE Voloshinova, 1952

Family PSEUDOPARRELLINAE Voloshinova, 1952

Genus *Epistominella* Husezima and Maruhasi, 1944

Type species *Epistominella pulchella* Husezima and Maruhasi, 1944

Epistominella exigua (Brady, 1884)

Plate 18, Figures 6-13

Pulvinulina exigua BRADY, 1884, p. 696, pl. 103, figs. 13, 14; - CUSHMAN, 1921, p. 340, pl. 68, figs. 3a-c.

Pseudoparrella exigua (Brady); - PHLEGER and PARKER, 1951, p. 28, pl. 15, figs. 6a-b, 7a-b; - LOEBLICH and TAPPAN, 1994, p. 146, pl. 307, figs. 1-7.

Pulvinulinella exigua (Brady); - WIESNER, 1931, p. 121; - PARR, 1950, p. 361; - HOFKER, 1951, p. 322, text figs. 219-221;

Epistominella exigua (Brady); - PHLEGER, et al., 1953, p. 43, pl. 9, figs, 35, 36; - BARKER, 1960, p. 212, pl. 103, figs. 13-14; - BOLTOVSKOY, 1978, p. 156, pl. 3, figs. 37, 38; - CORLISS, 1979, p. 13, pl. 2, figs. 7-8; - HERMELIN and SCOTT, 1985, p. 208, pl. 4, fig. 1; - BELANGER and BERGGREN, 1986, p. 337, pl. 6a-c; - MILLER and KATZ, 1987, p. 132, pl. 5, figs. 6a-b;- HERMELIN, 1989, p. 67, 68

Alabaminoides exiguus (Brady); - JONES, 1994, p. 103, pl. 103, figs. 13-14

Epistominella exigua (Brady); - THOMAS, 1990, p. 590; - KAIHO, 1992, p. 310, pl. 8, figs. 6a-c; - NOMURA, 1995, p. 276, pl. 3, fig. 3; - KATZ et al., 2003, p. 35, pl. 2, fig. 3; - HOLBOURN et al., 2013, p. 240.

Distribution in core: 57 specimens from 8 samples; highest occurrence at 0.63 and greatest abundance at depth 14.41 m, few intermittent occurrences at 15.23, 16.55 and 16.65 m.

***Emended diagnosis*:** (Based on material from this study) Test is small, slightly biconvex; sutures straight and flush with the surface. Aperture is an extraumbilical slit, bordered by serrate lip.

***Description*:** Test generally small, trochospiral, slightly lenticulate, slightly biconvex in cross-section; average dimension of 0.20 mm at the maximum diameter, 0.15 mm at the short diameter, thickness of 0.08 mm; wall calcareous, chambers are finely perforate and may be smooth, about 6 to $6^1/_2$ slightly inflated chambers present in the last whorl, increasing gradually in size, separated by flush, straight and radial sutures. All chambers are visible on spiral side, only those of the last whorl on the spiral side are evolute; aperture an extraumbilical slit, extending up the face of the final chamber on the umbilical side, bordered by serrate lip.

***Remarks*:** *E. exigua* differs from *E. vitrea* Parker in having about 5 to $5^1/_2$ instead of 6 to $6^1/_2$ chambers in the last whorl and a more angled test periphery (Hermelin 1989; Sen Gupta et al. 2009: pl. 60, p. A-62). *E. exigua* described from the Bering Sea is similar to the specimens illustrated by Gupta (1994: pl. 4, figs. 18, 19) from the Indian Ocean and the Red Sea, and specimens illustrated by Sen Gupta et al., (2009: pl. 59, p. A-61) from the northern Gulf of Mexico. Specimens studied here show intraspecific variation in the density of pores on their chambers; about 70% of the specimens in the assemblage have relatively high pore density, but down core this pore-density variation appears to be random.

***Distribution*:** *Epistominella exigua* is cosmopolitan, and has a geographical distribution in the Atlantic, Pacific and Indian Oceans (Brady 1884; Phleger et al. 1953; Smith 1964a; Boltovskoy 1978a; Corliss 1979; Schnitker 1980; Burke 1981; Mead 1985; Miller and Katz 1987; Hermelin 1989), Antarctic (Thomas 1990; Rasmussen et al. 2002), Caribbean Sea (Wilson and Costelloe 2011), and other oceans (Belanger and Berggren 1986, Miller and Kartz 1987; Hermelin 1989; Kaiho 1992; Lecroq et al. 2009). Murray (1991) noted that *E. exigua* has not been reported from the Mediterranean. *E. exigua* has a water depth range extending from 2500 m in the southeast Indian Ocean (Corliss 1979) to 4755 m at 'Challenger' station in Southern

Ocean (Jones 1994), down to the deep abyssal planes at >3.5 km in the north Atlantic (Miller and Katz 1987).

E. exigua has been described as an opportunistic, phytodetritus-exploiting species indicating a seasonally fluctuating input of organic matter to the sea floor (Thomas 1990; Thomas and Gooday 1996; Smart et al. 1994). It has been considered as an indicator species for Northeast Atlantic Deep Water (Weston and Murray 1985). The stratigraphical range of *E. exigua* is from the Middle Eocene to Recent, though its occurrence is rare from the middle Eocene and Late Eocene (Thomas 1990).

Epistominella pulchella Husezima and Maruhasi, 1944
Plate 2.18, Figures 14-16; Plate 2.19, Figures 1-3

Epistominella pulchella Husezima and Maruhasi 1944, p. 398, pl. 34, figs. 10a-c; - VILKS, 1989, p. 540, pl. 21-IV, figs. 13-15; - KATO, 1992, pl. 3, figs. 2a-c; - SETOYAMA and KAMINSKI in press, figs. 5, 8a-c

Distribution in core: 80 specimens from 16 samples; intermittent occurrences in the first 8.10 m; species absent down core thereafter.

Emended diagnosis: Test trochospiral, planoconvex to unequally biconvex, with evolute spiral side and involute and convex umbilical side; periphery carinate. Aperture an interiomarginal opening, bordered with a lip.

Description: Test medium in size, average diameter is 0.45 mm, thickness is 0.35 mm; weakly lenticular on the spiral side, trochospiral, two and a half to three whorls, unequally biconvex to planoconvex in cross-section with an involute and convex umbilical side; evolute spiral side is flat to low convex with an acute carinate periphery; wall calcareous, surface smooth, six to seven chambers visible on the umbilical side; sutures are slightly depressed, and oblique, maybe straight or gently curved, nearly radial; aperture an interiomarginal opening, extending to the apertural face of the final chamber on the umbilical side, bordered with a lip.

Remarks: *E. pulchella* is differentiated from *E. exigua* (Brady) in size and cross-section of the test, *E. pulchella* being bigger and planoconvex in cross-section. According to Ujiié et al. (1983), *E. pulchella* is a junior synonym of *E. pacifica* (Cushman). The material from the Bering Sea is morphologically similar to *E. pacifica* recorded by Figueroa et al. (2005) from the central south of Chile (adjacent to the Pacific Ocean), but *E. pacifica* is more convex to conical on the umbilical side (see also Bergen and O'Neil 1979; Bernhard et al., 2001: figs. 4 A a-c; Figueroa et al. 2005).

Distribution: *E. pulchella* has a geographical distribution in the Pacific, Arctic and Atlantic Oceans (Echols 2005), the Mediterranean, Japan and Bering Seas (Kato 1992; Setoyama and Kaminski, in press); its water depth ranges from 100 m in the Japan sea (Kato 1992; Compton et al. 2002), to 209 m in the north Atlantic Ocean (Echols, 2005) and 2140 m depth in the Bering Sea (Setoyama and Kaminski, in press). *E. pulchella* occurs as an infaunal species and has been suggested to be an indicator of sub-oxic conditions (Kaiho 1994, Bubenshchikova 2010). The stratigraphical range of *E. pulchella* is from the Lower Miocene to Holocene (Loeblich and Tappan 1988).

Superfamily PLANORBULINACEA
Family PLANULINIDAE Bermúdez, 1952
Genus *Planulina* d'Orbigny, 1826
Type species *Planulina ariminensis* d'Orbigny, 1826

Planulina ariminensis d'Orbigny, 1826
Plate 2.19, Figures 4-6

Planulina ariminensis d'Orbigny, 1826, p. 280, pl. 14, figs. 1-3
Anomalina ariminensis (d'Orbigny) - BRADY, 1884, p. 674, pl. 93, figs. 10, 11
Planulina ariminensis d'Orbigny - CUSHMAN, 1931, p. 110; - PHLEGER and PARKER, 1951, p. 32, pl. 18, figs. 4a, b; - PARKER, 1954, p. 540, pl. 11, figs. 27, 30; - BARKER, 1960, p. 192, pl. 93, figs. 10, 11; - LEROY and LEVINSON, 1974, p. 20, pl. 6, figs. 11-13; - POAG, 1981, p. 75, pl. 43, fig. 3; pl. 44, figs. 3a, b; - VAN MORKHOVEN et al., 1986, p. 38, 40, pl. 10, figs. 1-4; - DENNE, 1990, pl. 10, figs. 7a, b.; - JONES, 1994, p. 98, pl. 93, figs. 10-11; - ABU-ZIED et al. 2008, pl. 2, figs. 31-32;

- SEN GUPTA et al., 2009, p. 380, pl. 127, figs. 1-2; - HOLBOURN et al., 2013, p. 402.

Distribution in core: 26 specimens from 6 samples; isolated occurrences at depths 0.10 m, 2.64 m and between 15.69 to 15.79 m; highest abundance at 15.69 m.

Emended Diagnosis: (From Abu-Zied et al. 2008; Holbourn et al. 2013, illustrations of Van Morkhoven et al. 1986) Test planispiral, both sides flattened, evolute on the spiral side, partially evolute umbilical side, densely perforate; periphery truncate, aperture an equatorial slit with a narrow lip.

Description: Test planispiral, relatively large, sub-circular in outline, average dimension of 0.88 mm at maximum diameter, thickness of 0.15 mm; evolute on the spiral side and partially evolute umbilical side, periphery truncate, sides of the test flattened and almost parallel; acute and keeled periphery. Wall calcareous, distinctly perforate on the two sides; generally more coarsely perforate on the spiral side, ten to twelve narrow and curved chambers in the final whorl, flaring, increasing rapidly in size, overlapping, separated by strongly curved and slightly depressed sutures; aperture is an equatorial slit with a narrow lip, extending below the umbilical folium.

Remarks: *P. ariminensis* is differentiated from *P. weullerstorfi* (Schwager) by having both sides of the test flattened, almost parallel and evolute on both sides, the chambers being more flared, while *P. weullerstorfi* (Schwager) has a planoconvex shape and it is finely perforate on the umbilical side, coarsely perforate on the spiral side with more elongate, thick curved sutures, and a more compressed test. *P. ariminensis* is similar to *P. mexicana* but the latter is more finely perforate on both sides. Bering Sea specimens are similar to illustrated specimens from Mexico (Holbourn et al. 2013: p. 402, figs. 1-2), and also with the specimens illustrated from the Mediterranean Sea by Abu-Zied et al. (2008: pl. 2, figs. 31-32) being perforate on the two sides, and having the same number of chambers and same form of coiling.

Distribution: *P. ariminensis* is a cosmopolitan species which has a geographical distribution in the Atlantic Ocean (Austin and Evans 2000; Gooday and Hughes 2002;

Sun at al. 2006), Gulf of Mexico (LeRoy and Levinson 1974; van Morkhoven et al. 1986; Sen Gupta et al. 2009), Bering Sea (Ovsepyan et al. 2013) and other seas (Sun at al. 2006; Wilson and Costelloe 2011). *P. ariminensis* ranges from 1061 and 2918 m in the Gulf of Mexico, the Caribbean Sea and the Atlantic Ocean (LeRoy and Levinson 1974; Gooday and Hughes 2002; Sun at al. 2006; Wilson and Costelloe 2011). The stratigraphical range of *P. ariminensis* is Late Miocene to Recent (Holbourn et al. 2013).

Planulina wüllerstorfi (Schwager, 1866)

Plate 2.19, Figures 7-18

Anomalina wüllerstorfi Schwager, 1866, p. 258, pl. 7, figs. 105, 107

Planulina wuellerstorfi (Schwager) - CUSHMAN, 1929, p. 104, pl. 15, figs. 1, 2; - BERMÚDEZ 1949, p. 293, pl. 23, figs 37 - 39; - PHLEGER et al., 1953, p. 26, pl. 11, figs 1-2; - HOLBOURN et al., 2013, p. 416.

Cibicides wuellerstorfi (Schwager); - PFLUM and FRERICHS, 1976, p. 116, pl. 4, figs 2-4; - CORLISS, 1979, p. 13, pl. 2, figs. 13-16.

Planulina wuellerstorfi (Schwager); - PHLEGER et al., 1953, p. 49, pl. 11, figs. 1, 2; - BARKER, 1960, pl. 93, figs. 9a-c; - LOHMANN 1978, p. 26, pl. 2, figs. 1-4; - CORLISS, 1979, p.7, pl. 2, figs. 13-16; - VAN MORKHOVEN et al., 1986, p. 48, pl. 14; BELANGER and BERGGREN, 1986, p. 337, pl. 3, figs. 9a-11c; - MILLER and KATZ, 1987. p. 136, pl. 6, figs 2; - SCOTT and VILKS, 1991, p. 31, pl. 2, figs. 13, 14; pl.4, figs.14, 15; - ROBERTSON, 1998, p. 216, pl. 86, fig. 2; - OHKUSHI et al., 2000, p. 142, pl. 4, figs. 1a-c; - HOLBOURN et al., 2013, p. 416.

Distribution in core: 6 specimens from 5 samples; few and random occurrence at the top part of the core between intervals 0.74 and 2.24 m, isolated occurrence at depth 12.47 m, species absent thereafter.

Emended Diagnosis: (Revised based on illustrations and descriptions of Belanger and Berggren 1986; Scott and Vilks, 1991 and Bering Sea materials) Test is discoidal, trochospiral, flattened evolute spiral side; a convex, partially evolute umbilical side, aperture is an equatorial slit with a narrow lip extending beneath the umbilical point.

Description: Test calcareous, discoidal, planoconvex in cross-section, with a flattened evolute spiral side, a slightly convex, partially evolute umbilical side and a truncate, keeled periphery; average dimension is 0.73 mm in the longest diameter, thickness is 0.34 mm. Chamber walls are coarsely perforate on the spiral side, finely perforate on the umbilical side; low trochospiral chamber arrangement, nine to ten narrow chambers in the final whorl, curved, slightly inflated chambers, increasing rapidly in size, separated by thickened and strongly curved sutures which, on the spiral side, are slightly depressed, while sutures are slightly raised on the umbilical side; primary aperture is an equatorial slit with a narrow lip extending beneath the umbilical point.

Remark: *P. wuellerstorfi* is differentiated from *P. ariminensis* which is parallel at both sides, and more flared in coiling. Setoyama and Kaminski (in press) referred to specimens from the Bering Sea as *Fontobia wuellerstorfi* (Schwager), following Loeblich and Tappan (1987). We assign this species to *Planulina* because the test is discoidal, low trochospiral, and having an evolute umbilical side. *Fonthobia* usually have a compressed test, and an involute coiling on the umbilical side which is convex; a more recent description of *P. wuellerstorfi* (Holbourn et al. 2013), tallies morphologically with our specimens. Bandy (1967) observed that specimens of *P. wuellerstorfi* from depths over 1000 m from north Atlantic deep waters tend to have hooked or sigmoid sutures, whereas specimens from shallower environments have smoother, curved sutures. Specimens examined from Bering Sea Site U1342 appear to vary randomly in the coiling of their test, rate of expansion of their final chambers, width of the final whorl and the curvature of the sutures. There is also no significant intraspecific variation in the number or density of pores, mode of coiling and other morphological characteristics in the few specimens examined from U1342; occurrence of *P. wuellerstorfi* is very limited to the first half of the studied core.

Distribution: *Planulina wuellerstorfi* is a cosmopolitan species, typical of major oceans and marginal basins (van Morkhoven et al. 1986; Sen Gupta 1989; Schnitker 1980; Douglas and Woodruff 1981). *P. wuellerstorfi* has its water depth range extending from 1151 m in north Atlantic (Streeter 1973; Lohmann 1978; Belanger and Berggren 1986) to between 2500 and 4600 m in the southeast Indian Ocean (Corliss 1979). *P.*

wuellerstorfi is abundant mainly in lower bathyal and abyssal depths, and is generally used as a bathymetric indicator for water depths over 800 m (Holbourn 2013); it constitutes a significant portion of the benthic foraminiferal assemblage in waters deeper than 2500 m (Van Morkhoven et al. 1986). *P. wuellerstorfi* was considered a low to intermediate carbon (2.5-9 g/m^2 y) flux indicator by Altenbach et al. (1999). Kaiho (1994) and Bubenshchikova et al. (2010) classified this species as sub-oxic B (1.5-6.0 ml/l dissolved oxygen levels), based on empirical relations between the foraminiferal oxygen index and dissolved-oxygen levels in the modern ocean. *P. wuellerstorfi* also occurs as an epifaunal species (Bubenshchikova et al. 2008). Its stratigraphic range is from Middle Miocene to Recent (Holbourn et al. 2013).

Family NONIONIDAE Schultze, 1854

Subfamily NONIONINAE Schultze, 1854

Genus *Nonionellina* Voloshinova, 1958

Type species *Nonionina labradorica* Dawson, 1860

Nonionellina labradorica (Dawson, 1860)

Plate 2.20, Figures 1-5

Nonionina labradorica Dawson, 1860, p. 191- 192, fig. 4

Nonion labradoricum (Dawson); - LOEBLICH and TAPPAN 1953, p. 86, pl.17, figs. 1, 2; - HANSEN and LYKKE-ANDERSEN 1976, p. 37, pl. 21, figs.5 - 8.

Nonionellina labradorica (Dawson); - BANDY, 1953, p. 66, pl. 22, fig. 1; - VOLOSHINOVA 1958, p. 142; - KNUDSEN, 1971, p. 262, pl. 10, figs. 1-2; CRONIN, 1979, p. 805, pl. 5, fig. 6; - KELLER, 1980, p. 859, pl. 3, figs. 9-10; - SEJRUP et al., 1981, p. 293, pl. 2, figs. 5-7; - VILKS et al., 1982, p. 227, pl. 1., figs. 24 a-b; - LOEBLICH and TAPPAN 1987, p. 617, pl. 689, figs. 8-17; - GUSTAFSSON and NORDBERG, 2001, p. 9, pl. 1, fig. 6; - PATTERSON and KUMAR, 2002. p. 122, pl. 2, figs. 12, 18; - POLYAK et al. 2002, p. 261, pl. 2, fig. 10; - NARAYAN et al., 2005, p. 132, pl. 4, figs. 21, 22; - ABU-ZIED et al., 2008, p. 53, pl. 3, figs. 10 -13; - HOLBOURN et al., 2013, p. 374; - SETOYAMA and KAMINSKI, in press, figs. 6.1a, b, 8.19.

Distribution in core: 77 specimens from 22 samples; intermittent occurrences down core, abundance occurrence between intervals 17.09 to 18.55 m.

Emended diagnosis: (Based on Abu-Zied et al. 2008; Hansen and Lykke-Andersen 1976 and the Bering Sea specimens examined here) Initial part of the test trochoid while the later majority of the test is planispiral; chambers enlarging rapidly as added; small, deeply depressed umbilici on both sides; few pustules around the arched slit aperture.

Description: Test is biconvex, trochospiral in the very early stage, planispiral in the later part, tends to be involute; wall calcareous, finely perforate, surface smooth, thin and translucent; seven to eight chambers, enlarging rapidly as added, producing a somewhat flaring test; average number of chambers is eight in the final whorl, average length of the test is 0.45 mm at the maximum diameter; chamber thickness ranges between 0.12 to 0.30 mm, thickness of the last chamber exceeding that of the first chamber by about three times; chambers enlarging rapidly as added; small, deeply depressed umbilici on both sides, slightly inflated basal lobe, periphery sub-angular to round; sutures are gently curved, thin and slightly depressed, but more incised near the umbilicus. Aperture is a low equatorial arched slit, surrounded by few pustules at the base of the apertural face; apertural face is smooth, broad, sub-triangular and slightly perforate.

Remark: *N. labradorica* is distinguished by the initial part of the test being trochoid while the later part is planispiral (Hansen and Lykke-Andersen 1976). Bering Sea specimens closely resemble those reported by Hansen and Lykke-Andersen (1976) from east Greenland, but differ slightly from specimens illustrated by Dawson (1860), which have an outline that is non-lobulate. Keller (1980) illustrated a form with a lobulate outline from the Japan Trench (Pacific Ocean), which has an average number of eight chambers, and the degree of inflation of the chambers in the last whorl and the chamber coiling is very similar to specimens in this study. Bering Sea specimens have a smooth outline similar to specimens from the Pacific Ocean illustrated by Riveiro and Patterson (2007), and Matoba (1967). The Bering Sea specimens are similar to *N. labradorica* Dawson described by Abu-zied et al (2008: pl. 3, figs. 10-13) from the Swedish coast,

from the Mediterranean Sea by Gustafsson and Nordberg (2001: pl. fig. 6) and from Canada by Vilks et al. (1982: pl. 1, figs. 24a-b).

Distribution: *N. labradorica* is present in the NW Pacific, and the Atlantic Oceans (Cronin 1979; Keller 1980; Ohkushi et al. 2003; Bubenshchikova et al. 2010; Erbs-Hansen et al. 2012), the Bering Sea (Ovsepyan et al. 2013), Arctic and boreal seas bordering Alaska, Canada, Greenland, Norway and Denmark (Polyak 2002; Holbourn et al. 2013) and other regions (Gustafsson and Nordberg 2001; Patterson and Kumar 2002; Mazumder et al. 2003). *N. labradorica* has a bathymetric range between the neritic and abyssal (Holbourn et al. 2013). Its water depth ranges from 50 to 3500 m (Keller 1980; Gustafsson and Nordberg 2001; Polyak 2002; Patterson and Kumar 2002; Mazumder et al. 2003; Scott et al. 2008; Erbs-Hansen et al. 2012; Ovsepyan et al. 2013). *N. labradorica* has been considered a dysoxic species (Kaiho 1994; Bubenshchikova et al. 2010). The stratigraphical range of *N. labradorica* is from Pliocene to Recent (Hansen and Lykke-Andersen 1976; Holbourn et al. 2013).

Nonionella digitata Nørvang, 1945
Plate 2.20, Figure 6

Nonionella turgida (Williamson) var. *digitata* Nørvang 1945, p. 29, text-fig. 4
Nonionella digitata Nørvang, 1945; - TODD and LOW, 1967, pl. 5, fig. 8; - PATTERSON et al., 1998, p. 20, pl. 21, figs. 1-3; - PATTERSON and KUMAR, 2002. p. 122, pl. 2, fig. 11; - RIVEIROS and PATTERSON, 2007, p. 13, fig. 12, 5; - RIVEIROS and PATTERSON, 2008, p. 29, fig. 12.5; - SETOYAMA and KAMINSKI, in press, figs. 5.11-c, 8.18.

Distribution in core: 4 specimens from 3 samples; highest occurrence at 15.59 m, isolated occurrences at 18.67 and 19.44 m.

Emended diagnosis: Umbilical flap with long digitate extensions covering the umbilical region; aperture is a small interiomarginal arch, extending onto umbilical side, obscured by the digitate extensions.

Description: Test compressed, fragile, general outline round to elongate, slightly inflated, elliptical in shape, may be ovate, periphery rounded to elongate; average length of the test is 0.52 mm at the maximum diameter, 0.32 mm in width; slightly inflated basal lobe on the umbilical side. Wall calcareous, hyaline, fragile, smooth, finely perforate, rapidly increasing in size; umbilical side involute with only 5 to 6 chambers in the final whorl visible, sutures slightly depressed towards the umbilical area; distinctive flap-like extensions of final chambers subdivided into 7 to 8 digitate projections obscuring the umbilical region. Aperture is an interiomarginal, nearly equatorial arch, covered by digitate projection extending over umbilical side.

Remarks: Bering Sea specimens are similar to *Nonionella digitata* Nørvang, described by Riveiros and Patterson (2007), from northern British Columbia, Canada (NE Pacific) with distinctive finger-like projections covering the umbilical region. *N. digitata* is differentiated from other *Nonionella* by its umbilical flap with long digitate extensions, and differs especially from *N. labradorica* in the way the chambers are added: *N. labradorica* has its whorls progressively enlarging, producing a flaring final chamber, while *N. digitata* has flap-like extensions of the final chamber ending in finger-like projections. *N. digitata* is differentiated from *N. stella* Cushman and Moyer by its umbilical flap being more prominent with longer extensions. The few specimens of *N. digitata* recorded from Site U1342 do not show any significant intraspecific variation.

Distribution: *N. digitata* has a geographical distribution in the Arctic and Atlantic Oceans (Gross 2001), Okhotsk and Bering Seas, and the Pacific adjacent to British Columbia (Lembke et al. 2003; Riveiros and Patterson 2007; Ovsepyan et al. 2013), and the Gulf of Alaska (Bergen and O'Neil 1979). Its water depth ranges from 200 to 238 m in the Gulf of Alaska and British Columbia (Bergen and O'Neil 1979; Patterson and Kumar 2002; Riveiros and Patterson 2007), extending to 625 to 1752 m in the Pacific Ocean (Lembke et al. 2003; Riveiros and Patterson 2007; Bubenshchikova et al. 2008; Ovsepyan et al. 2013). *N. digitata* has been considered a deep infaunal species and an indicator of dysoxic conditions (Bubenshchikova et al. 2008).

Subfamily PULLENIINAE Schwager, 1877
Genus *Melonis* de Montfort, 1808

Type species *Melonis etruscus* de Montfort, 1808

Melonis barleeanus (Williamson, 1858)

Plate 2.20, Figures 7-12

Nonionina barleeana WILLIAMSON, 1858. p. 32, pl. 3. figs. 68, 69

Nonionina umbilicatula (Montagu) - BRADY, 1884, p. 726, pl. 109, figs. 8, 9

Nonion barleeanum (Williamson) - PHLEGER, et al., 1953, p. 30, pl. 6, fig. 4

Gavelinonion barleeanum (Williamson) - BARKER, 1960, p. 224, pl. 109, figs. 8, 9

Melonis barleeanum (Williamson) - PFLUM and FRERICHS, 1976, p. 122, pl. 7, figs. 5, 6; - WRIGHT 1978, p. 715, pl. 6, fig. 4; - CORLISS, 1979, p.10, 12, pl. 5, figs. 7, 8; - INGLE and KELLER, 1980, p. 135, pl. 2, figs. 7, 8; - O' NEILL, 1981, p. 1155, pl. 3, figs. 1, 6; - CARALP, 1988, figs. 3-4; - CARALP 1989, p. 40, figs. 13-4; - SEN GUPTA, 1994, p. 366, pl. 6, fig.1; - DOWSETT and ISHMAN, 1995, p. 154, pl. 1, fig. 5; - LUISA et al., 1997, p. 43, pl. 2, figs. 1-9;- JANNINK et al., 1998, p. 1497, pl. 1, figs. 7a-b; - OHKUSHI et al., 2000, p. 143, pl. 5, figs. 6a-b; - LICARI and MACKENSEN, 2005, p. 213, pl. 1, figs. 12, 13; - PANIERI, 2005, p. 253, figs. 4, 3 a-b; - ABU-ZIED et al., 2008, p. 53, pl. 3, figs. 16,17; - SEN GUPTA et al., 2009, p. 380, pl. 103, figs. 1-2; - MILKER and SCHMIEDL, 2012, p. 115, figs. 26.11-12. - HOLBOURN et al., 2013, p. 354; - SETOYAMA and KAMINSKI in press, figs. 6.4a-b, 6.5.

Distribution in core: 13 specimens from 7 samples; first and last occurrence at 12.98 and 19.92 m respectively; few intermittent occurrences in between this range.

Emended diagnosis: Open umbilical region; aperture an equatorial and interiomarginal curved slit bordered by a more prominent lip, extending to the umbilicus at the two sides.

Description: Test compressed, planispiral, involute and symmetrical; wall calcareous, hyaline and perforate; chambers broad, new chambers are added on the previous apertural face, enlarging gradually as added; average dimension at the longest diameter is between 0.30 and 0.37 mm; thickness between 0.12 and 0.15 mm, usually more than

10 chambers in the final whorl. Open umbilical region, sutures slightly raised, radial or straight to slightly curved, merged with thickened umbilical rim, periphery broadly rounded, peripheral outline smooth and slightly curvy; finely perforate except on the apertural face and on the sutures. Aperture an open, equatorial and interiomarginal curved slit, extending to an open umbilical region at the two sides, bordered with a pronounced lip.

Remarks: *Melonis barleeanum* has been placed by several authors in the genus *Nonion* which is morphologically similar, but a distinction from that genus is possible, because the umbilical region is open rather than closed as in *Nonion*. Thus, *M. barleeanum* is differentiated from *Nonion fabum* (Fichtel and Moll) by its open umbilical region. *M. barleeanum* is similar to *M. pompilioides* (Fichtel and Moll), but is differentiated by being more coarsely perforate (Luisa et al 1997; Bergsten 1994), with pronounced sutures which tend to be tangential to the umbilicus, in contrast to the radiate and less well defined sutures in *M. pompilioides*. Bering Sea materials are similar to *M. affinis* illustrated by Milker and Schmiedl (2012), but differ in that the latter has a less prominent apertural lip.

Van Marle (1991) noted that *Melonis barleeanum* (Williamson) is a junior synonym of *Melonis affinis* (Reuss). Schweizer (2006) synonymised *M. barleeanus* under *M. affinis* based on molecular analysis. Bering Sea specimens are similar to *M. barleeanum* (Williamson) from the Mediterranean Sea illustrated by Abu-Zied et al. (2008: pl. 3, figs. 16-17), and also similar to the specimens illustrated by Chendeş et al. (2004; p. iv, fig. 1) and Jannink et al. (1998: pl. 1, figs. 7a-b) from the northern Arabian Sea, and from the Pacific bordering central and southern Chile (Figueroa et al. 2005). The stratigraphical range of *M. barleeanum* in Site U1342 is restricted to the interval between 12.98 and 19.92 m.

Distribution: *M. barleeanum* is a cosmopolitan species which has a geographical distribution in the Atlantic, Pacific, Southern and Indian Oceans (Cushman 1939; Phleger et al. 1953; Corliss 1979; Ingle and Keller 1980; Hermelin and Scott 1985; Caralp 1989; Dowsett and Ishman; 1995; Labeyrie et al. 1996; Khusid et al. 2005; Panieri 2005), the Bering Sea (Ovsepyan et al. 2013), and other seas (Kurihara and Kennett, 1986; Kuhnt et al. 2007; Wilson and Costelloe 2011; Milker et al. 2009). *M.*

barleeanum is generally considered a bathyal species; but was recorded in the Gulf of Mexico from the neritic zone to the middle bathyal zone (Pflum and Frerichs 1976); its depth ranges between 500 and 3290 m in the northeast Atlantic (Caralp 1989; Labeyrie et al. 1996; Panieri 2005; Licari and Mackensen 2005); and it is also found within the oxygen minimum zone between 500 to 1000 m depths in the northern Arabian Sea (Jannink et al. 1998; Mazumder et al. 2003, Ovsepyan et al. 2013). *M. barleeanum* was recorded from the Indian Ocean at a deeper water depth range between 2500 and 4500 m (Corliss 1979; Ovsepyan et al. 2013).

  M. barleeanum occurs as an intermediate and shallow infaunal species (Corliss 1985; Corliss and Emerson 1990; Gooday 1994; Jorissen et al. 1995; Jorissen et al. 1998; Licari et al. 2003). Kuhnt et al. (2007) reported this species as an indicator of dysoxic conditions. *M. barleeanum* is known to be rare in the Oligocene, but abundant in the Middle and Late Miocene (Miller and Katz 1987; Katz and Miller 1993). Its stratigraphical range is Oligocene to Recent (Thomas 1985; Holbourn et al. 2013).

Genus *Pullenia* Parker and Jones, 1862
Type species *Nonionina bulloides* d'Orbigny, 1846

Pullenia simplex Rhumbler, 1931
Plate 2.20, Figures 13-16

Pullenia simplex Rhumbler; - WIESNER, 1931, p. 132, pl. 22, fig. 263; - ANDERSON, 1975, p. 95, pl. 11, fig. 10; - CORLISS, 1979, p. 9, pl. 4, figs. 5-6; - MACKENSEN, 1992, p. 670, pl. 2, fig.6; - KAIHO 1992, p. 310, pl. 8, fig. 4; - BARBIERI et al., 1999. p. 50, pl. 2, figs. 3-5; - KOHO et al., 2007, p. 43, pl. II, figs 6a-b.

Distribution in core: 257 specimens from 63 samples; occurrence is relatively consistent down core, with the exception of intervals 3.77 - 4.85 m, 6.80 - 7.71 m and 19.61 - 20.59 m where the species is absent; relatively abundant between intervals 1.13 - 1.38 m.

Emended Diagnosis: Depressed sutures and a sub-circular outline, aperture a narrow interiomarginal slit extending from one side of the umbilicus to the other.

Description: Test is medium-sized, slightly compressed, sub-circular in outline, planispiral and involute, slightly inflated, a sub-rounded periphery, having five to seven chambers in the final whorl which increases rapidly in size, the last chamber being flared; average dimension of the test ranges from 0.25 mm to 0.35 mm at the longest diameter, 0.12 mm to 0.16 mm in thickness. Wall calcareous, finely perforate with smooth surface, sutures radial, flushed to slightly depressed; aperture a narrow interiomarginal slit, extending across the periphery to the sides of the umbilicus, surrounded by a lip.

Remarks: *P. simplex* was originally described by Rhumbler; Wiesner (1931) published the report of the description (Corliss 1979: p. 9). *P. simplex* from the Bering Sea differ from the specimens illustrated from the Indian Ocean (Corliss 1979: p. 9, pl. 4, figs. 5-6) in not having as rapidly enlarging chambers; but are morphologically similar to specimens from the Portuguese continental margin (Koho et al. 2007: p. 43, pl. II, figs. 6a-b) in the chamber number and coiling. *P. simplex* is morphologically similar to *P. quinqueloba* (Reuss), but the latter differs in not having rapidly enlarging chambers (Belanger and Berggren 1986), and being more biconvex (see Holbourn et al. 2013: p. 448 fig. 2). In addition, *P. quinqueloba* (Reuss) has fewer chambers. *P. simplex* differs from *P. bulloides*, the latter having its chambers less undulose, whilst its umbilici are more open and its chambers enlarged more rapidly than in *P. simplex*.

Distribution: *P. simplex* has a geographical distribution in the Atlantic and Indian Oceans (Corliss 1979; Belanger and Berggren 1986; Corliss 1991; Mackensen 1992); the Southern Ocean (Anderson 1975; Mackensen and Douglas 1989; Barbieri et al. 1999) and Japan Sea (Kaiho 1992). Its water depth ranges from 200 and 3410 m in the Atlantic and Indian Oceans, and in the Antarctic (Corliss 1979, 1991; Belanger and Berggren 1986; Mackensen and Douglas 1989; Barbieri et al. 1999), this extends to 4976 m along the Portuguese continental margin in the Atlantic (Koho et al. 2007). *P. simplex* is an indicator of sub-oxic conditions (0.3-1.5 ml/l) based on empirical relations between the benthic foraminiferal oxygen index (BFOI) and dissolved-oxygen levels in the modern ocean (Kaiho 1994). The stratigraphical range is from Paleocene to Recent (Corliss 1979).

Family ORIDORSALIDAE Loeblich and Tappan 1984

Genus *Oridorsalis* Andersen, 1961

Type species *Oridorsalis westi* Andersen, 1961

Oridorsalis umbonatus (Reuss, 1851)

 Plate 2.21, Figures 1-10

Rotalina umbonata REUSS, 1851, p. 75, pl. 5, figs. 35 a-c

Pulvinulina umbonata (Reuss); - BRADY, 1884, p. 695-696, pl. 105, figs. 2a-c; - CUSHMAN, 1921, p. 339-340, pl. 71, figs. 1a-c; - HERON-ALLEN and EARLAND, 1932, p. 430, pl. 15, figs. 16-18.

Rotalia ecuadorensis - GALLOWAY and MOREY, 1929, p. 26, pl. 3, fig. 13

Eponides umbonatus (Reuss); - CHAPMAN and PARR, 1937, p. 108; - BERMUDEZ, 1949, p. 249, pl. 17, figs. 22-24; - PARKER, 1952b, p. 419, pl. 6, fig. 13;- PHLEGER et al., 1953, p. 42, pl. 9, figs. 9-10; - BARKER, 1960, p. 216, pl. 105, figs. 2a-c.

Pseudoeponides umbonatus (Reuss); - PARKER, 1954, p. 530, pl. 9, figs. 20, 21

Oridorsalis umbonatus (Reuss); - TODD, 1965 p. 23, pl. 6, fig. 2; - PFLUM and FRERICHS, 1976, p. 106, pl. 24, figs. 4

Oridorsalis tener tener (Brady); - PFLUM and FRERICHS, 1976, pl. 6, figs. 2-4

Oridorsalis tener umbonatus (Reuss); - PFLUM and FRERICHS, 1976, p. 108, pl. 6, figs. 5-7

Oridorsalis tener (Brady); - LOHMANN, 1978, p. 26, pl. 4, figs. 5-7; - CORLISS, 1979, p. 9, pl. 4, figs. 10-15

Oridorsalis umbonatus (Reuss); - WRIGHT, 1978, p. 724, pl. 6, figs. 13-14; *Oridorsalis tener* (Brady); - INGLE et al., 1980, p. 142, pl. 5, figs. 5-6.

Oridorsalis umbonatus (Reuss); - BOLTOVSKOY, 1980, p. 169, pl. 3, fig. 1; p. 170, fig. 8; - BELANGER and BERGGREN, 1986, p. 340, pl. 5, figs. 10a-c; - HERMELIN et al., 1989, p.141, pl.16, figs. 1-5; - MACKENSEN et al., 1990, p. 261, pl. 7, figs. 4-6; - SCOTT and VILKS, 1991, p. 31, pl. 2, figs. 15, 16; p. 34, pl. 4, figs. 4-5; - JONES, 1994, p. 99, pl. 95, fig.11; - AKIMOTO, 1994, p. 290, pl. 3, fig. 5; - BOLLI et al. 1994, p. 247, pl. 58, fig. 10-13; - SEN GUPTA, 1994, p. 365, pl. 6, fig. 11; SCHÖNFELD, 1995, p. 171, pl. 1, fig. 11; - OHKUSHI et al., 2000, p. 143, pl. 5, figs. 1a-c; - SEN

GUPTA et al., 2009, p. A-118, pl. 116, figs. 1-3; - HOLBOURN et al., 2013, p. 384; - SETOYAMA and KAMINSKI, in press, figs. 7.2a-c

Distribution in core: 142 specimens from 17 samples; a few isolated occurrences down core at 0 - 0.10 m, 5.26 - 5.41 m, 5.46 m, 15.79 m - 15.95 m and 18.95 - 19.22 m; relatively abundant between intervals 18.95 - 19.22 m.

Emended diagnosis: Test unequally biconvex, umbilical side is involute and less convex than spiral side; aperture an interiomarginal slit; supplementary apertures occur at intersection of spiral and inter-cameral sutures on the spiral side and at the sinuous bend along the sutures on the umbilical side.

Description: Test trochospiral, compressed, low trochospire; sub-circular to slightly lobate in outline, unequally biconvex in cross section, convex and evolute spiral side, with an involute, less convex umbilical side, keeled and sub-acute periphery. About twice as thick as wide, average dimension is 0.27 mm in diameter at the widest diameter, and 0.15 mm in thickness. Wall calcareous, finely perforate and smooth, about six to seven moderately inflated chambers in the final whorl, increasing in size gradually. Sutures slightly depressed, radial on spiral side, straight to sinuous on the umbilical side. Aperture an interiomarginal slit, extending from the closed umbilical area to the periphery, with lip and pustules surrounding it; supplementary openings on the umbilical side at the junction between the spiral side, and at the sinuous bend along the suture on the umbilical side.

Remarks: *O. umbonatus* and *O. tener* (Brady) have been reported to be morphologically similar (Hermelin 1989). *O. umbonatus* from the Bering Sea has straight sutures on the spiral side which differentiate it from *O. tener* (see Corliss 1979; Mead 1985). *O. umbonatus* from the Bering Sea shows intraspecific variation in test convexity: larger tests are more convex, and this may be related to maturity. Parker (1954) did not observe supplementary apertures in her small specimens, and Barker (1960) could not find supplementary apertures on any of his Pacific material. Supplementary apertures are difficult to see under the light microscope, but are obvious in SEM micrographs as rounded openings on the dorsal side (Plate 2.21: figs. 2, 4, 6 and 10)

Distribution: *O. umbonatus* has a geographical distribution in the Pacific, Atlantic and Indian Oceans (Corliss 1979; Butt 1980, Boltovskoy 1980; Keller 1980; Boersma 1984; Murray 1984; Mackensen et al. 1990; Kato 1992; Akimoto 1994; Schönfeld 1995; Sun at al. 2006; Noda et al. 2008; Bubenshchikova et al. 2010), the Arctic (Scott and Vilks 1991) as well as other regions (Wright 1978; Sen Gupta et al. 2009; Kender et al. 2008). Its water depth range extends from 95 to 1708 m at the 'Challenger' stations in the Pacific Ocean (Jones 1994), to between 289 and 5600 m in the Indian Ocean, SW and Atlantic Oceans, Weddell and other seas (Corliss 1979; Mackensen et al. 1990; Rasmussen 2007; Kender et al. 2008b; Noda et al. 2008; Sen Gupta et al. 2009; Jorissen et al. 2009).

The distribution of *O. umbonatus* in the northeast Atlantic has been linked to bottom water masses (Streeter 1973; Schnitker 1974, 1980; Weston and Murray 1985; Gaydyukoav and Lukashina, 1988; Lukashina, 1988). *O. umbonatus* is an indicator of sub-oxic conditions and a shallow infaunal species (Bubenshchikova et al. 2010). The stratigraphical range of *O. umbonatus* is from Middle Paleocene to Recent (Tjalsma and Lohmann 1983; Thomas 1990; Bolli et al. 1994; Jones 1994; Holbourn et al. 2013).

Family GAVELINELLIDAE Hofker, 1956
Subfamily GAVELINELLINAE Hofker, 1956
Genus *Gyroidina* d' Orbigny, 1826
Type species *Gyroidina orbicularis* d'Orbigny, 1826

***Gyroidina* sp. 1**
Plate 2.21, Figures 11, 12

Distribution in core: 2 specimens in 2 samples at 18.43 and 19.22 m

Description: Morphologically similar to *Gyroidina* sp. 2 (see *Gyroidina* sp. 2) but with raised umbilical sutures.

Remarks: Only two specimens were recorded from the interval studied. The major difference between *Gyroidina* sp. 1 and *Gyroidina* sp. 2 is the raised umbilical sutures; which is depressed in *Gyroidina* sp. 2. The two specimens are well preserved.

***Gyroidina* sp. 2**
Plate 21, Figures 13-16; Plate 22, Figures 1-4

***Distribution in core*:** 700 specimens from 47 samples; species absent in the uppermost 2.38 m of the core, intermittent occurrence down core, relative abundance between 5.55 - 5.46 m, 6.11 - 6.20 m and 10.87 m; highest abundance at 19.22 m.

***Description*:** Test medium to large, average dimension is 0.52 mm at the longer diameter, 0.37 mm at the shorter diameter, average thickness 0.30 mm, slightly compressed, tightly coiled, trochospiral, surface is smooth, unequally biconvex, umbilical side more convex, spiral side slightly flat in most individuals, but occasionally weakly convex. Wall calcareous, chambers gradually increasing in size as added, six to nine chambers in the final whorl; only 1 to $1\frac{1}{2}$ whorls per test. Sutures are backwardly curved, depressed, slightly flush with the surface on the spiral side, radial in the umbilical side. Aperture an interiomarginal slit at the middle of the apertural face, extending toward the periphery, bordered by a lip.

***Remarks*:** The biconvexity of most *Gyroidina* sp. 2 studied from the fauna causes it to appear like species of *Eponides*; however, the deep ventral side and the character of the aperture are features of *Gyroidina*. *Gyroidina* sp. 2 is morphologically close to *G. lamarckiana* (D'Orbigny), but it is differentiated by the fewer number of chambers in its final whorl; chambers in *Gyroidina* sp. 2 being more (10 to12), and also *Gyroidina* sp. 2 has an evolute coiling in the umbilical view, whilst *Gyroidina* sp. has involute coiling on the umbilical side. *Gyroidina* sp. 2 is morphologically similar to the material described as *G. lamarckiana* by Todd (1965) from the Pacific Ocean; it is thought to be conspecific with *G. lamarckiana* (D'Orbigny); but differs from *G. soldanii* d'Orbigny which has more distinct chambers from the spiral view and a greater number of chambers and whorls generally (see Bandy, 1953: p. 173, pl. 23, figs. 6a-c). *Gyroidina* sp. 2 specimens from core U1342 show slight intraspecific variation in their sizes and

coiling of their test; this seems to be related to maturity as the bigger ones exhibit a wider degree of coiling.

Distribution: *Gyroidina* sp. 2 is recorded only from the Bering Sea. In contrast, *G. lamarckiana* has a geographical distribution in the Pacific and Atlantic Oceans (Todd 1965; Boltovskoy 1980; Sun at al. 2006), the Mediterranean, Japan and South China seas (Wright et al. 1978; Keller 1980; Kuhnt et al. 1999) and other seas (Boltovskoy 1978 1980; Gupta and Smith 2010, Wilson and Costelloe 2011). It has a water depth range from 61m in Norway, down to 1574 m in the Pacific Ocean (Rosoff and Corliss 1992; Todd 1965), and extending to approximately 2000 m in the Japan Sea (Keller 1980) down to 4000 m in the South China Sea (Kuhnt et al. 1999). The known stratigraphical range of *G. lamarckiana* is from Oligocene to Recent (Boltovskoy 1978).

Family   ELPHIDIIDAE Galloway, 1933
Subfamily ELPHIDIINAE Galloway, 1933
Genus *Elphidium* de Montfort, 1808
Type species *Nautilus macellus* var. ß Fitchtel and Moll, 1798

Elphidium ustulatum Todd, 1957
Plate 2.22, Figures 5-8

Elphidium? ustulatum TODD, 1957, p. 230, pI. 28, fig. 16
Elphidium sp. 2; - VAN VOORTHUYSEN, 1958, p. 25, pl. 9, fig. 98
Protelphidium lecticulare GUDINA, 1966, p. 55, pl. 3, figs. 7-9, pl. 9, fig. 1
Protelphidium lecticulare GUDINA, 1969, p. 35, pl. 12, figs. 7, 8
Elphidium ustulatum KNUDSEN in FEYLING-HANSSEN et al. 1971, p. 283, pl. 13, figs. 12, 13; pl. 23, figs. 5-7; - KNUDSEN, 1973a, p. 159, pl. 5, figs. 5-7; - HANSEN and LYKKE-ANDERSEN, 1976, p. 16, pl. 13. figs. 7-12; - GREGORY and BRIDGE, 1979, p. 72, pl. 1, figs. 1-6; McDOUGALL, 1993, pl. 2, figs. 11, 12.

Distribution in core: 43 specimens from 17 samples; intermittent but low occurrences down core, first and last occurrence at 2.64 and 9.50 m respectively, relatively consistent occurrence from 7.71 to 9.50 m, highest abundance at 9.11 m.

Emended diagnosis: (Revised from Gregory and Bridge 1979 and Hansen and Lykke-Andersen 1976) Test involute, multiple apertures, slightly bi-umbonate, sutures distinct with sigmoidal curvature, elongate slits in forwardly curved section.

Description: Test rounded to slightly elliptical, compressed, slightly bi-umbonate, average dimension is 0.33 - 0.45 mm at the longer diameter, 0.28 - 0.40 mm at the shorter diameter, average thickness is 0.16   0.20 mm; wall calcareous with radial structure, finely perforate. Chambers not inflated, narrow, degree of coiling increases with size, number varies from seven to eleven. Sutures distinct, incised, containing medium to fine tuberculation (granular materials) around the sutural openings; surface flush with the chambers forming a sigmoidal curvature, central section of each suture deepens, curvature swinging gently backwards from umbilical area towards the periphery, no bosses or sutures in the umbilical area; sutures are closed at both ends, occupying approximately two-thirds of the length of the chamber; specimens vary from semi-transparent to opaque. Aperture is not visible, as it is usually concealed by granular calcite at the base of the apertural face, which may be flat, slightly convex, or triangular (Gregory and Bridge 1979). Hansen and Lykke-Anderson (1976) discussed the details of the test microstructure.

Remarks: Specimens from the Bering Sea are smaller in size to Todd's (1957) holotype, which has an average diameter of 0.45 - 0.57 mm at the longer diameter and a thickness of 0.20 – 0.26 mm. *E. ustulatum* from the Bering Sea differs from specimens recorded as *E.? ustulatum* by Gudina (1966, 1969; see also Gregory and Bridge 1979: p. 74) by being larger. *E. ustulatum* differs from *E. incertum* (Williamson), which has longer and curved sutural slits that are not incised. There is intraspecific variation among the specimens studied; more than half show medium to fine tuberculation (granular materials) around the openings.

Distribution: *E. ustulatum* was originally described from the Nuwok Member at Carter Creek, northern Alaska (Todd 1957); MacNeil (1957) determined the age of this unit to be upper Miocene or lower Pliocene. It has a modern geographical distribution in the North Sea (Gregory and Bridge 1979; Sejrup et al. 1991; Knudsen and Asbjörnsdóttirb

1991; Knudsen and Sejrup 1993), Norway, Denmark (Knudsen 1971) and north Greenland (Feyling Hanssen 1980). *E. ustulatum* occurs at 229 m depth in the central North Sea (Gregory and Bridge 1979). It occurs as a shallow infaunal species (Bubenshchikova et al. 2010), and has been considered an indicator of sub-oxic conditions (0.3-1.5 ml/l) based on empirical relations between the benthic foraminiferal oxygen index and dissolved-oxygen levels in the modern ocean (Kaiho 1994). The stratigraphical range of *E. ustulatum* throughout the Arctic region is from Pliocene to Pleistocene (McDougall 1993).

Elphidium **sp**. **1**
Plates 2.22, Figures 9-11

Distribution **in core:** 6 specimens from 6 samples occurrences at depths 1.38, 2.38, 5.41, 6.52, 9.40 and 9.50 m.

*Description***:** Test involute to partially evolute, robust, periphery rounded, compressed with umbilical regions slightly depressed, general outline somewhat lobate. Wall calcareous with radial structures, perforate; increasing gradually in size, about nine to ten chambers in final whorl; average dimension of 0.37 - 0.47 mm at the longer diameter, 0.30 - 0.43 mm at the shorter diameter, average thickness is 0.16 - 0.20 mm; sutures elongate, slightly curved and linking with umbilical spiral canal system, surrounded by tubercles or striae along the sutures forming an ornamentation around the umbilici; apertural face and the earliest part of the final whorl are covered by dense tuberculation. Aperture is a low interiomarginal equatorial arch, obscured by tuberculation covering the apertural face.

*Remarks***:** *Elphidium* sp. 1 is differentiated from *E. ustulatum* by its shorter and wider sutural openings, terminating before reaching the umbilical area. *Elphidium* sp. 1 is differentiated from *E. batialis* by its greater number of chambers, demarcated by relatively large perforations aligned with the radial sutural line. *Elphidium* sp. 1 is morphologically similar to specimens illustrated and described as *Elphidium magellanicum* Heron-Allen and Earland by Hansen and Lykke-Andersen (1976: pl. 13,

2-6) from Kattegat, Denmark, by having tuberculation covering the apertural face, number and form of chambers varies, *E. magellanicum* having fewer number and having chambers more inflated.

Elphidium **sp. 2**

Plate 2.22, Figure 12, 13

Distribution in core: 9 specimens from 6 samples; random occurrences at depths 0.74, 2.64, 9.50, 12.73, 12.98 m; lowest occurrence at 18.43 m.

Description: Test planispiral, involute, robust, slightly compressed, periphery broadly rounded, subcircular in outline, the later part of the final whorl is slightly lobate. Chambers moderately inflated, about 9-10 chambers in final whorl, chambers increasing gradually in size, no bosses or sutures in the umbilical area; sutures are closed at both ends; closure more rounded and terminates towards the umbilical area, occupying approximately two-thirds of the length of the chamber; wall calcareous, perforate and smooth, sutures incised, depressed and covered with tuberculation, apertural face is smooth imperforate. Aperture is not clearly seen.

Remarks: *Elphidium* sp. 2 is differentiated from *E. kugleri* (Cushman and Brönnimann 1948) described by Hansen and Lykke-Andersen (1976: pl. 9: 4-8) which has fewer strongly embracing chambers (7-8) and fused umbilical chamber parts though the two specie has perforate chamber walls.

Elphidium **sp. 3**

Plates 2.22, Figures 14-17

Distribution in core: 3 specimens from depths 15.23, 16.65 and 19.44 m.

Description: Test planispiral, involute, robust, slightly compressed, periphery rounded, subcircular in outline. Wall calcareous, perforate and smooth; chambers increasing gradually in size, ten to eleven in final whorl; the later part of the test shows a slightly lobate outline. Average dimension of 0.32 - 0.47 mm at the longer diameter, 0.30 - 0.43

mm at the shorter diameter, average thickness is 0.16 - 0.20 mm; pore diameter about 0.05 mm. Sutures are gently curved and crossed by distinct ponticuli.

Remarks *Elphidium* sp. 3 is morphologically close to *E. poeyanum* (d'Orbigny 1839) illustrated by Hansen and Lykke-Andersen (1976: pl. 9: 9-12) from the Recent of Florida, USA, by having nine to ten chambers, slightly compressed test, lobate outline, a rounded periphery and the same sutural form, but *Elphidium* sp. 3 differs having a more lobate outline. *Elphidium* sp. 3 is morphologically similar to *E. batialis*; having about the same number of slightly inflated chambers in their final whorls (9-10). It is differentiated from *E. batialis* which has relatively pronounced tuberculation extending in umbilico-posterior direction onto the lateral chamber wall of the final chamber (Hansen and Lykke-Andersen 1976: pl. 10: 6-12). *Elphidium* sp. 3 is differentiated from *E. kugleri* (Cushman and Brönnimann 1948) described by Hansen and Lykke-Andersen (1976: pl. 9: 4-8) which has its later chambers more flared.

Systematic Palaeontology Plates (2.1 – 2.22); interpretations and sample numbers (from Core U1342)

Plate 2.1
Scale bar = 100 μm (unless indicated)

1, 2. *Eggerella* sp. 1*(*A-2H-5-37-39 cm)
3 - 5. *Eggerella* sp.1 (A-2H-5-105-109 cm)
6. *Martinottiella communis.* (A-3H-5-91-92 cm)
7. *Martinottiella communis* (A-2H-5-105-109 cm)
8, **9.** *Martinottiella communis* (C-2H-5-78-81 cm)
10. *Quinqueloculina* sp. (D-2H-6-17-22 cm)
11. *Quinqueloculina* sp. (C-2H-5-25-28 cm)
12. *Quinqueloculina* sp. (A-3H-5-130-133 cm)
13. *Pyrgo murrhina* (D-1H-1-104-108 cm)
14. *Pyrgo murrhina* (A-2H-3-61-64 cm)
15. *Pyrgo murrhina* (D-1H-4-77-79 cm)
16. *Pyrgo murrhina* (D-1H-4-92-94 cm)
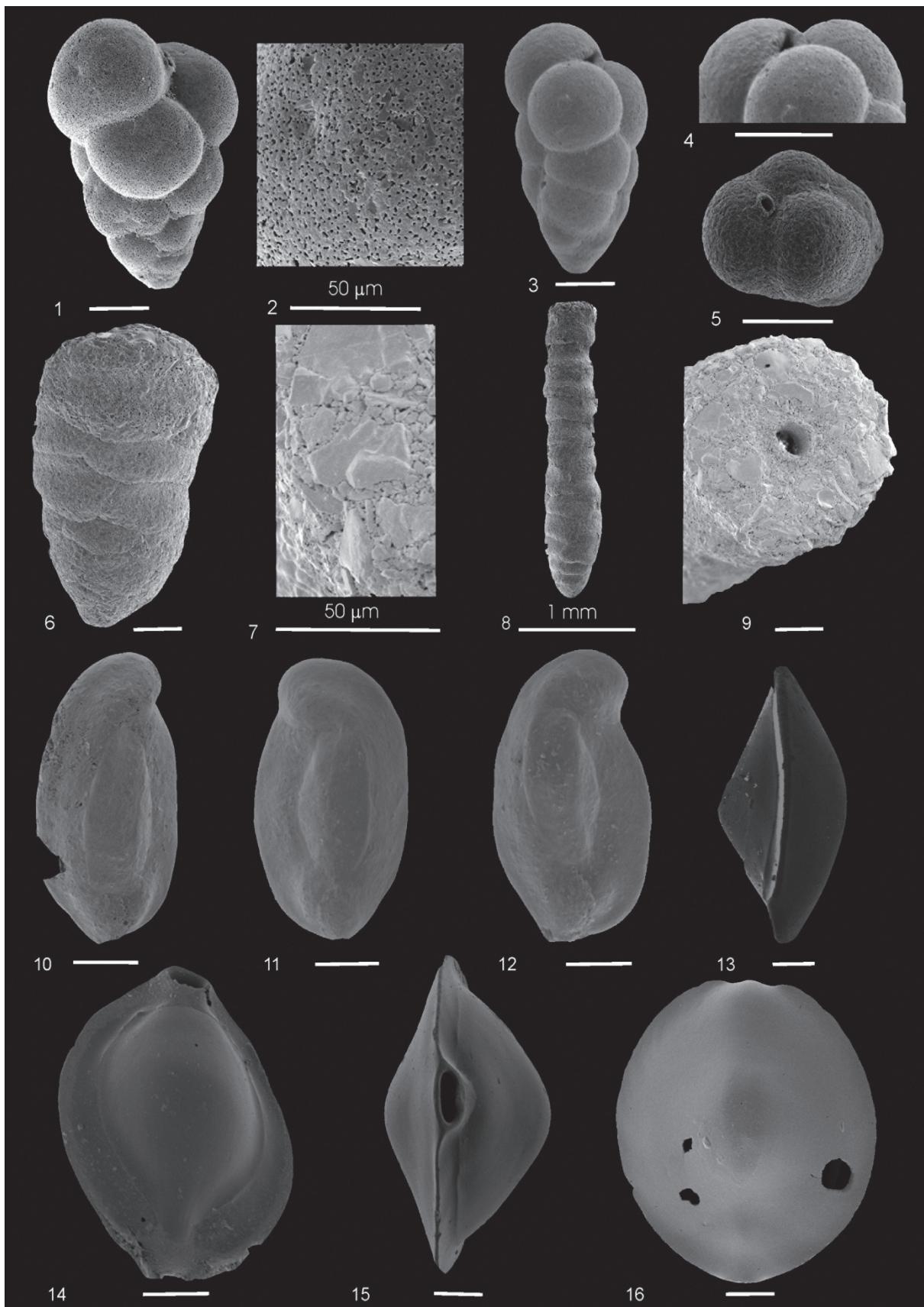
Plate 2.1

Plate 2.2
Scale bar = 100 μm (unless indicated)

1, 2. *Triloculina frigida* (D-1H-2-129-133 cm)
3. *Triloculina frigida (*A-2H-3-39-42 cm*)*
4. *Dentalina ittai* (D-1H-1-129-133 cm)
5. *Dentalina ittai* (C-2H-5-78-89 cm)
6, 7. *Dentalina ittai* (D-1H-2-89-93 cm)
8. *Dentalina ittai* (A-3H-5-12-16 cm)
9. *Dentalina ittai* (D-1H-2 105-109)
10. *Lotostomoides calomorphus* (D-1H-1-11-13 cm*)*
11. *Lotostomoides calomorphus* (D-H-4-106-108 cm)
12, 13, 15. *Lenticulina rotulata* (D-1H-1-11-13 cm)
14. *Lenticulina rotulata* (D-1H-1-129-133 cm)
16. *Lenticulina rotulata* (D-1H-2-25-29 cm)
17. *Lenticulina gibba* (C-2H-6-124-128 cm)
18. *Lenticulina gibba* (A-3H-3-134-138 cm)
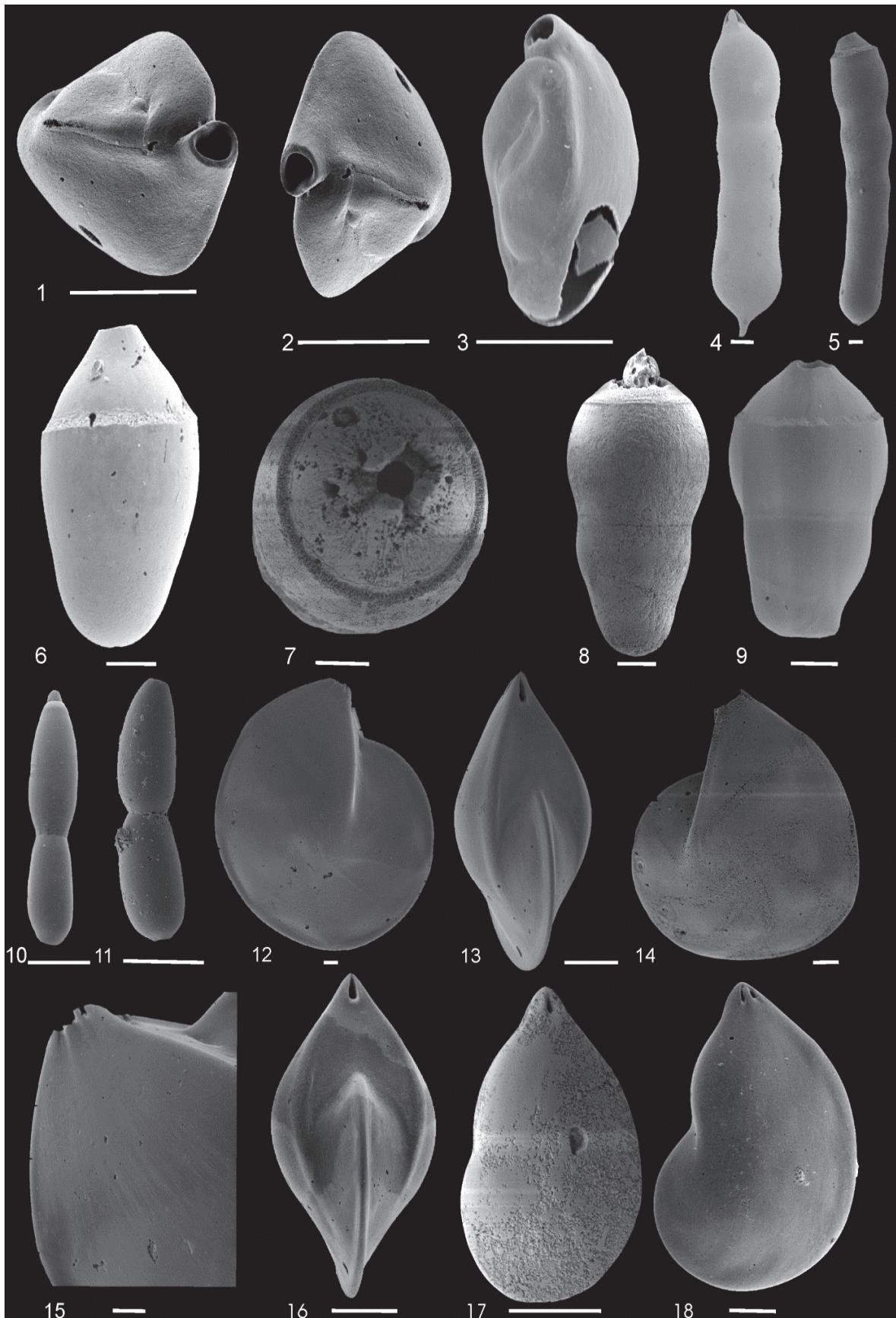
Plate 2.2

Plate 2.3
Scale bar = 100 μm (unless indicated)

1 - **3.** *Lenticulina gibba* (A-3H-3-134-138 cm)
4 - **5.** *Lenticulina gibba* (A-3H-3-134-138 cm)
6 - **7.** *Lenticulina gibba* (A-3H-5-36-39 cm)
8, 9, 11, 12. *Lagena hispida* (A-2H-5-65-67 cm)
10. *Lagena hispida* (A-2H-5-25-27 cm)
13, 14. *Lagena hispida* (A-2H-5-90-94 cm)
15. *Lagena hispida* (C-2H-6-98-100 cm)
16. *Lagena sulcata* (D-1H-1-139-141 cm)
17, 18. *Lagena sulcata* (D-1H-3-78-82 cm)
19. *Lagena nebulosa* (A-2H-5-76-79 cm)
20. *Lagena* sp. 1 (C-2H-5-50-53 cm)
21-22. *Lagena* sp.1 (C-2H-5-9-13 cm)
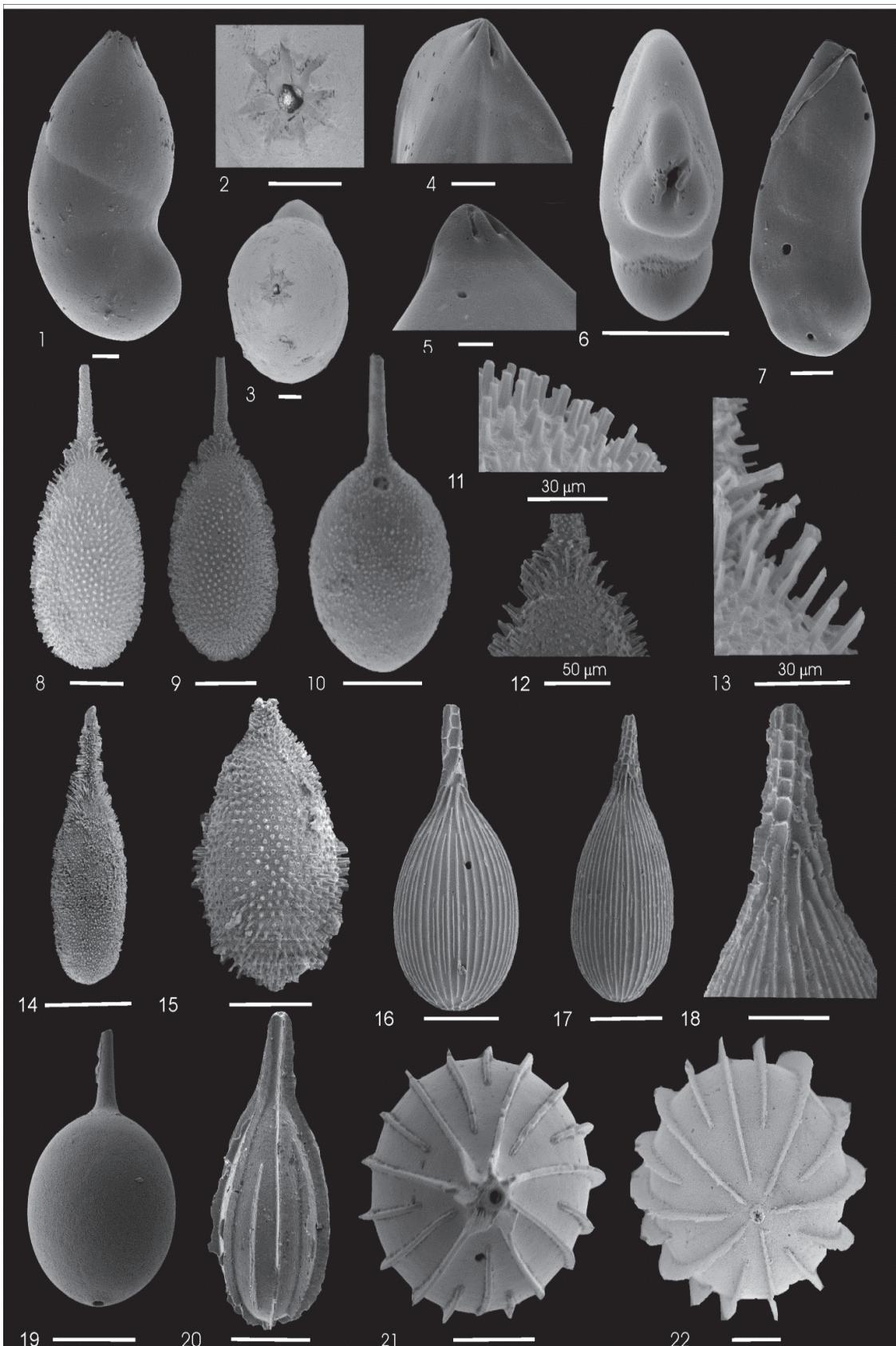
Plate 2.3

Plate 2.4
Scale bar = 100 μm (unless indicated)

1 - 2. *Lagena* sp.1 (C-2H-5-9-13 cm)
3 - 4. *Lagena* sp. 1 (D-2H-6-17-22 cm)
5, 6. *Lagena* sp. 2 (C-2H-6-114-115 cm)
7 - 11. *Lagena* sp. 3 (D-2H-6-17-22 cm)
12. *Procerolagena gracilis* (A-2H-3-102-104 cm)
13. *Procerolagena gracilis* (C-2H-7-0-2 cm)
14. *Procerolagena gracillima* (A-2H-51-53 cm)
15. *Procerolagena gracillima* (A-3H-5-145-147 cm)
16 - 17. *Reussoolina apiculata* (D-1H-1-11-13 cm)
18. *Reussoolina apiculata* (D-1H-2-89-93 cm)
19. *Reussoolina apiculata* (A-2H-5-115-119 cm)
20. *Cushmanina striatopunctata* (D-2H-6-17-22 cm)
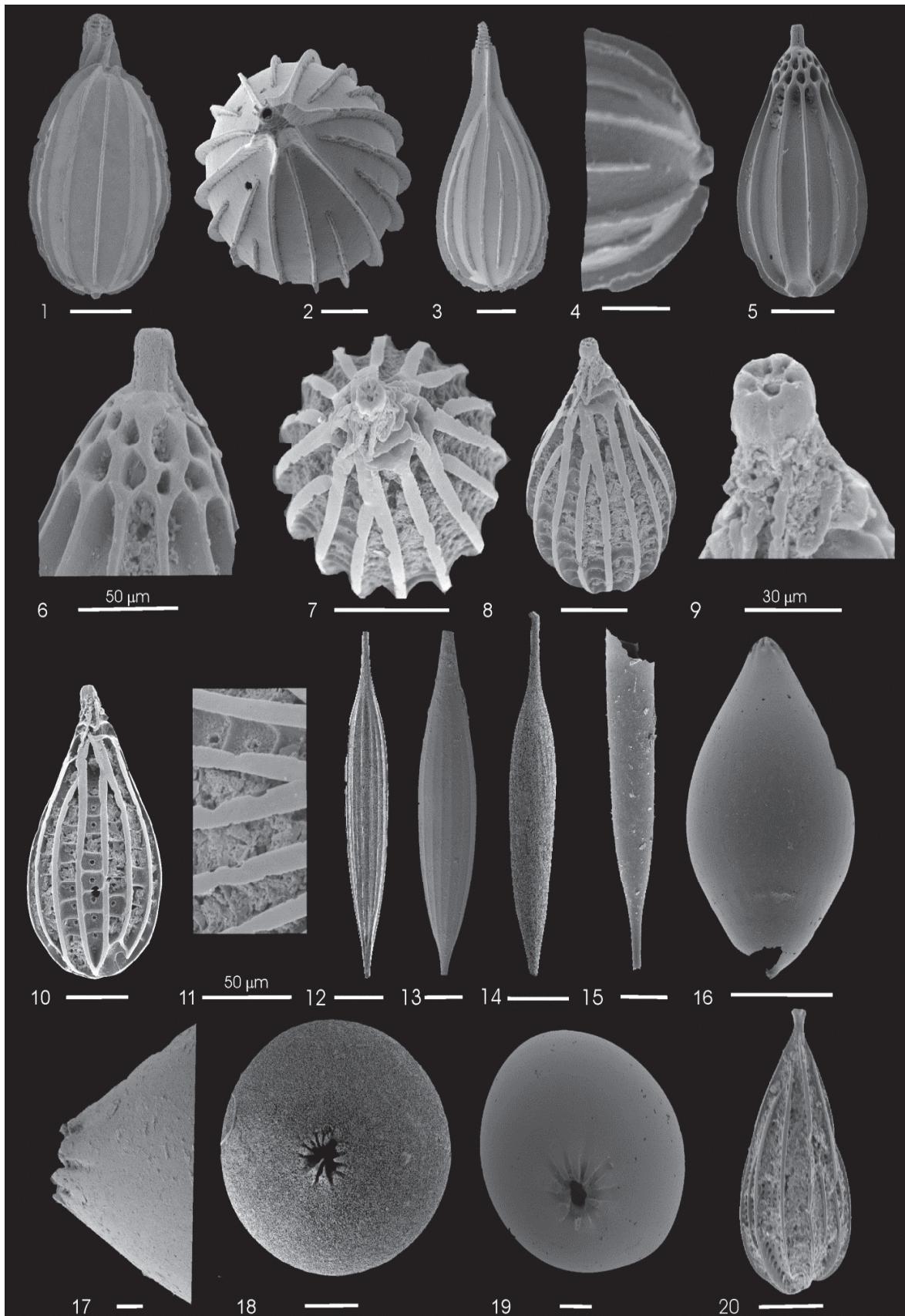
Plate 2.4

Plate 2.5
Scale bar = 100 μm (unless indicated)

1, 2. *Oolina hexagona* (A-3H-5-24-27 cm)
3. *Oolina hexagona* (A-3H-5-36-39 cm)
4 - 6. *Fissurina crebra* (D-1H-1-114-118 cm)
7. *Fissurina crebra* (A-2H-5-115-119)
8. *Fissurina crebra* (A-2H-5-65-67 cm)
9. *Fissurina crebra* (A-2H-6-81-84 cm)
10, 11. *Fissurina crebra* (A-3H-5-76-78 cm)
12, 13. *Fissurina minima* (D-2H-6-17-22 cm)
14, 15. *Fissurina minima* (C-2H-7-0-2 cm)
16. *Moncharmontzeiana petaloskelts* (A-3H-5-11-117 cm)
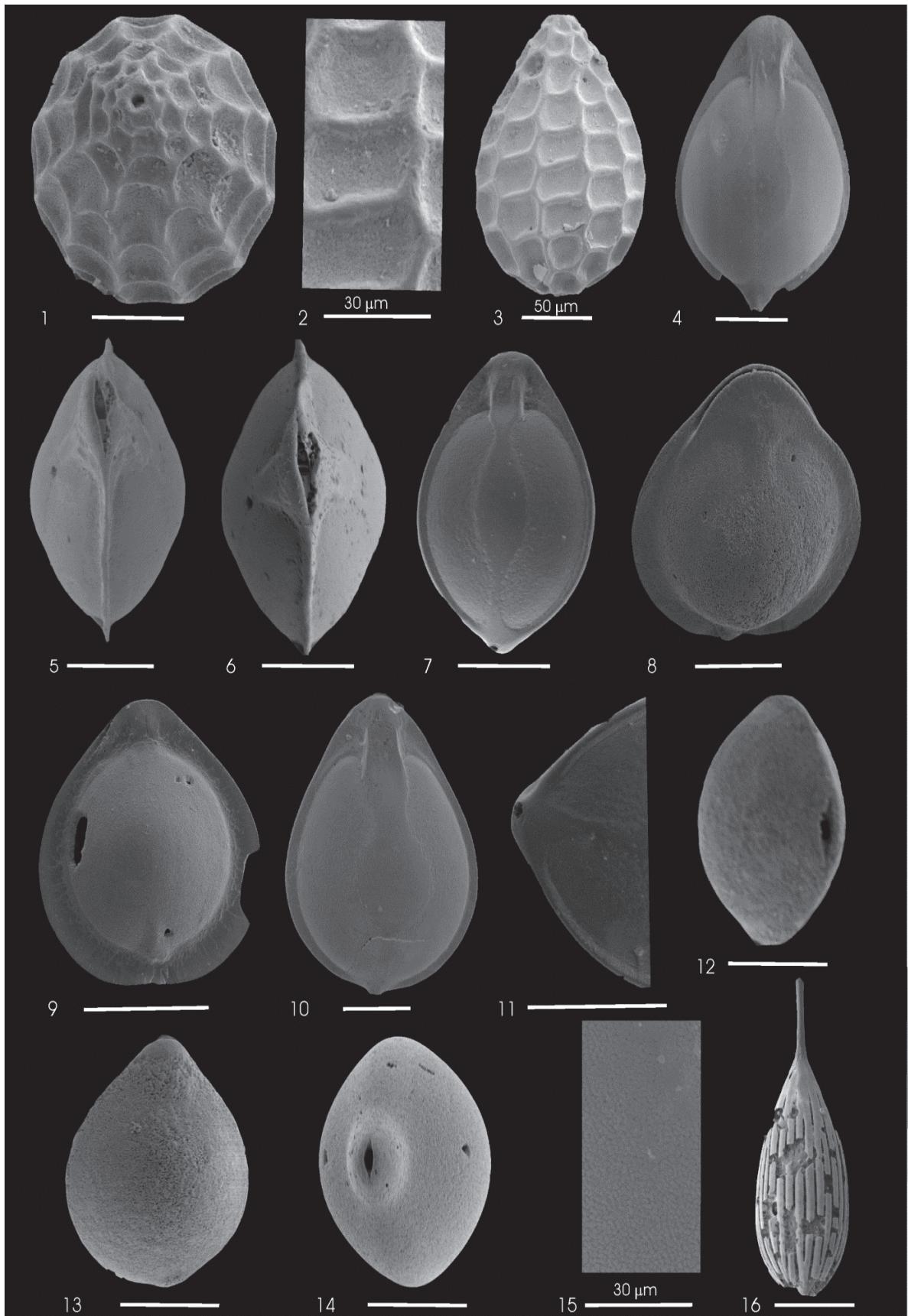
Plate 2.5

Plate 2.6
Scale bar = 100 μm (unless indicated)

1, 2. *Hoeglundina elegans* (D-1H-2-65-69 cm)
3. *Bolivina spissa* (D-1H-1-0-2 cm)
4. *Bolivina spissa* (D-1H-1-0-2 cm)
5, 6. *Bolivina spissa* (D-1H-1-0-2 cm)
7. *Bolivina spissa* (D-1H-1-0-2 cm)
8, 9, 10, 15. *Bolivina spissa* (D-1H-1-0-2 cm)
11. *Bolivina spissa* (D-1H-1-11-13 cm)
12 - 14. *Bolivina spissa* (D-1H-1-11-13 cm)
16. *Bolivina* sp. 1 (D-1H-1-0-2 cm)
17, 18. *Bolivina* sp. 1 (D-1H-1-0-2 cm)
19, 20. *Bolivina* sp. 1 (D-1H-1-26-28 cm)
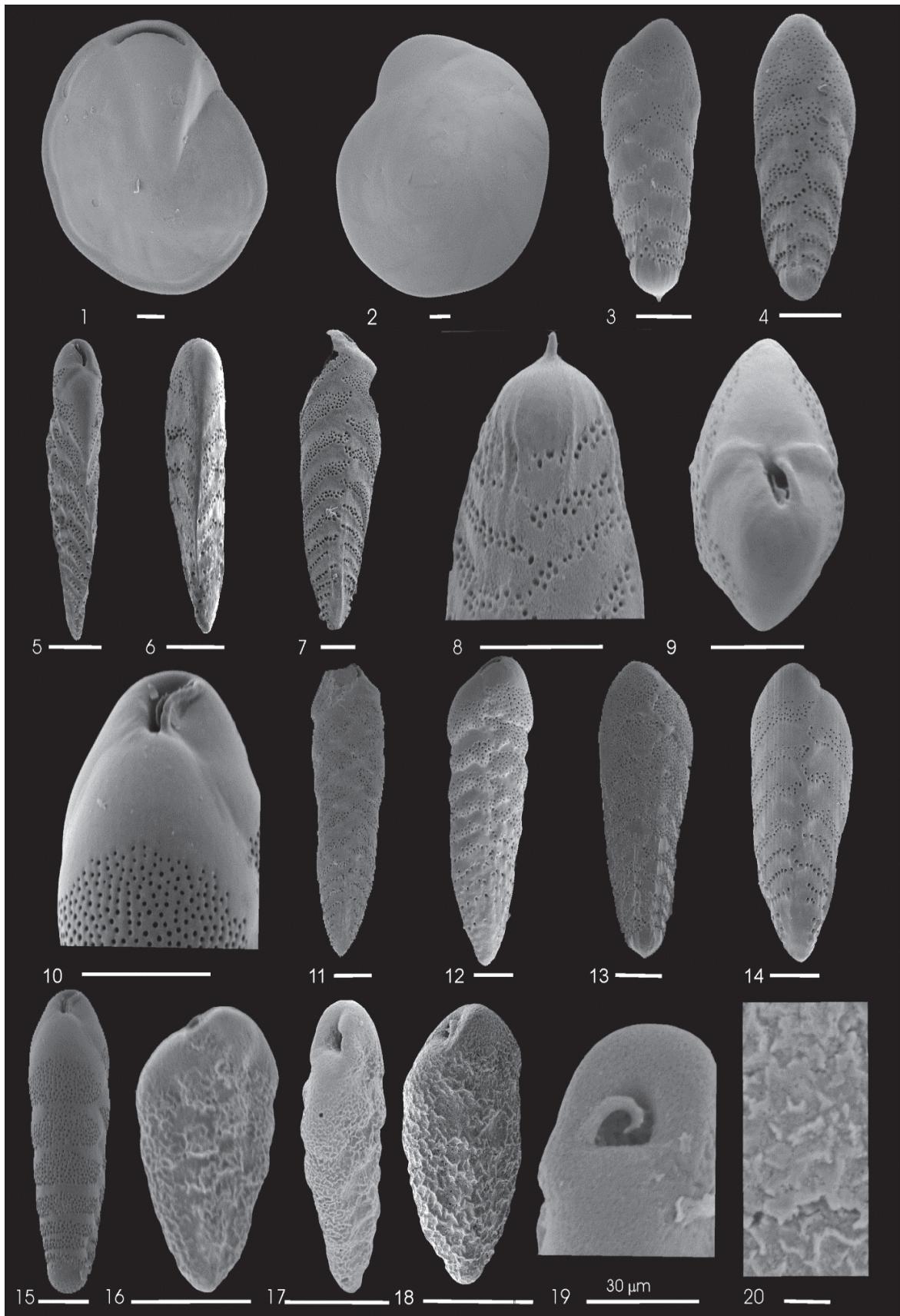
Plate 2.6

Plate 2.7
Scale bar = 100 μm (unless indicated)

1-3. *Bolivina* sp.1 (D-1H-1-0-2cm)
4. *Bolivina* sp. 2 (D-1H-1-139-141 cm)
5. *Bolivina* sp. 3 (D-1H-1-0-2 cm)
6. *Bolivina* sp. 3 (D-1H-1-139-141 cm)
7. *Bolivina* sp. 3 (D-1H-1-139-141 cm)
8, 9. *Bolivina* sp. 3 (D-1H-2-9-13 cm)
10. *Bolivina* sp. 3 (D-1H-2-75-80 cm)
11. *Bolivina* sp. 3 (D-1H-3-99-101 cm)
12, 13. *Bolivina* sp. 3 (D-1H-4-115-117 cm)
14. *Bolivina* sp. 3 (D-1H-4-92-94 cm)
15. *Bolivina* sp. 3 (A-2H-5-12-14 cm)
16. *Bolivina* sp. 3 (A-2H-6-40-46 cm)
17, 18. *Brizalina earlandi* (D-1H-1-0-2 cm)
19. *Brizalina earlandi* (D-1H-1-0-2 cm)
20. *Brizalina earlandi* (C-2H-7-25-27 cm)
21. *Brizalina earlandi* (D-1H-1-0-2 cm)

Plate 2.7

Plate 2.8
Scale bar = 100 μm (unless indicated)

1. *Brizalina alata* (D-1H-1-0-2 cm)
2. *Brizalina alata* (D-1H-1-26-28 cm)
3. *Brizalina alata* (D-1H-1-0-2 cm)
4 - 6. *Brizalina alata* (D-1H-1-0-2 cm)
7. *Brizalina alata* (D-1H-1-11-13 cm)
8, 9. *Brizalina alata* (D-1H-1-26-28 cm)
10. *Brizalina alata* (A-24-6-102-105 cm)
11, 12. *Cassidulina teretis* (D-1H-1-0-2 cm)
13. *Cassidulina teretis* (D-1H-1-39-41 cm)
14, 15. *Cassidulina teretis* (D-1H-1-39-41 cm)
16. *Cassidulina laevigata* (D-1H-2-49-53 cm)
17, 18. *Cassidulina laevigata* (D-1H-2-49-53 cm)
19. *Cassidulina laevigata* (D-1H-4-77-79 cm)
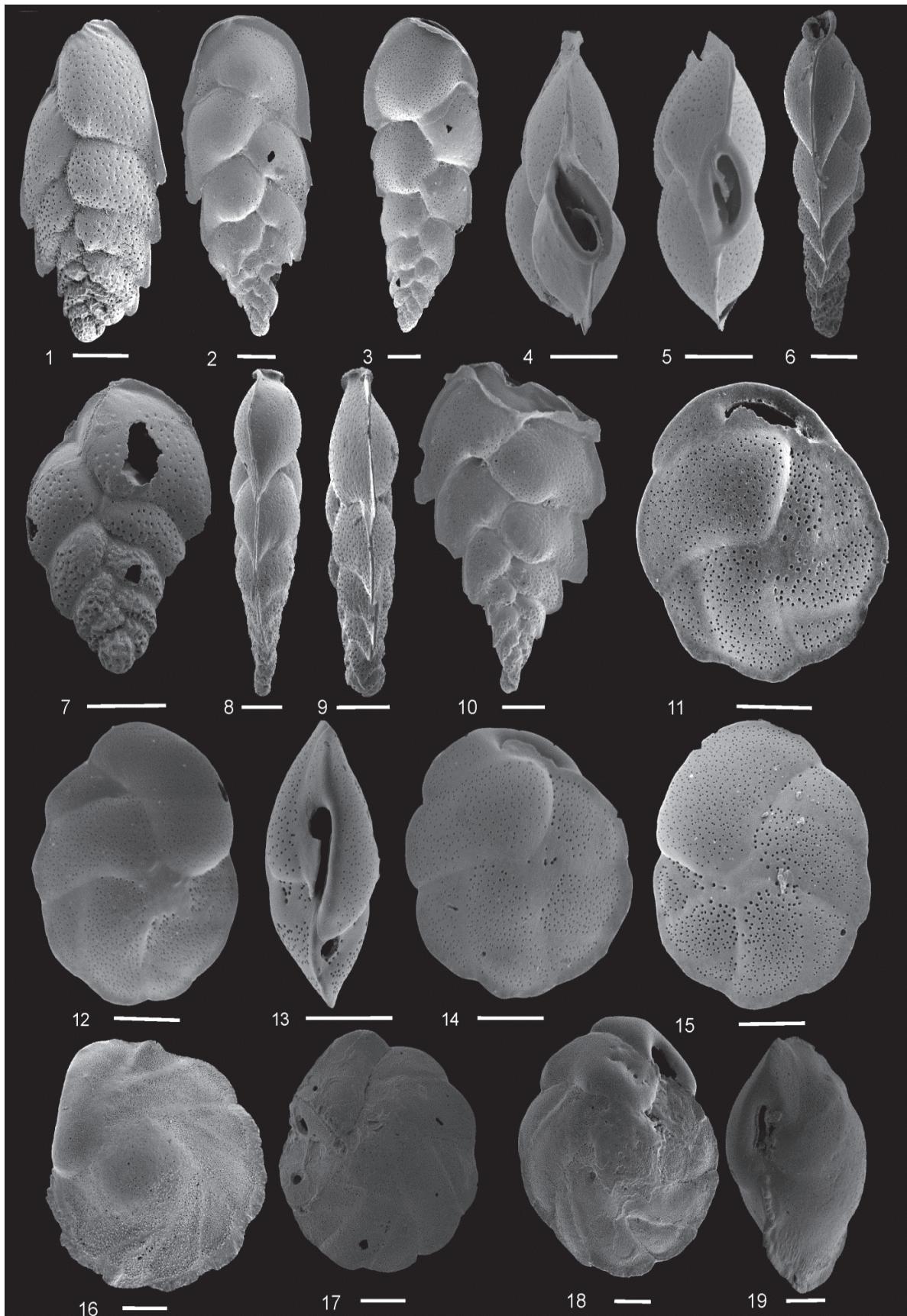
Plate 2.8

Plate 2.9
Scale bar = 100 μm (unless indicated)

1. *Cassidulina laevigata* (A 2H-5-115-119 cm)
2. *Cassidulinoidies parkerianus* (A-2H-3-99-101 cm)
3, 4. *Cassidulinoidies parkerianus* (D-1H-2-145-150 cm)
5. *Cassidulinoidies parkerianus* (A- 2H-3-61-64 cm)
6. *Cassidulina reniforme* (D-1H-39-41 cm)
7, 8, *Cassidulina reniforme* (D-1H-114-118 cm)
9, 10. *Cassidulina reniforme* (D-1H-114-118 cm)
11 - 14. *Cassidulina reniforme* (D-1H-39-41 cm)
15. *Globocassidulina subglobosa* (D-1H-1-39-41 cm)
16. *Globocassidulina subglobosa* (C-2H-6-108-112 cm)
17. *Globocassidulina subglobosa* (D-1H-1-39-41 cm)
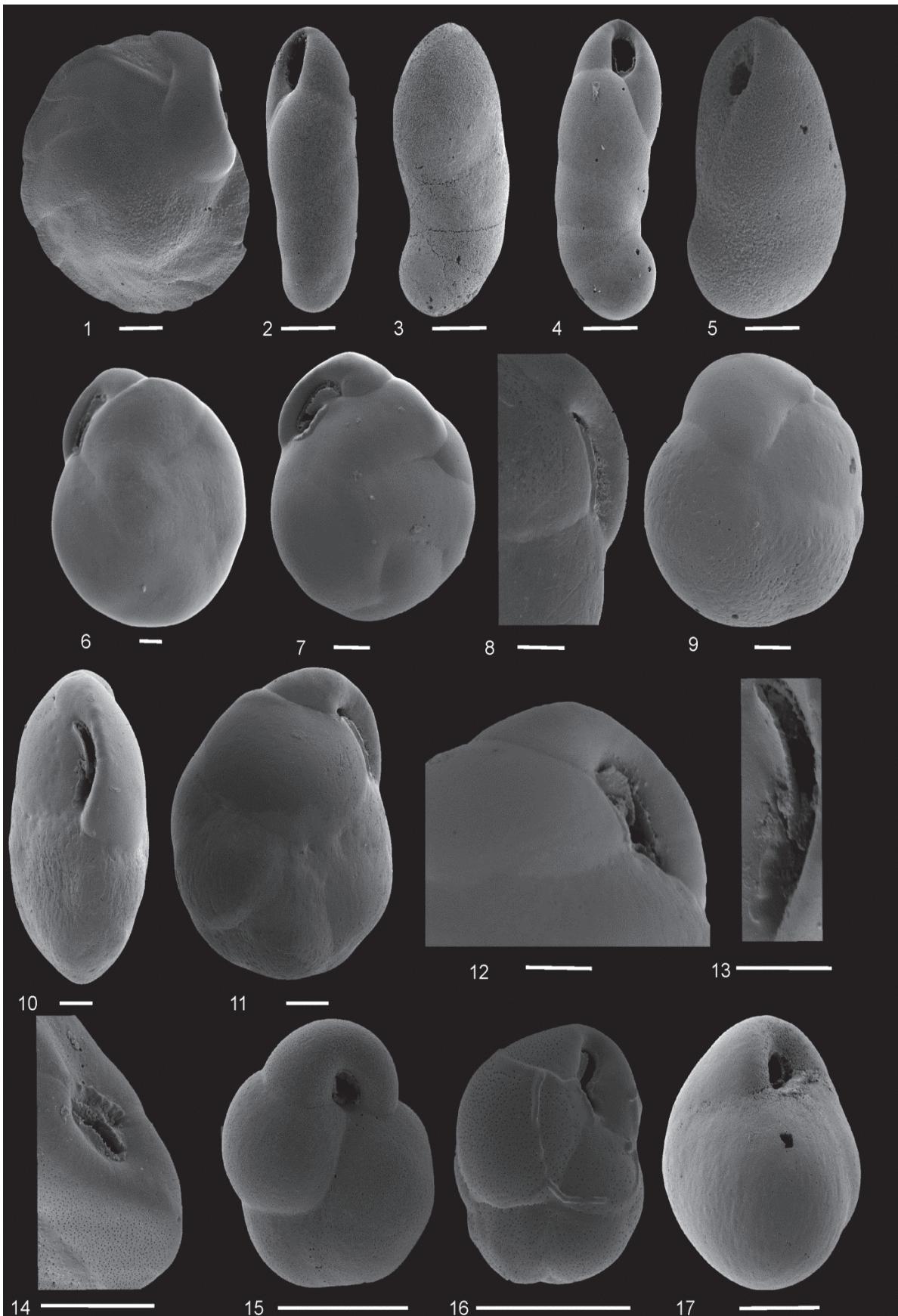
Plate 2.9

Plate 2.10
Scale bar = 100 μm (unless indicated)

1. *Globocassidulina subglobosa* (D-1H-1-75-79 cm)
2. *Islandiella norcrossi* (D-1H-1-39-41 cm)
3. *Islandiella norcrossi* (A-3H-3-124-128 cm)
4. *Islandiella norcrossi* (D-1H-1-39-41 cm)
5. *Islandiella norcrossi* (D-1H-2-105-109 cm)
6. *Islandiella norcrossi* (D-1H-2-129-133 cm)
7. *Takayanagia delicata* (D-1H-1-0-2 cm)
8. *Takayanagia delicata* (D-1H-1-11-13 cm)
9. *Takayanagia delicata* (D-1H-2-105-109 cm)
10. *Takayanagia delicata* (A-2H-6-128-130 cm)
11, 12. *Takayanagia delicata* (D-1H-1-26-28 cm)
13. *Takayanagia delicata* (A-2H-3-76-78)
14. *Ehrenbergina* sp. (D-1H-1-0-2 cm)
15. *Ehrenbergina* sp. (D-1H-1-11-13 cm)
16. *Ehrenbergina* sp. (D-1H-1-75-79 cm)
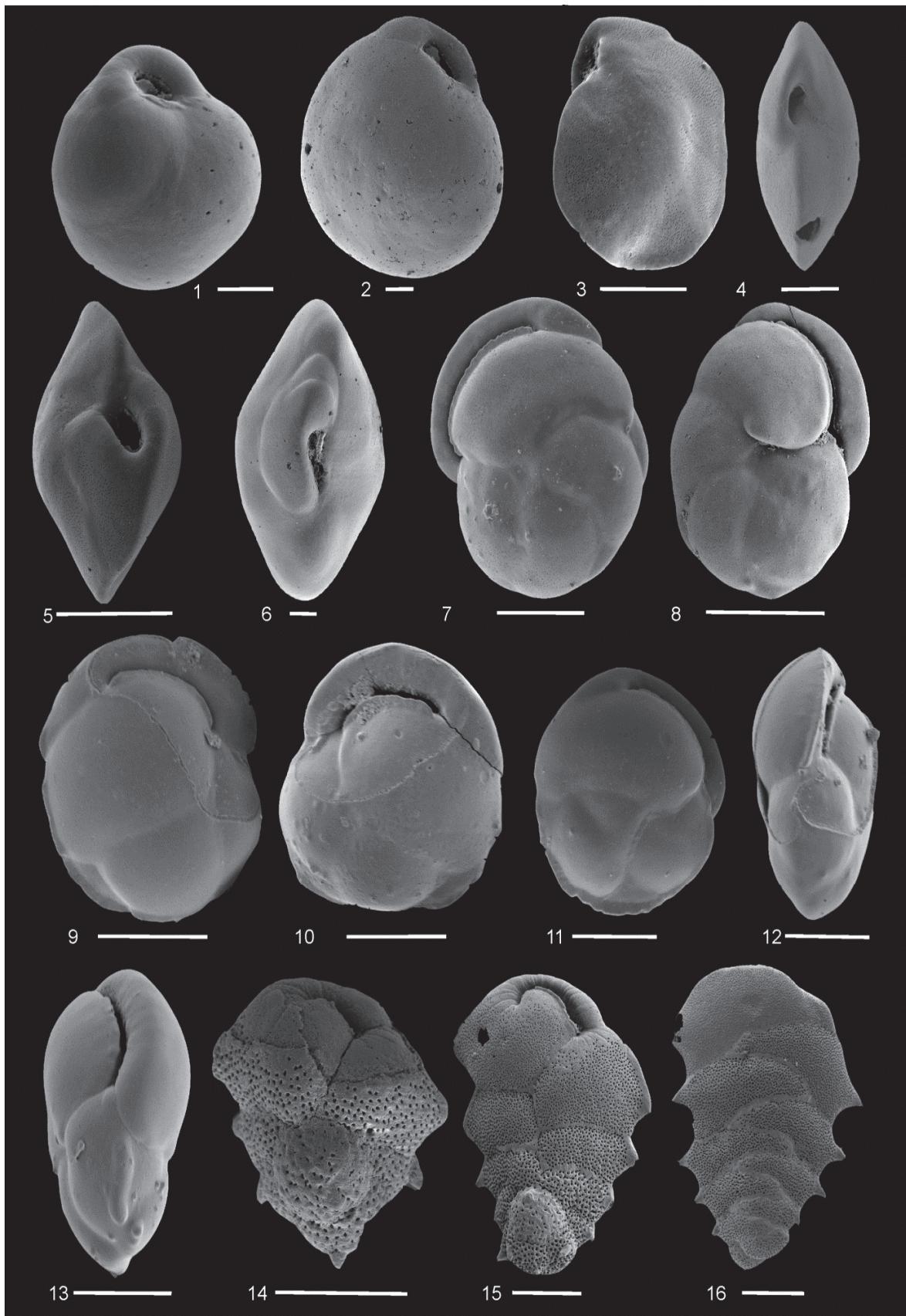
Plate 2.10

Plate 2.11
Scale bar = 100 μm (unless indicated)

1. *Ehrenbergina* sp. (D-1-H-1-26-28)
2. *Ehrenbergina* sp. (D-1-H-1-26-28 cm)
3. *Ehrenbergina* sp. (D-1H-1- 75-79 cm)
4. *Ehrenbergina* sp. (A 2H-5-37-39 cm)
5. *Ehrenbergina* sp. (D-1H-1- 75-79 cm)
6 - 9. *Ehrenbergina* sp. (A-2H-5-37-39)
10. *Ehrenbergina* sp. (D-1H-1-0-2 cm)
11. *Stainforthia fusiformis* (D-1H-1-0-2 cm)
12. *Stainforthia fusiformis* (A-2H-5-105-109 cm)
13. *Stainforthia fusiformis* (A-2h-6-130-134 cm)
14, 15. *Stainforthia fusiformis* (A-2h-6-130-134 cm)
16. *Bulimina exilis* (D-1H-1-0-2 cm)
17. *Bulimina exilis* (D-1H-1-0-2 cm)
18 - 20. *Bulimina exilis* (D-1H-2-26-28 cm)
21. *Bulimina exilis* (D-1H-2-89-93)
22. *Bulimina exilis* (D-1H-2-105-109 cm)
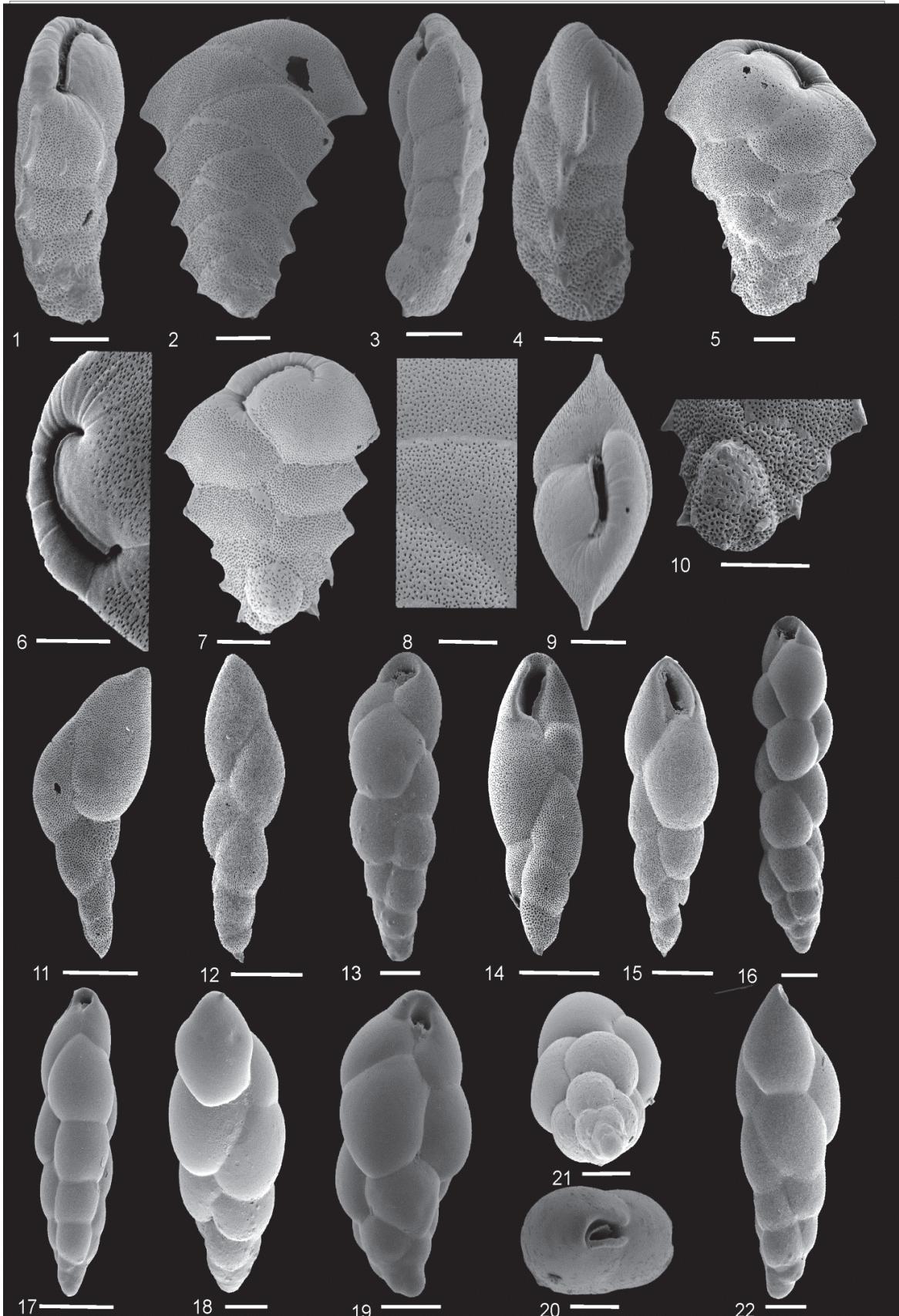
Plate 2.11

Plate 2.12
Scale bar = 100 μm (unless indicated)

1. *Bulimina exilis* (D-1H-1-0-2 cm)
2 - 4. *Bulimina mexicana* (D-1H-1-11-13 cm)
5. *Bulimina mexicana* (D-1H-1-89-93 cm)
6. *Bulimina mexicana* (D-1H-1-89-93 cm)
7. *Globobulimina auriculata* (D-1H-3-10-13 cm)
8. *Globobulimina auriculata* (D-1H-3-10-13 cm)
9. *Globobulimina auriculata* (A-2H-5-115-119 cm)
10, 11. *Globobulimina auriculata* (A-2H-6-113-117 cm)
12. *Globobulimina pacifica* (D-1H-1-26-28 cm)
13. *Globobulimina pacifica* (D-1H-1-26-28 cm)
14. *Globobulimina pacifica* (D-1H-1-1-39-41)
15. *Globobulimina pacifica* (D-1H-2-105-109 cm)
16. *Globobulimina pacifica* (D-1H-2-105-109 cm)
17. *Globobulimina pacifica* (D-1H-2-105-109 cm)
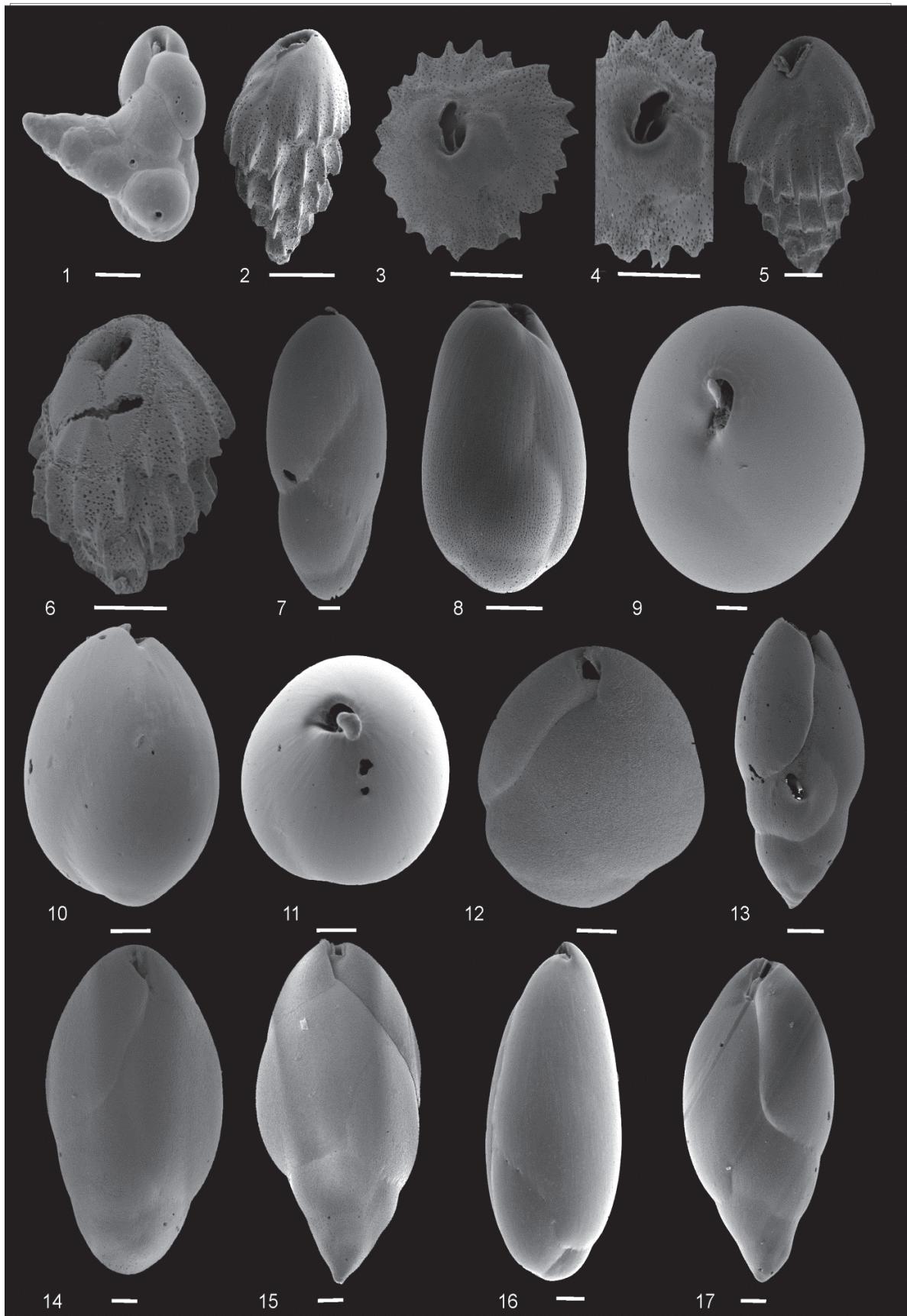
Plate 2.12

Plate 2.13
Scale bar = 100 μm (unless indicated)

1, 3, 4, 5. *Globobulimina pacifica* (D-1h-2-1050109 cm)
2. *Globobulimina pacifica* (D-1H-2-105-109 cm)
6. *Globobulimina pacifica* (C-2H-5-25-28 cm)
7. *Uvigerina bifurcata* (D-1H-1-0-2 cm)
8. *Uvigerina bifurcata* (D-1H-1-0-2 cm)
9, 10. *Uvigerina bifurcata* (D-1H-1-0-2 cm)
11. *Uvigerina bifurcata* (C-2H-4-102-106 cm)
12. *Uvigerina bifurcata* (C-2H-4-102-106 cm)
13, 14. *Uvigerina bifurcata* (C-2H-4-102-106 cm)
15. *Uvigerina bifurcata* (C-2H-5-25-28 cm)
16. *Uvigerina bifurcata* (C-2H-5-25-28 cm)
17. *Uvigerina bifurcata* (C-2H-5-25-28 cm)
18. *Uvigerina bifurcata* (C-2H-5-25-28 cm)
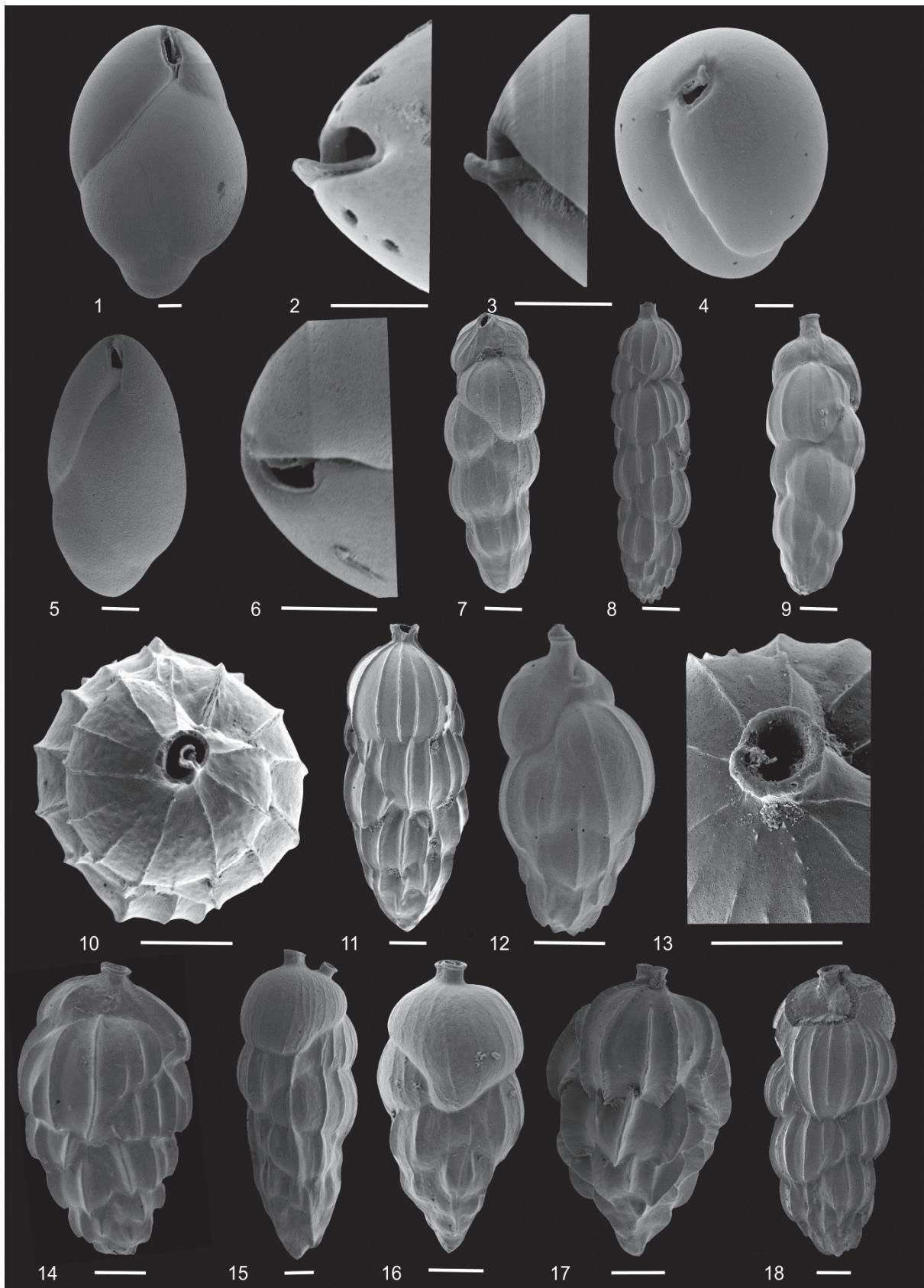
Plate 2.13

Plate 2.14
Scale bar = 100 μm (unless indicated)

1. *Uvigerina bifurcata* (C-2H-6-46-52 cm)
2. *Uvigerina bifurcata* (C-2H-6-46-52 cm)
3. *Uvigerina bifurcata* (C-2H-6-46-52 cm)
4. *Uvigerina hispida* (D-1H-4-77-79 cm)
5. *Uvigerina hispida* (D-1H-4-77-79 cm)
6. *Uvigerina hispida* (D-1H-4-77-79 cm)
7, 8. *Uvigerina hispida* (D-1H-4-77-79 cm)
9. *Uvigerina hispida* (D-1H-4-77-79 cm)
10. *Uvigerina hispida* (D-1H-1-0-2 cm)
11, 12. *Uvigerina hispida* (A-2H-3-117-119)
13. *Uvigerina senticosa* (D-1H-1-139-141 cm)
14. *Uvigerina senticosa* (D-1H-3-67-69 cm)
15. *Uvigerina senticosa* (D-1H-3-67-69 cm)
16, 17. *Uvigerina senticosa* (D-1H-4-77-79 cm)
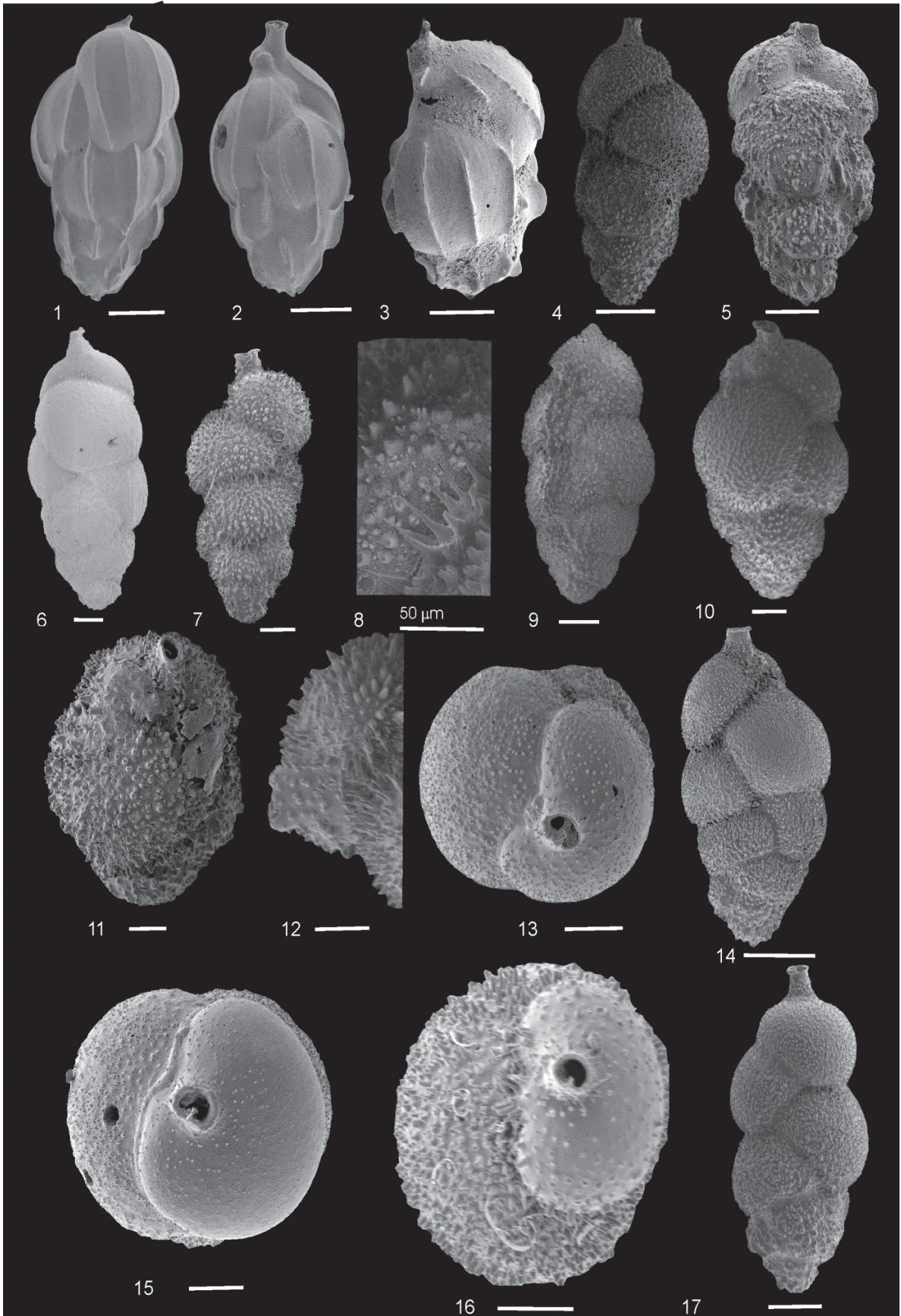
Plate 2.14

Plate 2.15
Scale bar = 100 μm (unless indicated)

1. *Uvigerina peregrina* (D-1H-1-75-79 cm)
2. *Uvigerina peregrina* (D-1H-1-75-79 cm)
3. *Uvigerina peregrina* (D-1H-1-75-79 cm)
4. *Uvigerina peregrina* (D-1H-1-75-79 cm)
5. *Uvigerina peregrina* (D-1H-1-0-2 cm)
6 - 9. *Uvigerina peregrina* (D-1H-1-0-2 cm)
10. *Uvigerina peregrina* (D-1H-1-0-2 cm)
11. *Uvigerina peregrina* (D-1H-2-115-120 cm)
12. *Uvigerina peregrina* (D-1H-1-75-79 cm)
13. *Uvigerina peregrina* (D-1H-1-52-56 cm)
14. *Uvigerina peregrina* (A-2H-3-102-104 cm)
15. *Uvigerina peregrina* (D-1H-1-139-141 cm)
16. *Uvigerina peregrina* (D-1H-2-115-120 cm)
17. *Uvigerina* sp. 1 (D-1H-1-0-2 cm)
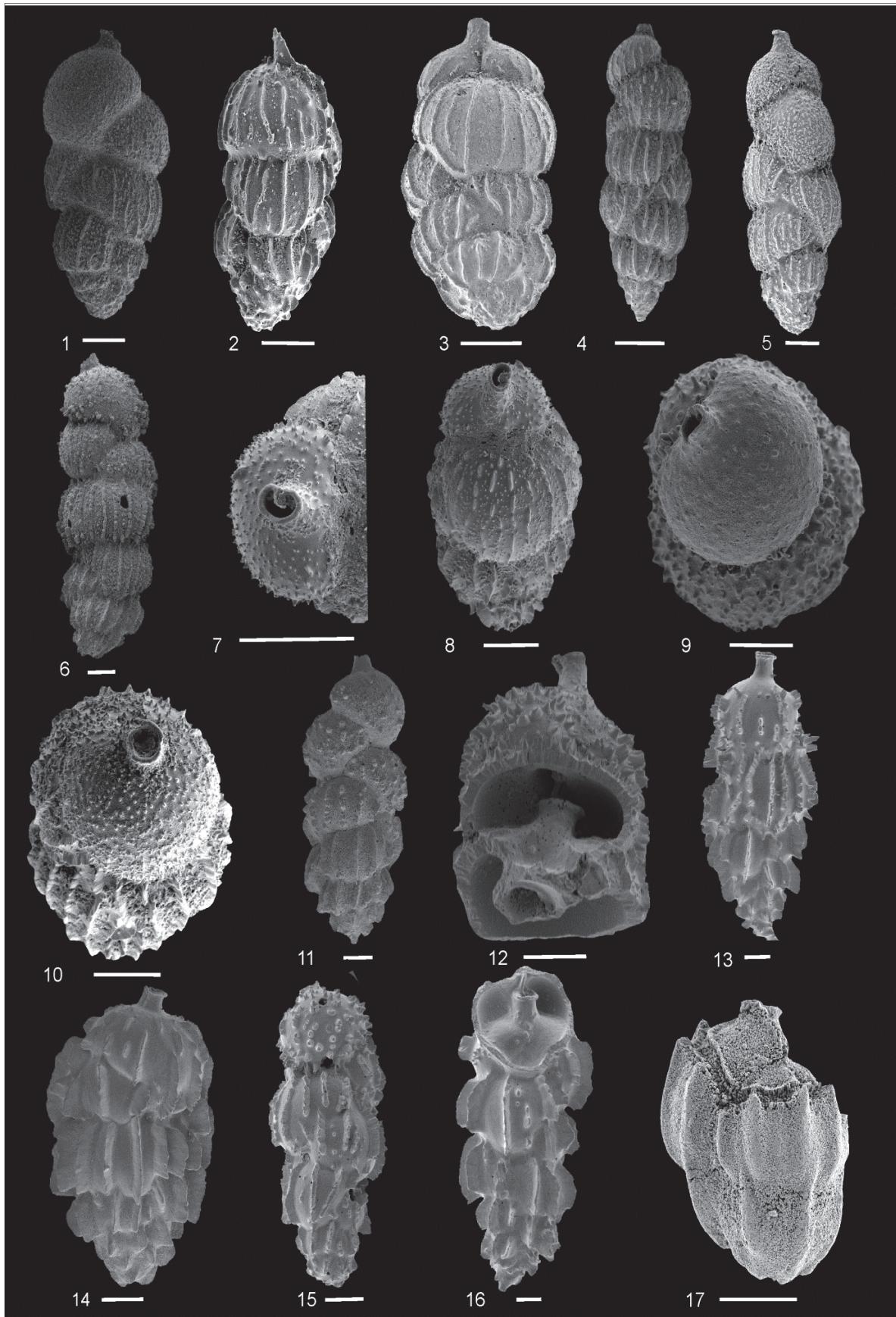
Plate 2.15

Plate 2.16
Scale bar = 100 μm (unless indicated)

1 - **4.** *Uvigerina* sp.1 (D-1H-1-0-2 cm)
5, 6. *Uvigerina* sp.1 (D-1H-3-99-101 cm)
7. *Uvigerina* sp.1 (D-1H-3-99-101 cm)
8. *Uvigerina* sp.1 (A-2H-3-117-119 cm)
9. *Angulogerina angulosa* (D-1H-1-114-118 cm)
10. *Angulogerina angulosa* (D-1H-1-114-118 cm)
11, 12. *Angulogerina angulosa* (D-1H-1-0-2 cm)
13. *Angulogerina angulosa* (D-1H-1-114-118 cm)
14. *Fursenkoina* aff. *texturata* (D-1H-1-11-13 cm)
15. *Fursenkoina* aff. *texturata* (C-2H-5-39-42 cm)
16 - **18.** *Fursenkoina* aff. *texturata* (C-2H-5-107-108 cm)
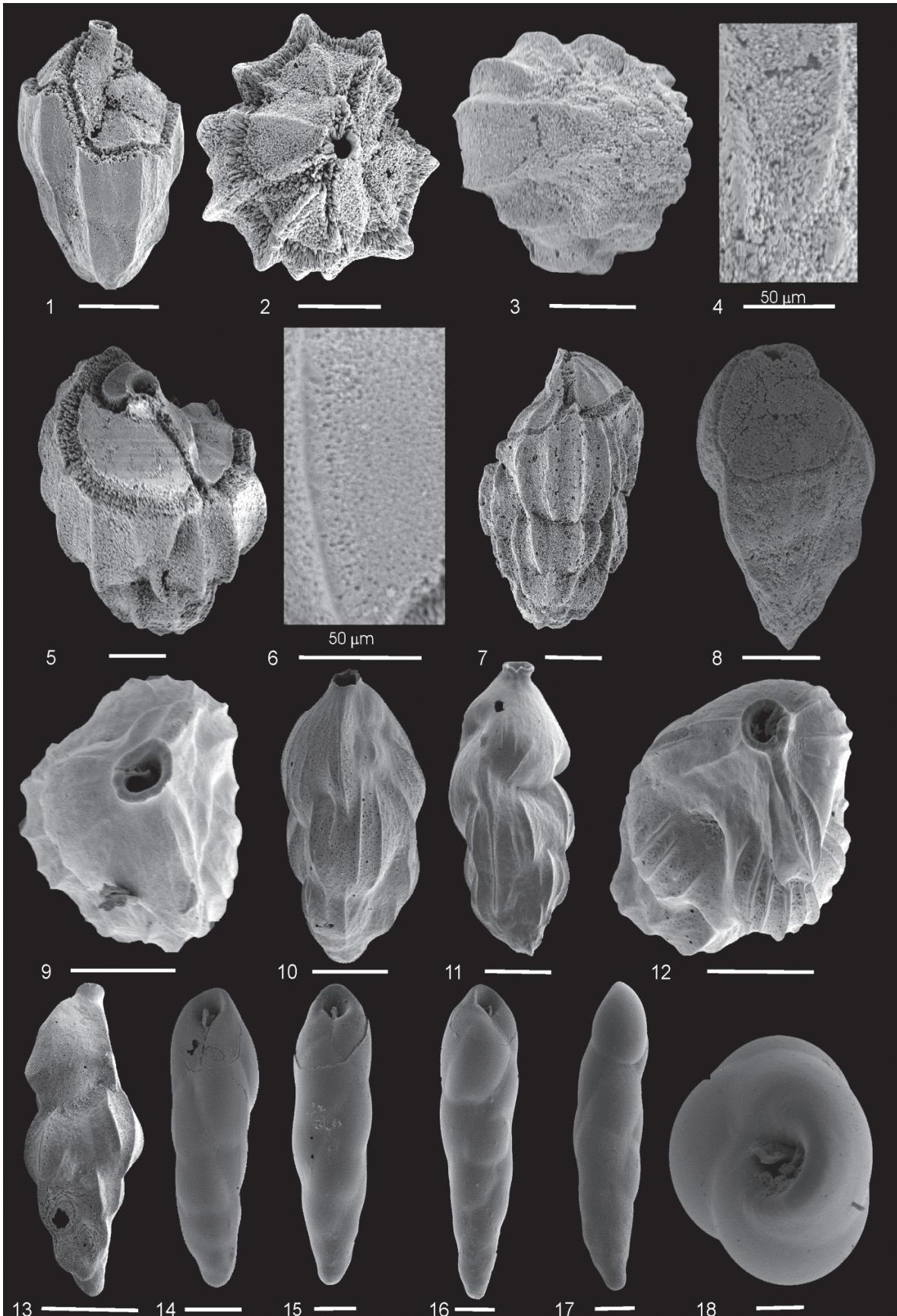
Plate 2.16

Plate 2.17
Scale bar = 100 μm (unless indicated)

1 - 3. *Fursenkoina* aff. *texturata* (C-2H-5-107-108 cm)
4. *Valvulineria araucana* (C-2H-4-102-108 cm)
5, 6. *Valvulineria araucana* (C-2H-4-102-106 cm)
7. *Valvulineria araucana* (C-2H-4-102-106 cm)
8. *Valvulineria araucana* (C-2H-6-48-52 cm)
9, 10. *Valvulineria araucana* (C-2H-6-48-52 cm)
11. *Valvulineria araucana*: apertural view (C-2H-4-127-131 cm)
12. *Valvulineria araucana* (C-2H-7-0-2 cm)
13. *Alabaminella weddellensis* (A-2H-5-65-67 cm)
14, 15. *Alabaminella weddellensis* (A-2H-6-93-97 cm)
16. *Alabaminella weddellensis* (A-2H-6-113-117 cm)
17. *Alabaminella weddellensis* (C-2H-5-9-13 cm)

Plate 2.17

Plate 2.18
Scale bar = 100 μm (unless indicated)

1, 2. *Cibicidoides* sp. (A-2H-3-102-104 cm)
3, 4. *Cibicidoides* sp. (C-2H-7-25-27 cm)
5. *Cibicidoides* sp. *(*A-3H-5-24-27 cm)
6 - 8. *Epistominella exigua* (C-2H-5-120-121 cm)
9 - 11. *Epistominella exigua* (C- 2H-5-120-121 cm)
12, 13. *Epistominella exigua* (C-2H-6-114-115 cm)
14, 15. *Epistominella pulchella* (D-1H-3-99-101 cm)
16. *Epistominella pulchella* (D-1H-1-0-2 cm)
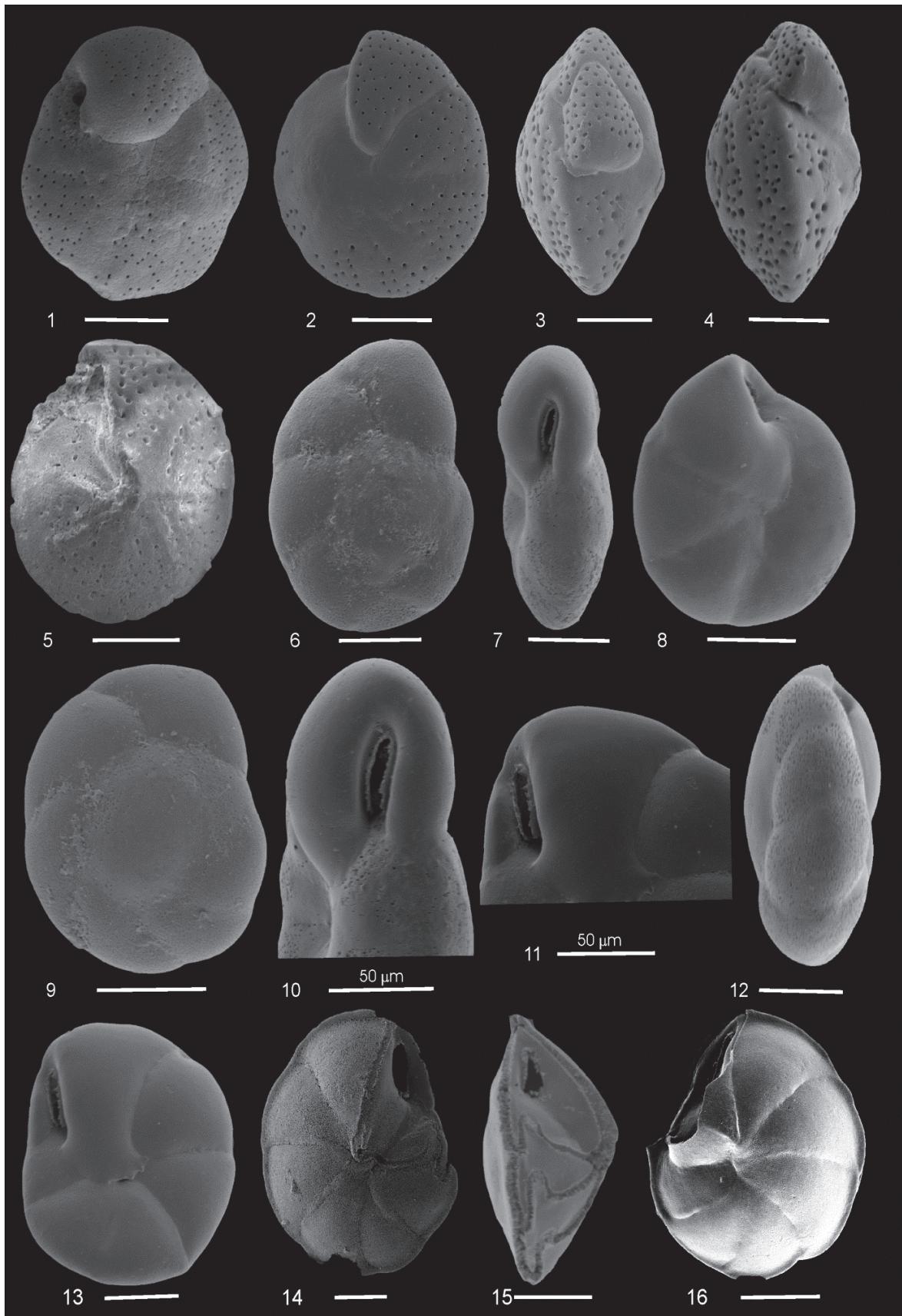
Plate 2.18

Plate 2.19
Scale bar = 100 μm (unless indicated)

1 - 3. *Epistominella pulchella* (D-1H-3-67-69 cm)
4. *Planulina ariminensis* (D-1H-1-11-13 cm)
5, 6. *Planulina ariminensis* (C-2H-6-98-100 cm)
7, 8. *Planulina wuellerstorfi* (D-1H-1-75-79 cm)
9, 10. *Planulina wuellerstorfi* (D-1H-2-75-79)
11, 12, *Planulina wuellerstorfi* (D-1H-2-49-53 cm)
13. *Planulina wuellerstorfi* (C-2H-6-108-112 cm)
14 - 16. *Planulina wuellerstorfi* (C-24-6-108-112 cm)
17. *Planulina wuellerstorfi* (C-2H-6-108-112 cm)
18. *Planulina wuellerstorfi* (A-3H-3-134-138 cm)
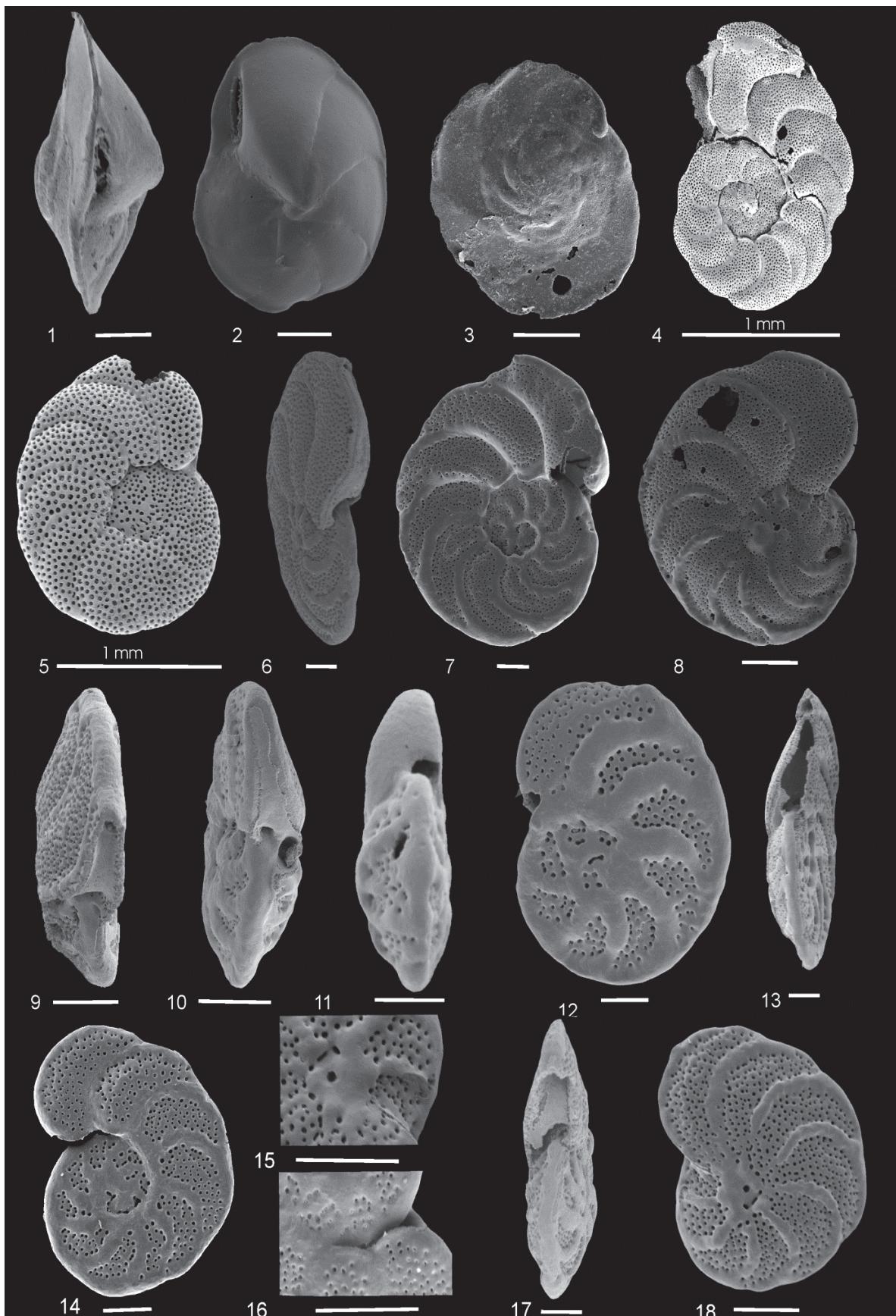
Plate 2.19

Plate 2.20
Scale bar = 100 μm (unless indicated)

1, 2. *Nonionella labradorica* (D-1H-1-39-41 cm)
3. *Nonionella labradorica* (D-1H-1-39-41 cm)
4, 5. *Nonionella labradorica* (A-2H-3-90-92 cm)
6. *Nonionella digitata* (C-2H-6-98-100 cm)
7. *Melonis barleeanus* (C-2H-4-127-131)
8. *Melonis barleeanus* (C-2H-5-120-121 cm)
9 - 12. *Melonis barleeanus* (C-2H-5-120-121 cm)
13. *Pullenia simplex* (D-1H-1-39-41 cm)
14. *Pullenia simplex* (D-1H-1-39-41 cm)
15. *Pullenia simplex* (1H-1-129-133 cm)
16. *Pullenia simplex* (D-1H-3-67-69)
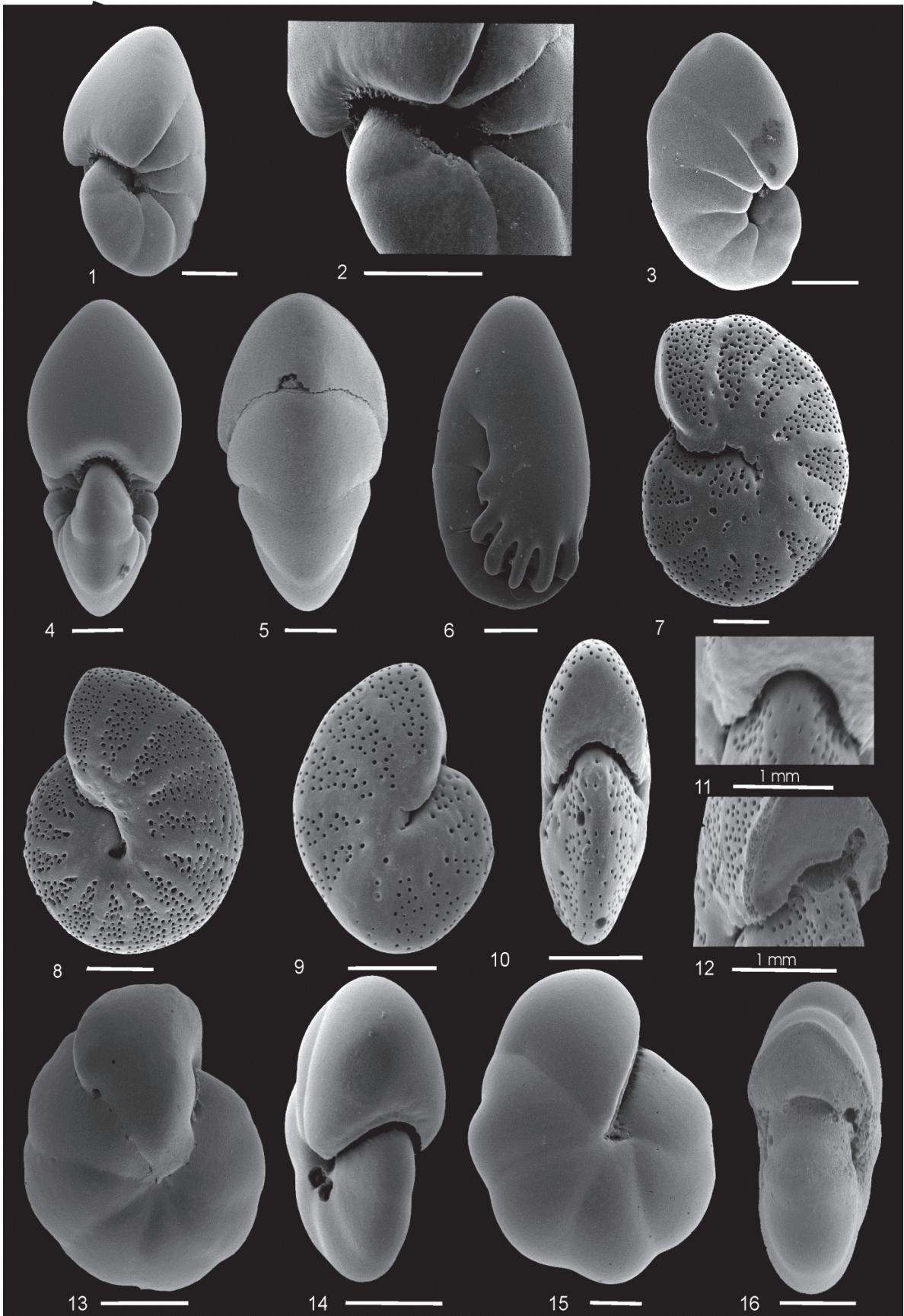
Plate 2.20

Plate 2.21
Scale bar = 100 μm (unless indicated)

1, 2. *Oridorsalis umbonatus* (D-1H-1-0-2 cm)
3, 4. *Oridorsalis umbonatus* (D-1H-1-0-2 cm)
5 - 8. *Oridorsalis umbonatus* (D-1H-1-11-13 cm)
9. *Oridorsalis umbonatus* (D-1H-1-11-13 cm)
10. *Oridorsalis umbonatus* (D-1H-4-77-79 cm)
11. *Gyroidina* sp. 1 (A-3H-5-12-15 cm)
12. *Gyroidina* sp. 1(A-3H-5-91-92 cm)
13. *Gyroidina* sp. 2 (D-1H-2-75-80 cm)
14. *Gyroidina* sp. 2 (D-1H-4-106-108 cm)
15. *Gyroidina* sp. 2 (A-2H-6-102-105 cm)
16. *Gyroidina* sp. 2 (A-2H-6-102-105 cm)
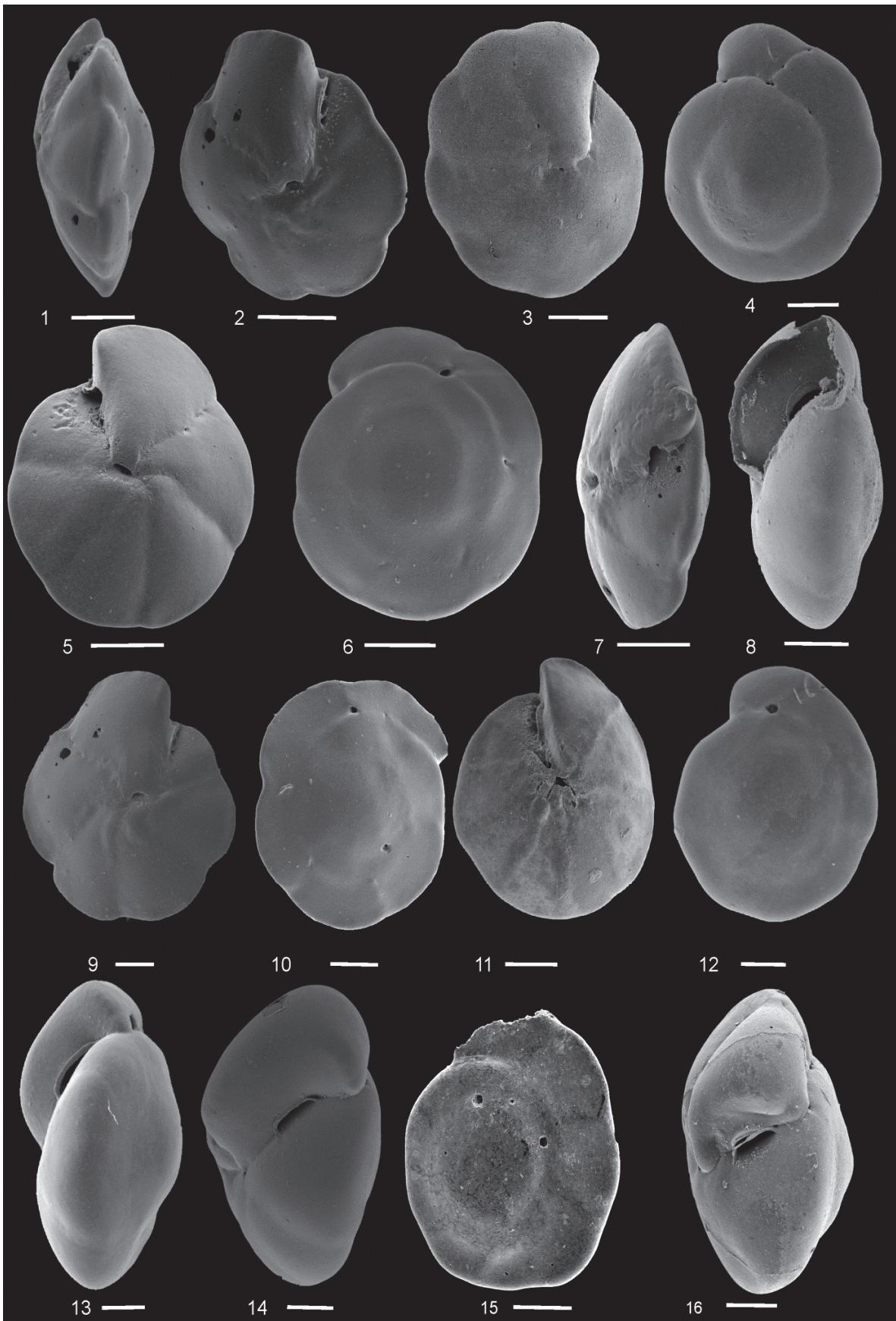
Plate 2.21

Plate 2.22

Scale bar = 100 μm (unless indicated)

1 - 3. *Gyroidina* sp. 2 (C-2H-4-102-106 cm)
4. *Gyroidina* sp. 2 (A-2H-6-102-106 cm)
5. *Elphidium ustulatum* (D-1H-4-92-94 cm)
6. *Elphidium ustulatum* (D-1H-4-92-94 cm)
7, 8. *Elphidium ustulatum* (D-1H-4-92-94 cm)
9. *Elphidium* sp. 1 (D-1H-1-139-141 cm)
10. *Elphidium* sp. 1 (D-1H-1-139-141 cm)
11. *Elphidium* sp**.** 1 (D-1H-4-92-94 cm)
12. *Elphidium* sp. 2 (C-2H-4-102-106 cm)
13. *Elphidium* sp. 2 (C-2H-4-102-106 cm)
14. *Elphidium* sp. 3 (C-3H-6-114-115 cm)
15. *Elphidium* sp. 3 (A-3H-5-H3-117 cm)
16, 17. *Elphidium* sp. 3 (A-3H-3-134-138 cm)
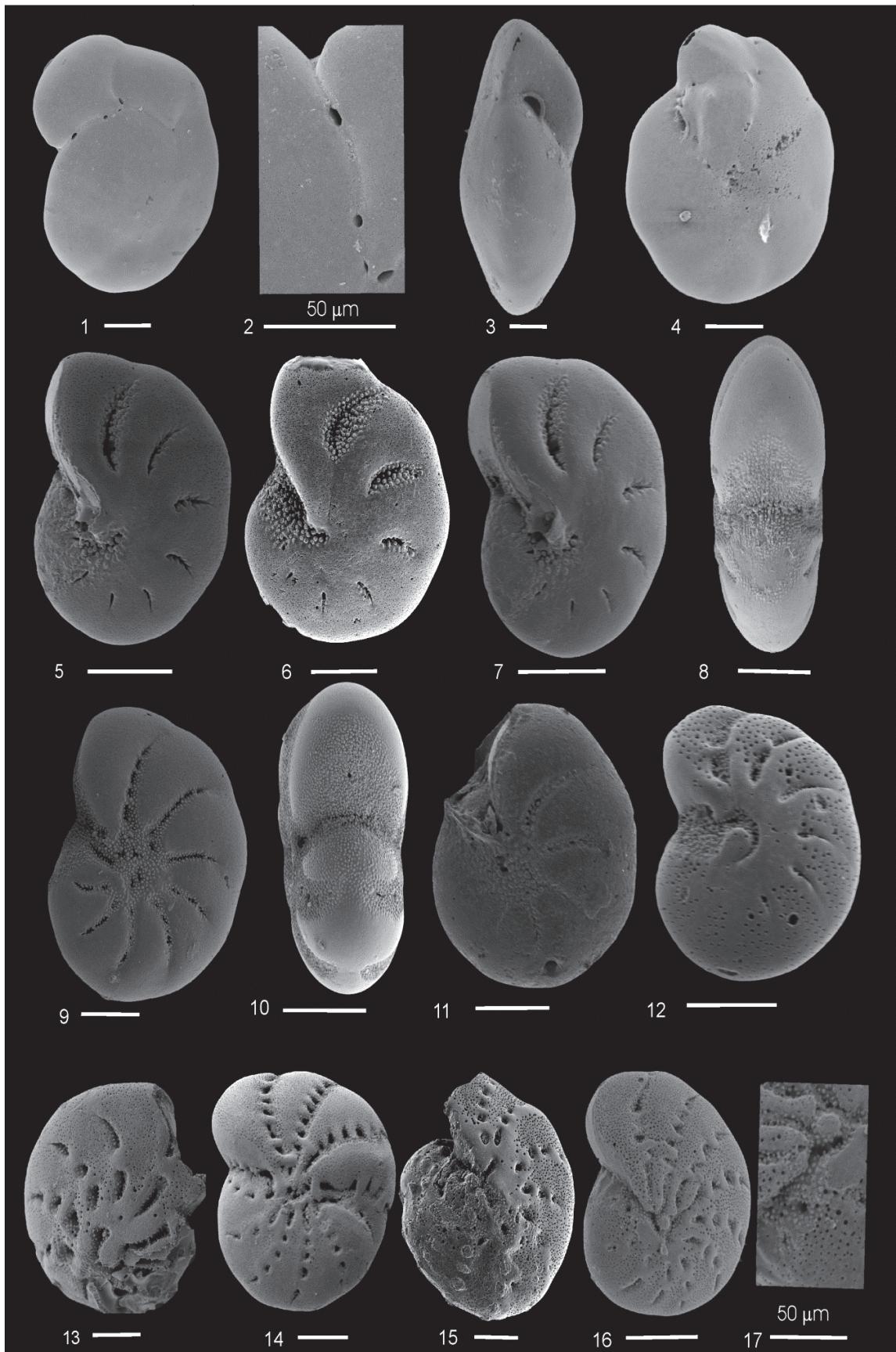
Plate 2.22

Chapter 3

Pore density in the benthic foraminifer *Bolivina spissa* (Cushman) from the Bering Sea: a realistic test of seabed oxygen conditions?

Chapter 3: Pore density in the benthic foraminifer *Bolivina spissa* (Cushman) from the Bering Sea: a realistic test of seabed oxygen conditions?

Abstract

Recent studies have reported a link between foraminiferal shell pore density (PD) and bottom water dissolved oxygen levels (BW-O_2), asserting that oxygen concentrations in bottom waters can be quantitatively reconstructed at low oxygen levels. I assess this relationship for the calcareous benthic foraminifer *Bolivina spissa* (Cushman), by comparing its PD with interpreted sea bottom-water BW-O_2 from six horizons in the late Quaternary section of IODP Site U1342, Bowers Ridge, Bering Sea. The BW-O_2 is estimated by a combination of benthic foraminiferal faunas (deep infaunal group %), and the presence of sediment laminations, thought to indicate dysoxia/anoxia. *B. spissa* shows PDs spanning 0.0013 - 0.0104 P/μm^2, but there is no apparent correlation between PD and interpreted BW-O_2. Thus, assuming it is bottom water oxygen concentrations that are primarily driving both faunal assemblages and the development of laminations, changes in bottom water oxygen levels may not be the primary or sole driver of PD for *B. spissa* at this site: other environmental parameters, including bottom-water nitrate concentration (BW-NO_3^-) may have influenced *B. spissa* PD, and/or PD might be recording sediment pore water oxygen concentration (PW-O_2). Alternatively, both the lifestyle of *B. spissa*, and/or the potential time-averaging of the samples, may have obscured any primary signal. This analysis cautions the use of *B. spissa* PD analysis for determining BW-O_2 where sedimentological or accompanying palaeontological data are unclear, or where precise sampling is impossible.

3. Introduction

Lutze (1986) emphasised the usefulness of pore density (PD) and pore size as diagnostic features for the identification of several species of foraminifera; however, only few publications (e.g. Finlay et al. 1983; Moodley and Hess 1992; Glock et al. 2011; Kuhnt et al. 2013) have discussed the functionality of these pores, and examined whether they are important for the survival of benthic foraminifera in their microhabitat. Earlier publications examined the microstructure of the pores, which are often covered by

sieve-like micro porous organic plates (Arnold 1954a, 1954b), or by one or more organic layers (Sliter 1974; Berthold 1976; Leutenegger 1977). Though several terms have been given to these pores, including "pore diaphragms", "sieve plates", "pore plugs", "dark discs", and "pore plates", only a few studies have investigated their ability to enable dissolved materials to pass into the cytoplasm of foraminiferal cells. The pores may function to promote the uptake of oxygen and in return release CO_2 as a by-product of respiration (Berthold 1976; Leutenegger 1977). It has also been demonstrated that certain benthic foraminifera (e.g. *Bolivina pacifica*) that are tolerant of low oxygen, have their cell mitochondria more abundant near the pores, relative to those species that occupy relatively well-oxygenated waters. This suggests a relationship between pores, mitochondria and respiration (Leutenegger 1977; Sen Gupta and Machain-Castello 1993). Bernhard and Alve (1996) showed that in some of these benthic species, mitochondria move through the cytoplasm and pseudopodia, and were concentrated in the apertural cytoplasm.

Overall morphological characteristics of the benthic foraminiferal test have also been suggested to relate to varying oxygen levels in seawater (Rathburn and Corliss 1994; Kaiho 1994): these include: changes in test size of individual species (Sen Gupta and Machain-Castillo 1993; Kaiho 1994); and intra-species changes in test morphology such as pore density and ornamentation (Perez-Cruz and Machain-Castello 1990; Glock et al. 2011; Kuhnt et al. 2013). Morphological and abundance reactions of benthic foraminifera to their immediate environment are extensively used as proxies for palaeoceanographic and palaeoecological reconstructions, involving assessments of organic flux to the sea bed (e.g. Lutze 1980; Lutze and Coulbourn 1984; Caralp 1984, Lutze et al. 1986; 1989; Carney 1989; Jorissen et al. 1992; Gooday 1993; Kaiho, 1999; Den Dulk et al. 2000; Fontanier et al. 2002, 2006) or oxygen-level (e.g. Kaiho 1991, 1994, 1999b; Den Dulk et al. 2000, Glock et al. 2011, Kuhnt et al. 2013). Sea floor oxygenation depends mainly on factors that include the original dissolved oxygen-level, and the amount and quality of organic matter available at the seafloor (see Jorissen et al. 1995: TROX model see Fig. 3.2). Because of the difficulties in differentiating changes in oxygenation and organic matter influx to the sea floor, Kuhnt et al. (2013) considered it difficult to use assemblage data alone to decide on changes in water-mass oxygen content or organic influx to the sea floor; this remains a challenging area of foraminiferal studies. It has been suggested that in oxygen-depleted habitats, low

metabolic rates decrease the secretion of calcite by benthic foraminifera, thereby resulting in the production of thinner, less-ornamented and more-porous tests (Kaiho 1994; Bernhard 1986; Rhoads and Morse 1971). This pattern seems to indicate that species of benthic foraminifera from oxygen depleted or oxygen deficient habitats should show moderately high porosity, pore-densities and larger pore-sizes, which set these benthic foraminifera aside as low-oxygen indicators based on their morphology.

In a more recent effort to unravel environmental influences on the pore density of *Bolivina spissa* (Cushman), including water-depth, temperature, bottom-water oxygen and nitrate concentrations, Glock et al. (2011) suggested that the pores in the test of *B. spissa* reflect intracellular nitrate respiration, and that *B. spissa* switches from oxygen to nitrate respiration when oxygen concentrations are depleted. The ability to store nitrate inside the cells and to switch to nitrate respiration in times when less or no oxygen is available has been documented for several benthic foraminiferal species (Risgaard-Petersen et al. 2006; Høgslund et al. 2008; Glud et al. 2009; Piña-Ochoa et al. 2010). All these investigations point to the possibility of using PD and pore size as proxies for changes in bottom water oxygenation.

In a laboratory investigation, Moodley and Hess (1992) demonstrated that *Ammonia becarri* (Linné) shows an increase in pore-size and higher porosity on the chambers formed under low oxygen (dysoxic) conditions, possibly as a coping strategy to decreased oxygen (Corliss 1985). Leutenegger and Hansen (1979) observed that concentrations of mitochondria below the inner pore entrances in benthic foraminifera point to a pore function related to respiration (gas exchange). A more recent study on the relationship between PD in benthic foraminifera and bottom-water oxygen content by Kuhnt et al. (2013) on *Bolivina pacifica* and *Fursenkonia mexicana* (both deep infaunal species) shows an inverse correlation between PD and bottom water oxygen content, which suggest that both species may have increased their pore numbers to improve the ability of oxygen uptake in dysoxic environments or intervals. In this study, changes in the PD of the test on the same benthic foraminifer species (*B. spissa*) were compared down core, across an interpreted varying oxygen gradient (BW-O_2, based on other proxies, see below) to see how interpreted BW-O_2 influences the PD.

This study examines *B. spissa* from 6 horizons determined to indicate different BW-O_2 based on sedimentary characteristics (laminated and non-laminated intervals)

and faunal assemblages. It tests the veracity of the PD method in *B. spissa* as a means of estimating bottom-water oxygen concentration (BW-O_2).

3.1 Infaunal foraminifer preference for low oxygen conditions

Studies on sedimentary basins with low-oxygen bottom water off the California coast (Phleger and Soutar 1973; Douglas and Heitman 1979) and on sapropels from the Mediterranean Sea (Parker 1958), were amongst the first studies that recognised that ancient, as well as recent, low oxygen environments were inhabited by specific benthic foraminiferal assemblages. Deep-sea benthic foraminifera tend to live across a depth gradient, from 1 to 10 cm, where oxygen becomes increasingly deficient from the surface downwards (Jorissen et al. 2007). The Trophic Oxygen (TROX: Fig. 3.2) model of Jorissen et al. (1995) explains the benthic foraminiferal living depth in terms of availability of food and oxygen concentration. The depth in the sediment down to which organisms can live is determined by oxygen availability, and in the presence of oxygen, the vertical distribution of organisms is controlled by food availability (Jorissen et al., 1995).

Abundant foraminifera have been reported from low-oxygen environments (Schumacher et al. 2007, Sen Gupta and Machain-Castillo 1993, Douglas and Heitman, 1979, Phleger and Soutar 1973, Smith 1964b); these have a characteristic taxonomic composition, and are dominated by bolivinids, buliminids, globobuliminids and some other taxa when oxygen concentration falls below 1ml/l (Bernhard 1986; Sen Gupta and Machain-Castillo 1993; Bernhard and Sen Gupta 1999). Differences in dissolved oxygen concentrations and organic carbon supply at the sediment-water interface play a major role in the control of deep sea benthic foraminiferal assemblages and their morphological characteristics as reflected in benthic foraminiferal test size, thickness and porosity (e.g. Kaiho 1994; Thomas and Gooday 1996; Kuhnt et al. 2013). Many elongated, commonly biserial or triserial taxa, have been described as being abundant at very low oxygen concentrations; it has been suggested that their morphology also corresponds to an infaunal microhabitat (Corliss and Chen 1988; Corliss and Fois 1990; Corliss 1991), although this is not always supported (see Jorissen et al. 2007).

Two groups of taxa with different life strategies have been shown to evolve after the disappearance of less resistant taxa at low bottom-water oxygen concentrations: the deep infaunal taxa, at the onset of low-oxygen conditions in bottom water, migrate from the deeper sediment layers to the sediment surface (Jorissen 1999); whilst the epifaunal or shallow infaunal taxa that have inherent tolerance for low-oxygen conditions (Jorissen et al. 2007), then become established at the sea bed. No foraminiferal species appear to be adapted exclusively to low-oxygen conditions (Sen Gupta and Machain-Castillo 1993); according to Murray (2001), foraminifera generally only start to become impacted by oxygen levels when concentration values of dissolved oxygen fall below approximately 1 ml/l: above these levels, there will be no correlation between oxygen and the composition of the faunas. Often, a number of taxa are considered indicative of low-oxygen conditions; the relative abundance and test morphology of such species and their relative abundance in the entire calcareous fauna were expressed as a percentage of the total benthic foraminiferal fauna and is used as a semi-quantitative indication of bottom water oxygenation (Jorissen et al. 2007; Schumacher et al. 2007)

Expedition 323 Scientists (2011) reported that laminated intervals at Bowers Ridge, Bering Sea, are possibly indicative of the local depth of the oxygen minimum zone (OMZ: See Chapter 1), which reduced the effects of infaunal burrowing and bioturbation. At Site U1342, ~71 to 100% infaunal species were recorded at horizons that correlate closely with laminated sedimentary intervals. This is in line with Jorissen et al. (1995), who suggested that deep infaunal taxa often considered indicative of low-oxygen conditions, are only present when the organic flux is significantly high (giving rise to the dark coloration that is associated with laminated intervals). The flux of organic material is respired by organisms (i.e foraminifers, bacteria etc.) at the sea bed, and this leads to a decrease in dissolved oxygen in the ambient waters (Jorissen et al. 1995).

In summary, oxygen concentrations are thought to have a direct influence on the faunal composition only in areas where bottom water concentrations become so low (less than or equal to 1 ml/l; Murray, 2001) that this causes reduced competitive ability and/or reproductive ability of taxa in the environment. In such cases, taxa less resistant to reduced oxygen disappear, giving room for deep infaunal taxa and denitrifiers to rise to the surface, as these are well adapted to low oxygen conditions (Jorissen, 1999). In this study, we use the percentage deep infaunal taxa to the entire assemblage as a semi-

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quantitative proxy for BW-O$_2$. Although the dominance of this group (e.g. above ~70%: Schumacher et al. 2007) is thought to be a response to oxygen levels below 1 ml/l, there is as yet no known direct way of calculating dissolved oxygen level from infaunal percentage alone.

3.2 Materials and methods

3.2.1 Source of materials

Specimens of *Bolivina spissa* were analysed from core sediments recovered by IODP Expedition 323 (Expedition 323 Scientists 2009), at ~ 818 m water depth from Site U1342 on the Bowers Ridge, Bering Sea (Fig. 3.1). Sediments from the depth interval between 0 and 11.15 m were analysed. On Bowers Ridge, an average sedimentation rate of 4.5 cm/kyr is documented (Expedition 323 Scientists 2011). Sediments from this site comprise predominantly biogenic (mainly diatom frustules with varying proportions of calcareous nannofossils, foraminifers, silicoflagellates, and radiolarians), siliciclastics (mainly silt and very fine sand, and also isolated clasts of pebble to cobble size), and volcaniclastic (mainly fine ash) material. The most prominent sedimentary features are decimetre to metre-scale bedded alternations of sediments, together with variation in colour and texture. Sediments from Site U1342 are generally bioturbated; finely laminated, preserved alternations between millimetre-scale laminae of biogenic and terrigenous material are also present (Expedition 323 Scientists 2009). In general, the colour of the sediment ranges from very dark greenish grey and dark grey, to biogenic-rich olive grey to olive, with dark grey to black or shades of light grey, to white ash layers (Expedition 323 Scientists 2011). Samples used for this study were collected from the Kochi Core Centre, Japan in 2010, and were processed (freeze-dried and wet-sieved over 62-μm to liberate the microfossils) in Prof. Christina Ravelo's laboratory at the University of California, Santa Cruz.
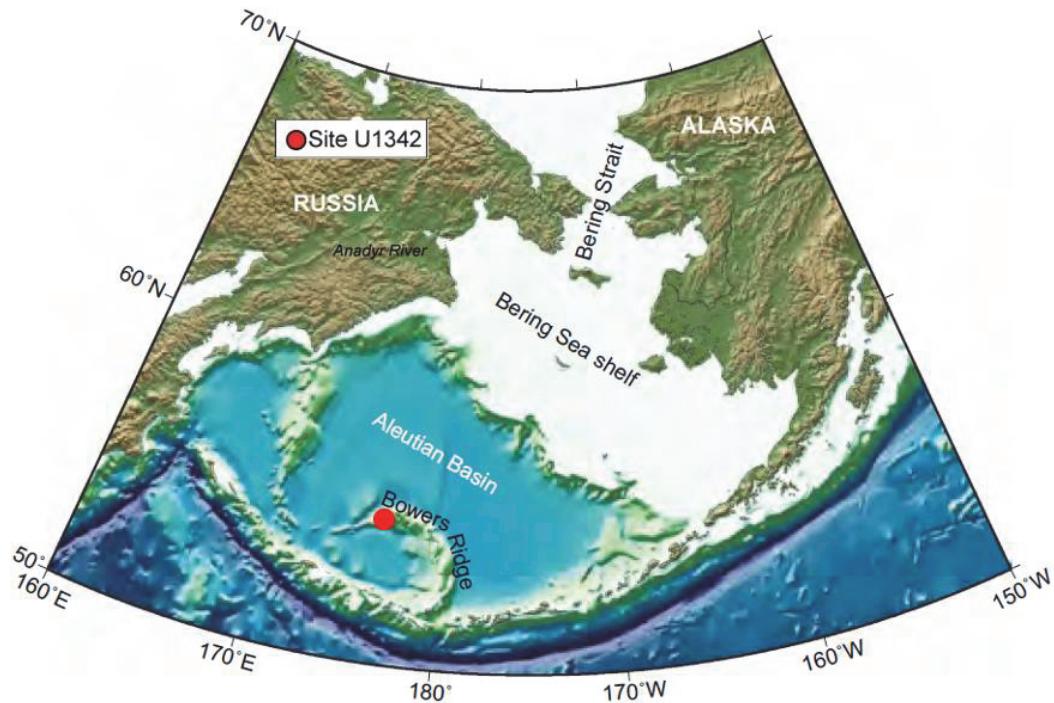
Figure 3.1 Bathymetric map of the Bering Sea, with the marked location of Site U1342 (red dot) on the Bowers Ridge, Southern Bering Sea (adapted from Expedition 323 Scientists 2011), is the source of *Bolivina spissa* specimens used in this study.

Subdivision of benthic foraminifera into microhabitat and oxygen indicator groups (Table 3.1) carried out in accordance with the study on variations of the OMZ of the Okhotsk Sea of Bubenshchikova et al. (2010) and other studies (see Kaiho 1994; Jorissen et al. 2007; Glock et al. 2011), would suggest that *B. spissa* is tolerant of dysoxic waters (typical of 0.1 to 0.3 ml/l of dissolved oxygen in seawater) and is deep infaunal. This classification also places *Bolivina pacifica* and *Fursenkonia mexicana* (also used in the study by Kuhnt et al. 2013), as dysoxic and deep infaunal species. *B. spissa* has been shown to be very tolerant to variations in oxygen concentration (Bernhard et al. 2001), and can survive in anoxic waters (Bernhard and Bowser 2008); this makes *B. spissa* a suitable candidate for this study of PD versus variable BW-O_2.

Benthic foraminifera species microhabitat group (from previous studies)							
Benthic foraminifera fauna recorded from Core 1342 (~20.60 m-ccsf)	Deep infauna (Dysoxic): >4 to 10 cm below sea-sediment interface	Intermediate infauna (Suboxic): ~1 to 4 cm below sea-sediment interface	Shallow infauna (Suboxic): 0-2 cm below sea-sediment interface	Epifauna (Oxic): 0-1 cm	Phytodetritivores	Denitrifiers	Unassigned
Alabaminella weddellensis				X	X		
Angulogerina angulosa							X
Bolivina sp. 1	X						
Bolivina sp. 2	X						
Bolivina sp. 3	X						
Bolivina spissa	X	X				X	
Brizalina alata	X						
Brizalina earlandi	X						
Bulimina exilis	X						
Bulimina	X	X	X				
Cassidulina				X	X		
Cassidulina reniforme			X				
Cassidulina teretis				X			
Cassidulinoidies parkerianus							X
Cibicidoides sp.			X	X			
Cushmanina striatopunctata							X
Dentalina ittai.							X
Eggerella sp. 1			X				
Ehrenbergina var. *compressa*							X
Elphidium sp. 1			X				
Elphidium sp. 2			X				
Elphidium sp. 3			X				
Elphidium			X				
Epistominella				X	X		
Epistominella pulchella							X
Fissurina crebra			X				
Fissurina minima			X				
Fursenkoina aff. *texturata*	X					X	
Globobulimina auriculata	X						
Globobulimina pacifica	X						
Globocassidulina subglobosa		X	X	X	X		
Gyroidina sp. 1							X
Gyroidina sp. 2							X
Hoeglundina				X			
Islandiella			X		X		

Benthic foraminifera fauna recorded from Core 1342 (~20.60 m-ccsf)	Benthic foraminifera species microhabitat group (from previous studies)						
	Deep infauna (Dysoxic): >4 to 10 cm below sea-sediment interface	Intermediate infauna (Suboxic): ~1 to 4 cm below sea-sediment interface	Shallow infauna (Suboxic): 0-2 cm below sea-sediment interface	Epifauna (Oxic): 0-1 cm	Phytodetritivores	Denitrifiers	Unassigned
Karreriella sp.							X
Lagena hispida							X
Lagena nebulosa							X
Lagena sp. 1							X
Lagena sp. 2							X
Lagena sp. 3							X
Lagena sulcata							X
Lenticulina			X				
Lotostomoides calomorphus							X
Martinottiella communis	X						
Melonis		X					
Moncharmontzeia							X
Nonionella digitata	X						
Nonionellina labradorica		X					
Oolina hexagona							X
Oridorsalis umbonatus				X	X		
Planulina ariminensis				X			
Planulina wuellerstorfi				X			
Procerolagena gracilis							X
Procerolagena gracillima							X
Pullenia simplex			X				
Pyrgo murrhina				X			
Quinqueloculina				X			
Reussoolina apiculata							X
Stainforthia fusiformis							X
Takayanagia			X				
Triloculina frigida				X			
Uvigerina		X					
Uvigerina hispida		X	X				
Uvigerina		X	X				
Uvigerina		X					
Uvigerina sp. 1		X					
Valvulineria araucana							X

Table 3.1 Core U1342 benthic foraminifer's microhabitat preference and characteristics in accordance with consistent groupings in some selected studies (Corliss and Chen 1988; Gooday 1988; Thiel et al. 1989; Corliss 1991; Steinsund et al. 1994, Steinsund and Hald 1994; Kitazato and Ohga 1995; Licari et al. 2003; Risgaard-Petersen et al. 2006; Høgslund et al. 2008; Ivanova et al. 2008; Bubenshchikova et al. 2008; Alve 2010, Glock et al. 2011).

The qualitative method used to infer oxygenation from assemblages in this study is based on the Kaiho (1994) ecological groupings and the Jorissen et al. (1995) conceptual model for BW-O_2. Unlike Kaiho (1994), relative abundance of deep infaunal foraminifera expressed as a percentage of the total benthic foraminiferal fauna in the samples was used, and these values were used as a qualitative measure of BW-O_2 at various depths (Table 3.2). This is because the Kaiho (1994) oxygen index (the calculation to convert faunas to oxygen) has received some criticism (Murray, 2001, Jorissen et al. 2007). According to the TROX-model (Trophic-Oxygen-Microhabitat-Reaction) of Jorissen et al. (1995), foraminiferal microhabitat in oligotrophic ecosystems is limited by availability of food particles within the sediment, whereas in eutrophic systems, a critical oxygen level decides to what depth in the sediment most of the species can live. In mesotrophic areas, microhabitat depth is of maximum importance (Fig. 3.2). The more organic carbon influx into the water column leads to more carbon in the deep infauna; this invariably lowers the dissolved oxygen content of the pore water due to respiration. However, the main distinction in microhabitat characteristics is that between epifaunal and infaunal organisms (Jorissen et al. 1995).
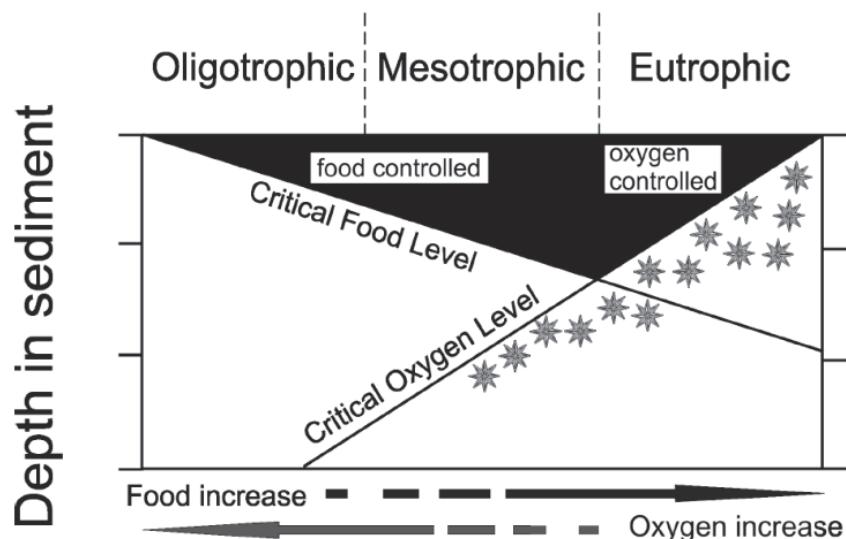
Figure 3.2 TROX (Trophic Oxygen)-model explaining the benthic foraminiferal living depth (shaded area) in terms of availability of food and oxygen concentration (after Jorissen et al. 1995). Stars in the figure represent benthic foraminifers.

Among the deep infaunal benthic foraminifera species recorded at Site U1342 are

Globobulimina spp., *Bulimina exilis*, *Fursenkoina* aff. *texturata, Bolivina spissa, Brizalina alata* and *Brizalina earlandi*. Oxygen levels were qualitatively estimated from the percentage abundance of deep infaunal species against the total percentage abundance of faunas at various depths, by assigning benthic foraminiferal species into groups following Kaiho's (1994), and their microhabitats in accordance with the regional faunal study of Bubenshchikova et al. (2008) where species occur. Where species do not occur, the living depth was assigned based on morphologically similar species. As an independent measure of oxygenation, sedimentary layers with bioturbation are considered to represent higher concentrations of oxygen in bottom waters (depending on the degree of bioturbation involved), as benthic invertebrates invade sediment laminae in aerobic conditions (Kaiho 1991). Expedition 323 Scientists (2011) suggest that stratigraphic intervals where there is lamination are possibly indicative of the local depth of the OMZ; relatively high percentages of infaunal species (shallow and deep infaunal) recorded at these depths further suggest that the laminated intervals are associated with low oxygen horizons.

3.2.2 Sampling Procedure

All *B. spissa* specimens were targeted from each of the 24 samples (i.e from six horizons) at different depths analysed down the studied interval. On Bowers Ridge, an average sedimentation rate of 4.5 cm/kyr is documented (Expedition 323 Scientists, 2011), this suggests a deposition rate of 2 cm per ~444 years (narrowest thickness where specimens were taken for this study: see Table 3.2). A total of 227 *Bolivina spissa* (Cushman) specimens were picked from some depths within the 11.15 metres of core sampled for this study; out of which 121 megalospheric specimens (from sexual reproduction) were analysed. Due to the different morphologies in the test of megalospheric and microspheric specimens of *B. spissa*, there is a considerable difference in the PD between the sexually and asexually produced forms: the megalospheric specimens consistently show increasing PD from earlier to later chambers, and therefore this parameter can be more readily quantified in these forms (see also Glock et al. 2011).

The megalospheric specimens equate to ~53% of the total *B. spissa* from the studied interval (0 to 11.15 m: Fig. 3.3). These specimens are sourced from 24 samples

at different depths. The sampling strategy was influenced by the occurrence and paucity of *B. spissa* in the 11.15 metres of core sampled. Geological samples used for paleoceanographic reconstructions are always time-averaged, relatively low resolution, and contain a mixture of faunas that inhabited the site during (possibly) several decades or longer. Such samples will not always capture precise fluctuations in O_2-levels at the sea bed. In order to make best use of the number of specimens studied and to negate some of the effects of time averaging, in most cases several samples (in succession) are grouped into a composite interval (after a careful logging was carried out on the core photographs) where the sedimentological and paleontological signature of that interval (see Table 3.2 for the thickness of the various interval) indicates a consistent environment (low oxygen versus more oxygenated levels; see Table 3.2).

The total percentage of deep infaunal species (based on the morphology criteria of Kaiho 1994, and oxygen-related benthic foraminiferal groups according to the classification of Bubenshchikova et al. 2008) in the sediment at sampled depths have been used as the primary proxy for BW-O_2 conditions. Percentage abundance of deep infauna at various intervals (Fig. 3.3) was calculated following this strategy (Appendix 4a). The 24 samples with *B. spissa* were grouped into 6 defined intervals (Table 3.2). 1) Sourced from a 2 cm interval beginning at depth 0.00 m, and representing unlaminated sediment characterised by a benthic fauna interpreted to signal low oxygen (*viz* 44.56% deep infauna). 2) Sourced from a 2 cm interval beginning at 0.25 m, and representing laminated sediment characterised by a benthic fauna thought to signal dysoxia (*viz* 78.77% deep infauna). 3) Sourced between 0.38-2.42 m, an interval from which 16 samples have been assessed, all of these representing unlaminated sediments with a benthic fauna that consistently signal well-oxygenated conditions (*viz* 1.50 % to 7.60 % deep infauna); only 6 of these samples where *B. spissa* is present were analysed, each sample varying from between 2 to 4 cm thickness of sediment. 4) Sourced between 2.54-2.69 m, comprising 2 samples within an unlaminated interval with a benthic fauna that signals consistently well-oxygenated conditions (*viz* 25.30% to 26.30 % deep infauna), each about 4 cm thick. 5) Sourced between 3.88-8.36 m, an interval from which 38 samples have been examined and representing an unlaminated interval with a benthic fauna that signals consistently well-oxygenated conditions (*viz* 0.70% to 15.50 % deep infauna). Here, 12 of the samples (where there are >1 *B. spissa* specimen) from this interval were analysed for *B. spissa*, each sample varying between 2 to 3 cm

thickness of sediment. 6) Sourced from the lowermost interval between 10.98-11.15 m, and comprising of 2 samples, 2 and 4 cm thick respectively. This represents an unlaminated interval with a benthic fauna that signals consistently dysoxic conditions (*viz* 55.20% to 95.50 % deep infauna).
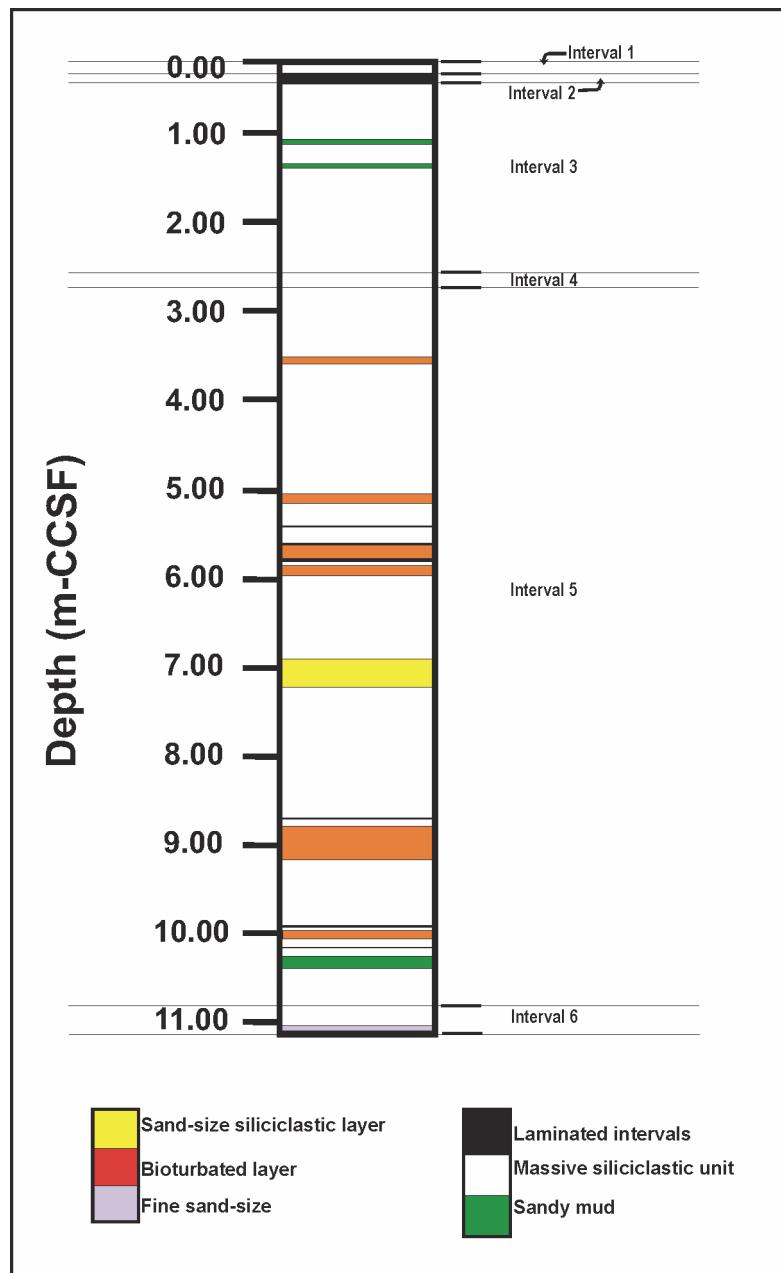
Figure 3.3 Simplified sedimentary log of Site U1342, Bowers Ridge; showing intervals at the top 11.15 m where *B. spissa* specimens for Pore density analysis were taken.

Foraminiferal fragmentation through the 6 intervals was determined by quantifying the ratio of broken and/or dissolved specimens (fragments) to the ratio of

whole specimens (not broken) of benthic foraminifera at each of the intervals (Appendix 5). Percentages of fragmentations were then determined from the values. The degree of fragmentation has been used as a qualitative proxy for dissolution (Metzler et al. 1982; Thunell 1976; Berger 1970).
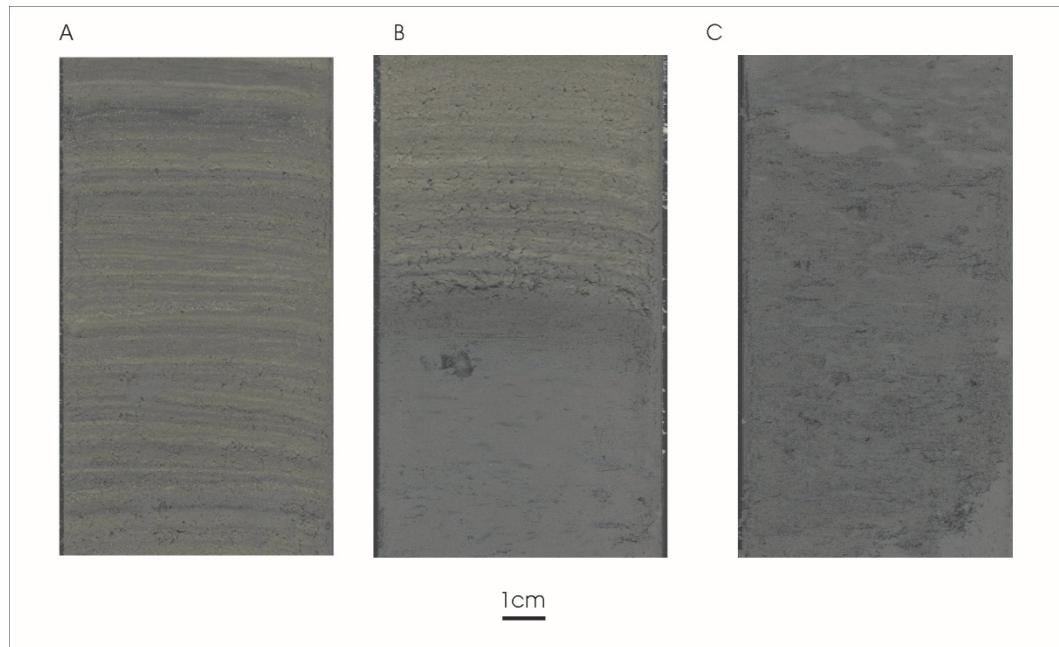
Figure 3.4 Representative laminated versus bioturbated intervals from the upper 11.13 m of the core at IODP Site U1342, Bering Sea. Laminated, organic-rich intervals ('A': taken from 0.25 m depth) are considered to signify low-oxygen bottom conditions and are typically associated with benthic foraminiferal assemblages that have a deep infaunal signature. Bioturbated levels ('C': intervals taken from 1.28 m depth) indicate an oxygenated sea bed. 'B' shows the transition between two different sea bed oxygen states (0.29-0.38 m). Scale bar is 1 centimetre.

Hole	Core	Section	Top depth (cm)	Bottom depth (cm)	Interval serial number	Depth serial number	Total number of *B.spissa* specimens for each depth	Individual sample depths (m)	Thickness (cm) of individual sample	Number of sampled depth / interval	% deep infaunal species (Bubenshchikova, 2008)	Av. % deep infaunal species (%)	Lamination	Well-oxygenated	Total number of *B.spissa* specimens for each interval
D	1H	1	0	2	1	1	20	0.00-0.02	2	1	44.70	44.70	No	No	20
D	1H	1	24	26	2	2	25	0.23-0.25	2	1	78.90	78.90	Yes		25
D	1H	1	39	41		3	4	0.38-0.40			7.60		No	Yes	
D	1H	1	52	56		4	2	0.51- 0.55			2.50				
D	1H	1	89	93		5	2	0.88-0.92			1.50				
D	1H	1	129	133	3	6	2	1.28-1.32	2 to 4	6	4.50	4.92			13
D	1H	2	65	69		7	1	2.14-2.18			4.60				
D	1H	2	89	93		8	2	2.38-2.42			6.00				
D	1H	2	105	109	4	9	3	2.54-2.58	4 and 5	2	25.30	26.05			12
D	1H	2	115	120		10	9	2.64-2.69			26.30				
D	1H	3	89	92		11	1	3.88-3.91			3.60				
D	1H	3	99	101		12	7	3.98-4.00			12.10				
D	1H	3	112	115		13	2	4.11-4.14			10.90				
D	1H	4	25	29		14	1	4.74-4.78			3.60				
D	1H	4	77	79		15	2	5.26-5.28			0.80				
D	1H	4	106	108		16	2	5.55-5.57			1.30				
D	1H	4	115	117	5	17	5	5.64-5.66	2 to 3	12	14.40	8.20			44
A	2H	3	39	42		18	2	5.74-5.77			4.00				
A	2H	3	52	54		19	2	5.87-5.89			8.30				
A	2H	3	61	64		20	3	5.96-5.99			10.30				
A	2H	3	90	92		21	7	6.25-6.27			15.50				
A	2H	4	149	151		22	10	8.34-8.36			0.70				
A	2H	6	113	117	6	23		10.98-11.02	2 and 4	2	95.50	72.47		NO	7
A	2H	6	128	130		24		11.13-11.15			55.20				
Total number of *B. spissa*															121

Table 3.2 Sample depths and composite intervals (1 to 6) with the associated number of benthic foraminifera and the percentage of deep infauna used as a proxy for BW-O$_2$ conditions (low oxygen versus more oxygenated levels) at various depths and intervals.

3.2.3 Specimen preparation

B. spissa specimens were gently cleaned in an ultrasonic bath, mounted on aluminium stubs and coated with gold. Specimens were imaged using a Hitachi S-3600N Scanning Electron Microscope (SEM) in the Geology Department, University of Leicester, UK. Magnifications of up to 700 times have been used to image pore ultrastructure; this enables clear focus, identification, and counting of the pores afterwards. To compensate for charging effects on some of the specimens, the SEM partial vacuum mode was

activated. It has been noted that PD increases within a single *B. spissa* test from the early to the later chambers (Glock et al. 2011) which was also observed here. Therefore, as a way of calibration and uniformity, the first few chambers (up to 10) on *B. spissa* were imaged. PD was quantified (see Appendix 4b) for an area of 10,000 μm^2 on one side of each *B. spissa* test within the first ten chambers (i.e. first 5 pairs) from the SEM photographs (Plate 3.1); this is due to the homogeneity of pore distribution on B. spissa test. PD is expressed as pores per μm^{-2} ($P/\mu m^2$) of the area measured.
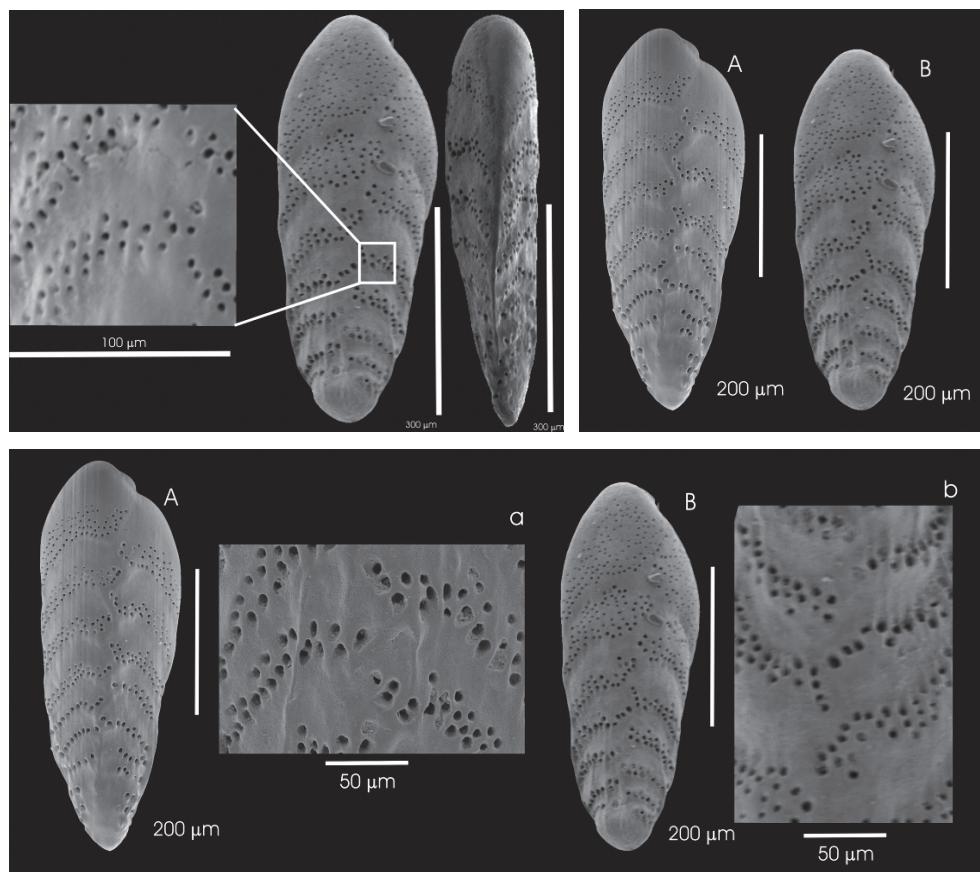
Plate 3.1 Pore density and general morphology of *Bolivina spissa*. Top left box gives illustration of an estimated area of 10,000 μm^2 where PD was quantified on each specimen. Specimen A shows a typical specimen from a laminated sedimentary interval; while B is a specimen from a bioturbated interval. Note the findings in this study indicate there is no significant difference in the PD between specimens from levels interpreted to have different oxygen levels.

3.2.4 Statistical approach

Simple linear-plots (cross-plots) of PD values on *B. spissa* specimens versus percentage

deep infauna (as proxy for BW-O$_2$) as determined from 6 defined intervals, including 3 determined as representing low oxygen (including one laminated interval), and 3 more oxygenated (non-laminated), are used to assess the relationship between PD and BW-O$_2$ (Fig. 3.5).

Various percentile values of PD on *B. spissa* from these intervals were determined (Table 3.3). Box and whisker plots have been constructed from the percentile values to quantify the relationship between the PD and the BW-O$_2$ conditions without making any assumptions of the underlying statistical distributions (Fig. 3.6). Calculated BW-O$_2$ from the PD of *Bolivina spissa* (after equation in Glock et al. 2011: p. 28, fig. 7 A) versus interpreted BW-O$_2$ from faunal assemblages was plotted (Fig. 3.7).

3.3 Results

Table 3.2 summarises the number of specimens yielded from the 6 defined sample intervals, and presents sedimentological and faunal evidence for their interpretation as well-oxygenated or poorly oxygenated intervals.

Pore counts between specimens of *B. spissa* range from 13 to 104 pores per 10,000 μm^2. Calculated mean pore values vary from 0.0045 P/μm^2 to 0.0056 P/μm^2 (Table 3.4: lowest PD = 0.0013 P/μm^2; highest PD = 0.0104 P/μm^2) on the first 10 chambers of all *B. spissa* specimens analysed across the six intervals. Calculations were made to find the different percentile value of *B. spissa* PD through the sampled intervals (Table 3.3); box and whisker plots were constructed to statistically and visually analyse the data spread (Fig. 3.6). The lowest median PD value being 0.0045 P/μm^2 is recorded from interval 4, showing 26.05 % deep infauna foraminiferal species (2.54-2.64 m). The median PD value of 0.0050 P/μm^2 is recorded from laminated interval 2 (0.25 m: 78.90% deep infaunal species), whilst the highest median PD value of 0.0056 P/μm^2 is recorded from interval 5 (3.88-8.36 m: 3.60% deep infaunal species) indicating an interval with increased oxygenation (Table 3.3).

Analysis of *B. spissa* PD versus estimated BW-O$_2$ from various sedimentary horizons at Site U1342 shows no correlation (Fig. 3.5).
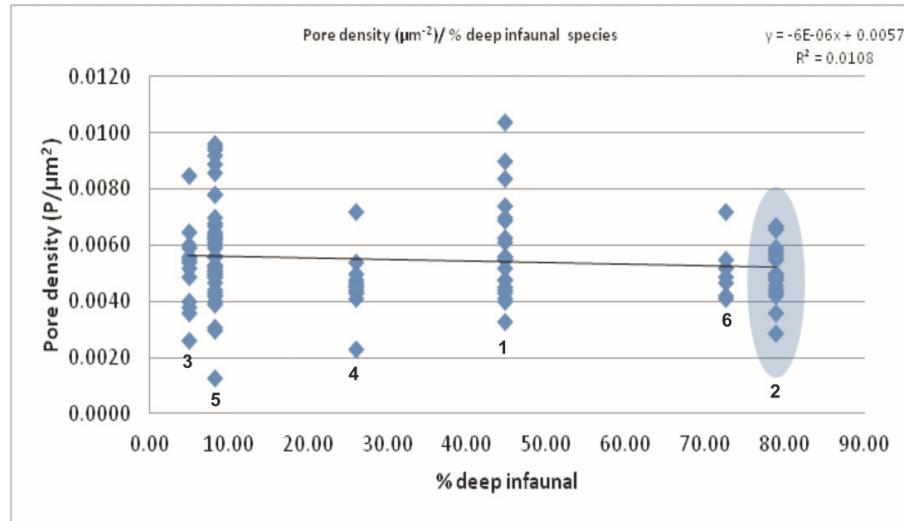
Figure 3.5 Linear plot of PD (vertical axis) on the test of *B. spissa* specimens from laminated (Interval 2: identified by the oval shape) and non-laminated intervals (1, 3, 4, 5, 6), versus the percentage of deep infaunal foraminifera (horizontal axis, used as a relative proxy of seabed oxygen level, with oxygen level interpreted to be decreasing from left to right in the figure). A total of 121 *B. spissa* specimens were measured down core, being a subset of the total specimens in the samples. Horizontal axis shows the percentage of associated infaunal species at each interval (see Bubenshchikova et al. 2008).
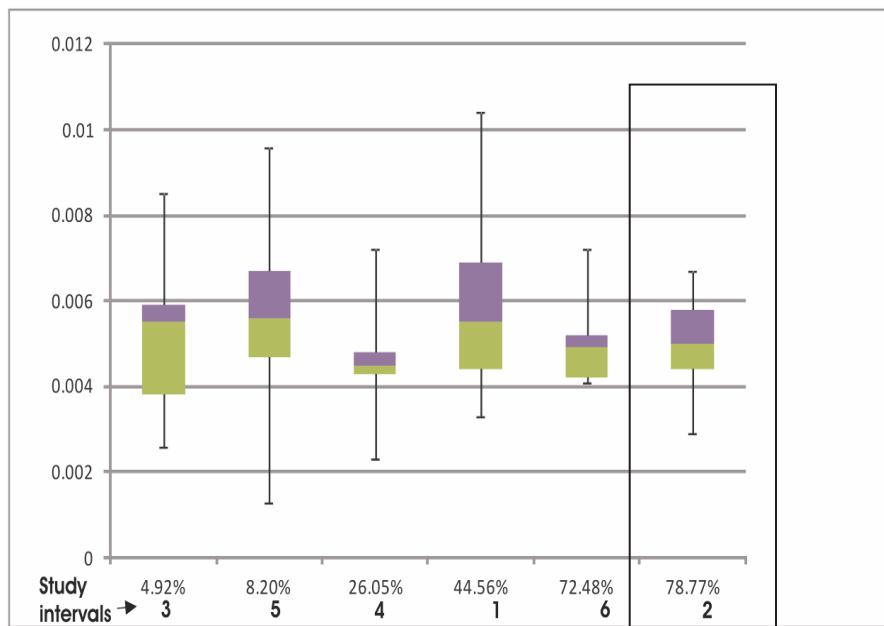
Figure 3.6 Box and whisker plots (statistically and visually showing the data spread) for PD variation in *B. spissa* from intervals 1 to 6: laminated interval 2

(enclosed in box) and non-laminated intervals (1, 3, 4, 5, and 6). Pore density (P/μm^2) is on the vertical axis; average percentage of deep infaunal foraminifera at each interval (indicating relative oxygen level at such interval) is noted. Green shade: PD range from 25th percentile to 50th (median) percentile; purple shade: PD range from median percentile to 75 percentile.

Analysis of PD data using box and whisker plots enables visual and statistical analysis of the data spread, which shows high variation in PD for the 121 specimens, with between 7 and 44 specimens analysed from each of the six intervals. Mean PD values for all the specimens vary between 0.0045 P/μm^2 and 0.0056 P/μm^2 (Table 3.4). Half of the PD values are distributed between the 25th and 75th percentile (see Fig. 3.5), while the outliers are indicated in the total PD range. Thus, for interval 1, the PD values fall between 0.0055 P/μm^2 (median PD) and 0.0069 P/μm^2 (i.e. the spread is almost evenly distributed between the 50th (median) and 75th percentile); ~60% of *B. spissa* specimens at this interval have PD between 0.0055 P/μm^2 and 0.0069 P/μm^2. For laminated interval 2, the median PD values are 0.0050 P/μm^2. Generally, the PD values do not show any significant correlation with interpreted BW-O$_2$ (Figs. 3.5, 3.6). Generally, consistently low percentages of foraminifer fragmentation are recorded through the 6 intervals studied (Table 3.5).

Hole	Core	Section	Top depth (cm)	Bottom depth (cm)	Sampled Interval number	Depth (range) CCSF (m)	Sampled depths	Composited Depth thicknes (cm)	Number of specimens in an interval	% deep infaunal species (Bubenshchikova, 2008)	Av. % deep infaunal species (Bubenshchikova, 2008)	Lowest value (number of pores per 10,000 µm²)	25th percentile (number of pores per 10,000 µm²)	50th percentile (median:number of pores per 10,000 µm²)	75th percentile (number of pores per 10,000 µm²)	Highest value (number of pores per 10,000 µm²)
D	1H	1	0	2	**1**	0.00	1	2.00	20	44.56	44.56	33	44	55	69	104
D	1H	1	24	26	**2**	0.25	1	2.00	25	78.77	78.77	29	44	50	58	67
D	1H	1	39	93	**3**	0.38-2.38	6	54.00	13	7.60	4.92	26	38	55	59	85
D	1H	2	105	120	**4**	2.54-2.64	2	15.00	12	25.30	26.05	23	43	45	48	72
D	1H	3	89	92	**5**	3.88-8.36	11	62.00	44	3.60	8.20	13	47	56	67	96
A	2H	6	113	117	**6**	10.98 – 11.13	2	17.00	7	95.50	72.48	41	42	49	52	72
									121							

Table 3.3 Sampled intervals (1-6) from Core U1342; pore counts and percentile distribution of PD; interval 2 is laminated; a total of 121 *B. spissa* specimens were measured down core whilst the total interval studied is 11.13 m.

Hole	Core	Section	Top depth (cm)	Bottom depth (cm)	Interval number	Depth (range) CCSF (m)	Lowest PD (P/μm²)	Lowest PD (P/μm²) BW-O₂ (μmol/l) read off Glock et al. (2011)	25th percentile PD (P/μm²)	25th percentile BW-O₂ (μmol/l) read off Glock et al. (2011)	Median PD (P/μm²)	Median PD (P/μm²) BW-O₂ (μmol/l) read off Glock et al. (2011)	75th percentile PD (P/μm²)	75th percentile BW-O₂ (μmol/l) read off Glock et al. (2011)	Highest pore density (P/μm²)	Highest pore density (P/μm²) BW-O₂ (μmol/l) read off Glock et al. (2011)
D	1H	1	0	2	1	0.00	0.0033	>5.0	0.004	>5.0	0.0055	~4.0	0.0069	~2.2	0.0104	~1.6
D	1H	1	24	26	2	0.25	0.0029	>5.0	0.004	>5.0	0.0050	>5.0	0.0058	~3.0	0.0067	~2.4
D	1H	1	39	93	3	0.38-2.38	0.0026	>5.0	0.004	>5.0	0.0055	~4.0	0.0059	~3.2	0.0085	~1.8
D	1H	2	105	120	4	2.54-2.64	0.0023	>5.0	0.004	>5.0	0.0045	>5.0	0.0048	>5.0	0.0072	~2.1
D	1H	3	89	92	5	3.88-8.36	0.0013	>5.0	0.005	>5.0	0.0056	~3.8	0.0067	~2.4	0.0096	~1.7
A	2H	6	113	117	6	10.98-11.13	0.0041	>5.0	0.004	>5.0	0.0049	>5.0	0.0052	>5.0	0.0072	~2.1

Table 3.4 Sampled intervals from Core U1342; pore counts and percentile distribution of PD in this study; interval 2 is laminated; total interval studied is 11.13 m. PD from three of the intervals studied (intervals 1, 3 and 5) have their median PD corresponding to the Peruvian OMZ BW-O₂ below ~5.0ml/l (Table 3.2); PD from the other intervals (2, 4 and 6) corresponds to BW-O₂ above ~5.0ml/l at Peruvian OMZ (see Glock et al. 2011).

3.4 Discussion

Overall, there appears to be no regular pattern in the distribution of PD on the tests of *B. spissa* from the different interpreted oxygen levels at site U1342. Indeed, an anecdotal reading of the data in figure 3.5 and 3.6 suggests that *B. spissa* may have more pores on its test in oxygenated settings, than in low-oxygen microhabitats. Several explanations can be posited for the apparent mismatch between PD and interpreted bottom water oxygen-level.

3.4.1 Oxygen-levels may have been above the threshold level to influence PD values

PD values calculated in this study were compared with a similar study on environmental influences on the PD of *B. spissa* conducted by Glock et al. (2011; pg. 28; fig. 7 A) off the Peruvian oxygen minimum zone (OMZ). That study claimed lower PD values (0.0013 P/μm^2 up to 0.0050 P/μm^2) correspond to higher BW-O$_2$ of above ~5.0 ml/l (see Table 3.4; Fig. 3.7). In this study, oxygen levels may sometimes have been above this value, possibly above the threshold at which oxygen-levels would influence the PD of *B. spissa* (see Fig. 3.7). However, as average PDs in this study are above 0.0050 P/μm^2 (see Tables 3.3 and 3.4), a direct comparison with Glock et al. (2011) would suggest low levels of oxygen did sometimes exist. Thus, hypothesised higher oxygen levels cannot account for the inability of *B. spissa* PD to reconstruct meaningful BW-O$_2$. The wide spread of PD data indicates that either there is no simple correlation between PD and BW-O$_2$, or BW-O$_2$ was highly variable.
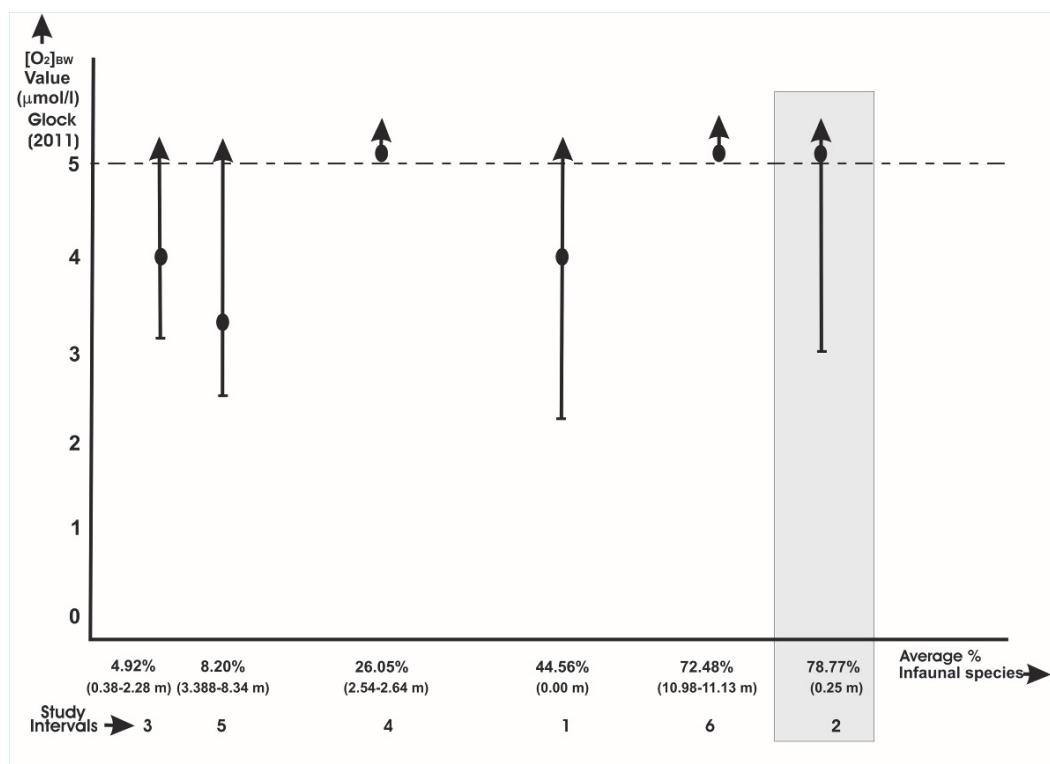
Figure 3.7 Range of dissolved oxygen for intervals 1 to 6 interpreted in this study. Vertical-axis shows BW-O$_2$ compared with a study by Glock et al. (2011: figure 7A) from the Pacific margin of the Peruvian oxygen minimum zone; horizontal-axis shows percentage of infaunal foraminifera (indicating relative oxygen level). *B. spissa* PD from three of the intervals studied (intervals 1, 3 and 5) have their median PD (see Table 3.4) corresponding to BW-O$_2$ that is below ~5.0 ml/l, the other intervals (2, 4 and 6) corresponds to above ~5.0 ml/l, where the Glock et al. (2011) correlation breaks down. Bars at the base of each line show the corresponding BW-O$_2$ (Table 3.4) upper limit of the 75th percentile of the PD values. Large dots on the lines depict the median BW-O$_2$ value; while the arrows show the corresponding BW-O$_2$ for the 25th and the lowest percentile PD values somewhere above 5 ml/l. Shaded area (i.e interval 2) represents the only laminated depth in the interval studied.

3.4.2 Transportation of fossil assemblages

Intermittent evidence of tractive sediment movement (see Expedition 323 Scientists, 2011) indicates bottom water currents influenced Site U1342. The possibility of bottom

water currents winnowing or sorting the sediments may lead to mixing of the primary faunal signal in the sediment. However, for the sampled six intervals there is little sedimentary evidence of transportation, signalled by the low percentage of fragmentation of foraminifera recorded throughout the interval and by the different size fractions (> 62 μm) of sediment and foraminifera (Table 3.5; Appendix 5).

Particle reworking also occurs during bioturbation, and these processes include both sediment reworking and burrow ventilation (Kristensen et al. 2011). Through burrow construction and maintenance, as well as ingestion and defecation, substratum bio-mixing takes place. Sediments, organic matter and microorganisms including benthic foraminifera are thus displaced vertically and laterally within the sediment matrix. This may have occurred in the sampled intervals here, since only one level is clearly laminated. However, in all intervals sampled, horizons were chosen with limited bioturbation, so that if present, this mixing of faunas is either cryptic, or regarded as of limited effect. Furthermore, the averaging of a number of samples across intervals deemed oxygenated or poorly oxygenated should have mitigated some of the effects of mixing from bioturbation; assemblages are distinct, and would likely be homogenous if there was complete mixing.

Hole	Core	Section	Top depth (cm)	Bottom depth (cm)	Interval serial number	Depth serial number	Total of Counts (Benthics)	Species diversity	Total number of foram fragments (F)	Number of whole (W)	Fragmentation ratio (F:W)	Foraminifera Fragmentation %
D	1H	1	0	2	1	1	495	24	41	449	0.091	9.13
D	1H	1	24	26	2	2	583	12	11	566	0.019	1.94
D	1H	1	39	41		3	320	18	8	315	0.025	2.54
D	1H	1	52	56		4	285	16	3	282	0.011	1.06
D	1H	1	89	93	3	5	210	12	13	195	0.067	6.67
D	1H	1	129	133		6	114	19	5	110	0.045	4.55
D	1H	2	65	69		7	173	14	14	161	0.087	8.70
D	1H	2	89	93		8	250	21	32	218	0.147	14.68
D	1H	2	105	109	4	9	226	16	24	202	0.119	11.88
D	1H	2	115	120		10	395	24	45	338	0.133	13.31
D	1H	3	89	92		11	28	5	2	18	0.111	11.11
D	1H	3	99	101		12	166	17	16	155	0.103	10.32
D	1H	3	112	115		13	56	17	2	45	0.044	4.44
D	1H	4	25	29		14	56	6	2	40	0.050	5.00
D	1H	4	77	79		15	349	20	14	335	0.042	4.18
D	1H	4	106	108		16	304	16	12	292	0.041	4.11
D	1H	4	115	117	5	17	380	18	16	362	0.044	4.42
A	2H	3	39	42		18	359	18	8	351	0.023	2.28
A	2H	3	52	54		19	427	21	9	422	0.021	2.13
A	2H	3	61	64		20	336	18	10	326	0.031	3.07
A	2H	3	90	92		21	357	18	14	343	0.041	4.08
A	2H	4	149	151		22	141	10	15	126	0.119	11.90
A	2H	6	113	117	6	23	316	14	21	302	0.070	6.95
A	2H	6	128	130		24	356	16	8	348	0.023	2.30

Table 3.5 Percentages of foraminifer fragmentation through the 6 intervals: consistently low percentages of fragmentation are recorded suggesting minimal transport and dissolution.

3.4.3 Intra-niche movement

Benthic foraminiferal faunas commonly inhabit a few centimetres of depth in the sediment at the seabed, and this interval coincides with the range from well-oxygenated to dysoxic conditions (Jorissen et al. 2007). The bioturbated zone below the sediment-water interface typically has a heterogeneous distribution of benthic foraminifera, the distribution being related to the subsurface habitats of some species and also to taphonomic processes (Richard and Sen Gupta 1989). Therefore, *B. spissa*, if anything, would be recording the oxygen of pore waters (PW-O_2) at the depth at which it was living, as opposed to BW-O_2 that other proxies are attempting to estimate (laminations and overall assemblages). The high range of oxygen estimated by pore density (Fig. 3.7) is consistent with a migratory pattern, although we can provide no direct evidence that PW-O_2 is being recorded in pore density. According to Stabeno et al. (1999) and Takahashi (2005), productivity is high in the Bering Sea at present, causing seasonal organic carbon influx through the water column which leads to dysoxic conditions at the seabed. Often, infaunal benthic foraminifera migrate vertically to where food and oxygen availability meets their demand (Jorissen et al., 1997; Nomaki et al. 2005; Duijnstee et al. 2003). Species that are deeply infaunal in well-oxygenated settings have been shown to occur close to the sediment surface in eutrophic, oxygen-depleted environments (Mackensen and Douglas 1989; Kitazato 1994; Rathburn and Corliss 1994). Saffert and Thomas (1997) have also shown that foraminiferal migration in response to environmental variables is dominantly upward toward the sediment-water interface. Specimens of *B. spissa* may have migrated vertically through the seabed sediment in response to seasonal variations in environmental conditions. Thereby specimens that were living at different levels of bottom-water oxygenation were possibly mixed as a result of vertical intra-niche movement (e.g. see Figs. 3.8 A and B) during their life time. Thus, *B. spissa* examined at various depths may have 'mixed' the primary oxygen signal via vertical migration.
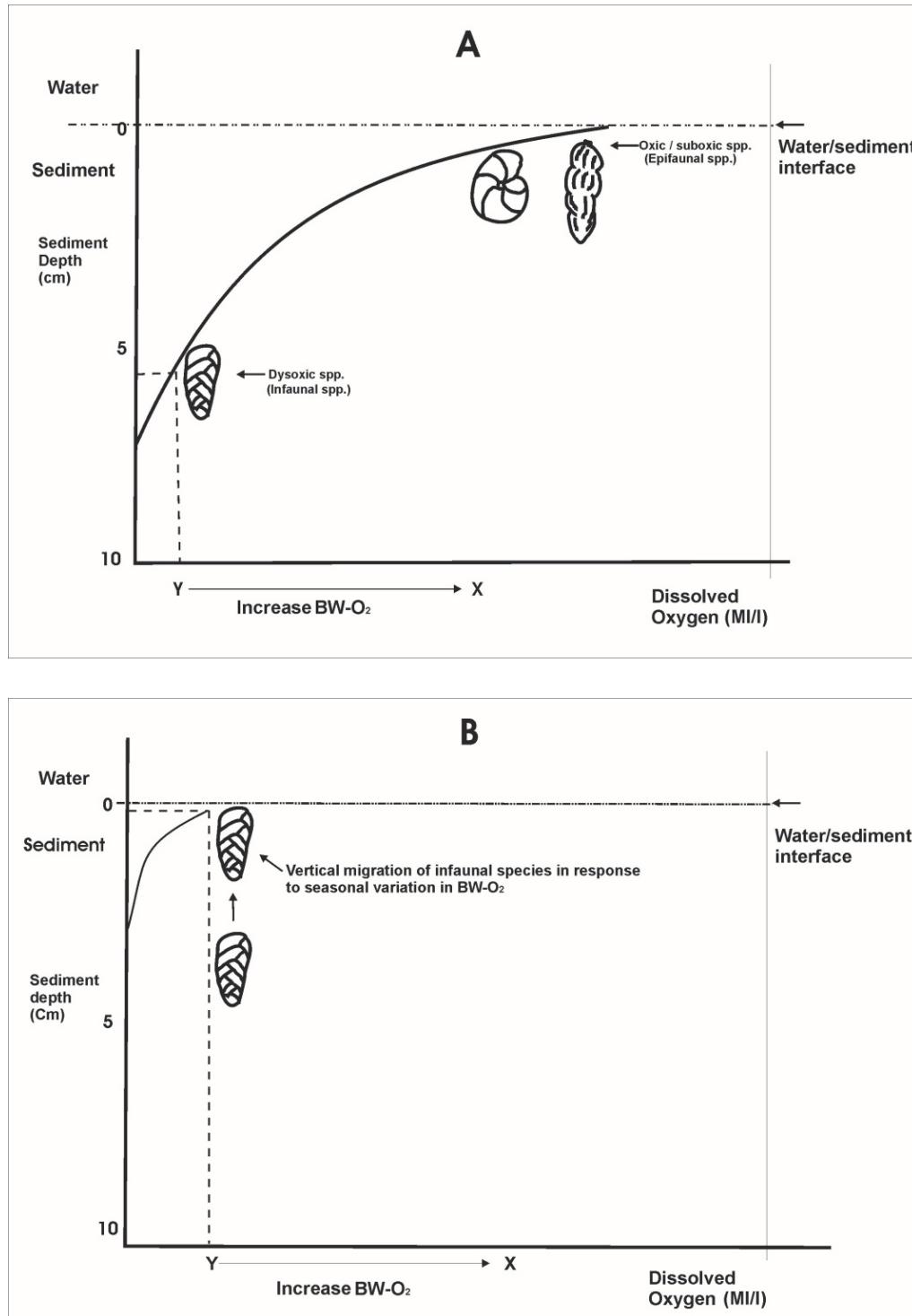
Figure 3.8 A and B Idealized schematic of intra-niche movement in response to different environmental conditions: vertical-axis shows sediment depth: 'A' shows oxic and suboxic species at the water-sediment interface in a well-oxygenated condition; 'B' shows an infaunal species in a less oxygenated environment moving up (arrows) within the sediment in response to seasonal fluctuations in the food supply and corresponding changes in oxygen-level at depth. Infaunal species adapt

**to dysoxic conditions by moving towards the water-sediment interface; these
movements may be responses either to the availability of food at the sediment
surface, or to changes in oxygen concentrations within sediment pore-waters.**

3.4.4. Nitrate respiration and other alternate modes of survival

Risgaard-Petersen et al. (2006) observed that certain benthic foraminiferal species
switch to nitrate respiration during oxygen depletion in the water column, thus
suggesting that the pores have a physiological function for intracellular nitrate-uptake.
Glock et al. (2011) suggested that the PD of *B. spissa* is probably more sensitive to
bottom water nitrate (BW-NO_3^-) than to BW-O_2. The fact that several benthic species
are able to survive anoxia indicates the significance of nitrate respiration (full reduction
of nitrate to dinitrogen gas: Risgaard-Petersen et al. (2006)); nitrate respiration seems to
be widespread among foraminifera from oxygen depleted habitats (Risgaard-Petersen et
al. 2006; Glud et al. 2009; Høgslund et al. 2008; Piña-Ochoa et al. 2010). Piña-Ochoa et
al. (2010) attributed the diverse metabolic capacity for benthic foraminifera, which
enables them to respire with oxygen and nitrate and to sustain respiratory activity, as
one of the reasons for their successful colonization of diverse marine sediment
environments.

Recent findings on survival strategies of *B. spissa* show that it takes up nitrate for
respiration through the pores or uses these to release denitrification products like N_2O or
N_2, and that they seem to adapt their pore-densities to survive in extreme habitats
(Glock et al. 2011). *B. spissa* specimens may have lived at different levels of bottom-
water oxygenation and possibly switched to nitrate respiration during anoxia or less
bottom-water oxygenation, and therefore did not need additional pores on their test as a
strategy for survival. Glock et al. (2011) speculated as to whether the pores in *B. spissa*
were involved in nitrate respiration. Nitrate storage and eventual usage may have been
part of the strategies adopted by *B. spissa*, though this cannot be confirmed from this
study.

3.5 Conclusions

In this study no significant correlation was identified between the PD of *B. spissa*
and interpreted BW-O_2. In part, this might reflect that *B. spissa* can utilise BW-NO_3^- for

respiration during episodes of sea bottom dysoxia or anoxia and/or that it is monitoring PW-O$_2$. Other, factors, including mixing of assemblages by *in-vivo* migration of foraminiferal assemblages between microhabitats, or post-mortem sediment transport and bioturbation may have obscured the primary PD signal. This study cautions against the use of PD analysis in *B. spissa* as a means of determining sea bottom oxygen conditions unless precise lamination-by-lamination sampling can be undertaken, in a setting where all taphonomic processes are clearly understood.

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Abstract

Benthic foraminiferal assemblages were analysed down core in chronological order (at ~13 cm intervals) from IODP Expedition 323 Site U1342 (~818 m water depth), equating to the last ~597 Kyr (~20.6 m composite core depth) and representing sediments formed during the Tarantian and Ionian stages of the Pleistocene (late Quaternary). Some 68 species of benthic foraminifera have been identified and these consist dominantly of shallow infaunal taxa such as *Uvigerina* spp., *Islandiella norcrossi* and *Cassidulina* spp. Eight temporally discrete intervals are distinguished down core by the abundances of key species: Interval 1, *Uvigerina bifurcata*-dominated; Interval 2, *Cassidulina laevigata*-dominated; Interval 3, *Uvigerina bifurcata / Takayanagia delicata*-dominated; Interval 4, *Islandiella norcrossi*-dominated; Interval 5, second *Uvigerina bifurcata*-dominated; Interval 6, *Takayanagia delicata / Alabaminella weddellensis*-dominated; Interval 7, second *Uvigerina bifurcata / Takayanagia delicata*-dominated and Interval 8, *Takayanagia delicata*-dominated. The foraminiferal assemblages signal a well-oxygenated sea bed for intervals 1, 3 and 7, whilst intervals 2, 4, 5, 6, and 8, suggest the strong influence of phytodetritus flux to the seabed. The dominance of infaunal benthic foraminifera (such as *Bolivina spissa, Brizalina alata*) at certain horizons suggests that some laminated intervals were caused by low oxygen at the seabed, whilst in other intervals the occurrence of coarse terrigenous IRD suggests sea bed currents (with a winnowing effect) were the formative mechanism of lamination. The phytodetritus-rich or oxygenated intervals show no clear relationship with the glacial-interglacial oscillation of the past ~597 Kyr at the site, or with larger scale environmental change in the Bering Sea during the late Pleistocene.

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4. Introduction

Much recent research on modern deep-sea faunas has shown that benthic foraminifera convey a significant amount of information about conditions on the seabed, and have played an important part in efforts to understand these conditions (Gooday et al. 1992; Kaiho 1994, 1999; Kuhnt et al. 1999; Levin and Gage 1998; Jorissen et al. 2007; Takahashi 2005; Sun et al. 2006; Kender et al. 2008; Alve 2010; Bubenshchikova et al. 2010; Glock et al. 2011; Kaminski 2012; Kuhnt et al. 2013). Many of these studies aimed at obtaining a general understanding of past environmental conditions; for example deep sea benthic foraminifera are known to respond to changes in organic carbon flux and oxygen availability in modern seabed settings (e.g. Corliss 1985; Kaiho 1994; Thomas and Gooday 1996; Jorissen et al. 2007), and have been shown to respond to environmental variability in the Bering Sea during the last glacial cycle (Gorbarenko et al. 2005; Okazaki et al. 2005).

Benthic foraminifera, along with sedimentological and diatom assemblage data from Site BOW-8A (Fig. 4.1: black square; nearby to Site U1342 on the Bowers Ridge, Bering Sea) have been used to investigate changes to surface water productivity and bottom water ventilation during the late Quaternary (Katsuki and Takahashi 2005). On the Umnak Plateau (southern Bering Sea), phytodetritivore dominated assemblages of *Alabaminella weddellensis* are characteristic of the last glacial maximum, while species considered tolerant of low oxygen conditions (of the genera *Rutherfordoides* and *Bulimina* spp.) dominated faunas during the deglacial when surface water productivity was most pronounced (Okazaki et al. 2005).
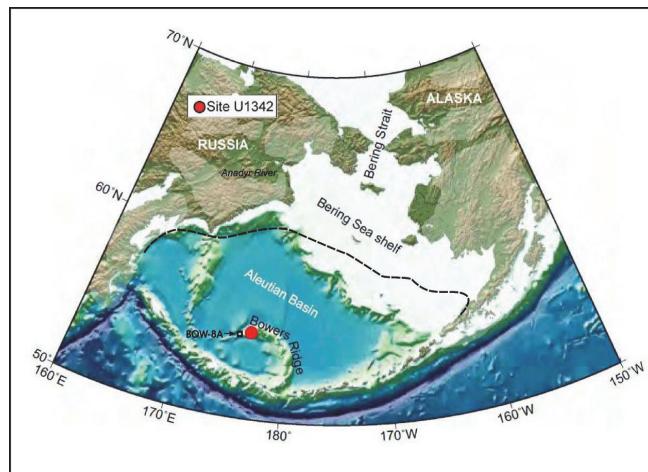
Figure 4.1 Geography of the Bering Sea: presently, seasonally sea-ice covered areas of the Bering Sea are found mainly over the northern continental shelf (demarcated with a dashed line; Niebauer et al. 1999). Bowers Ridge site U1342 is indicated by red dot; Site BOW-8A is represented with a black square. Shaded areas (smoky patches) are believed to have had ice sheets at times in the Quaternary (Niebauer et al. 1999)

In this chapter, total benthic foraminiferal assemblages have been examined from 20.59 m composite depth (m-CCSF) of core recovered from Site U1342, western Bowers Ridge, Bering Sea (Fig. 4.1), this, being a subset of data from a 41.35 m long composite core recovered during Integrated Ocean Drilling Program (IODP) Expedition 323 in year 2009. The entire 41.35 m interval spans the late Pleistocene and Holocene, although the majority of the Holocene was not recovered (Expedition 323 Scientists, 2011). Notwithstanding the loss of much of the Holocene from the uppermost part of the core, the studied 20.59 m interval equates to the past ~597 Kyr. Age calibration is by means of oxygen isotope stratigraphy (Knudson and Ravelo in review, personal communication). In this chapter, the total benthic foraminifer faunal abundances and species diversity is assessed down core, and is used to recognise 8 discrete intervals: the possible ecological implication of these intervals is discussed. Environmental data gleaned from 'ice rafted debris' (IRD) are also used to interpret the environmental record down core, and where applicable are compared with the foraminiferal dataset.

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4.1 Materials and methods

4.1.1 Sample analysis of foraminifera

Samples used for this study were previously prepared in Prof. Ravelo's laboratory at the University of California, Santa Cruz. Samples were freeze-dried, washed through a 62 μm mesh screen to liberate the microfossils, split into two fractions (one of which the oxygen isotope stratigraphy was generated from), and stored in labelled vials before picking. A total of 158 samples were picked for benthic foraminifera and IRD analyses, at ~13 cm intervals through the upper ~20.6 m of the core (the total core length spans 41.35 m). A minimum of 300 individuals of benthic foraminifera were targeted for picking from each sample, and placed into reference slides. Where there were fewer than 300 available, all available benthic foraminifer were picked for analysis. Samples that contained significantly more than 300 benthic foraminifer specimens were divided using a micro hand-splitter until a suitable aliquot was achieved (i.e. half, quarter, one-eighth sizes) for benthic foraminiferal analysis. The Hitachi S-3600N scanning electron microscope in the Geology Department at University of Leicester was used for imaging the benthic foraminifera. Magnifications of up to 700 times have been used to image the test ultra-structure. The SEM is also used to gauge the relative preservation condition of specimens, especially to determine incidences of abrasion. To compensate for charging effects on some of the specimens (especially the relatively large ones), the SEM partial vacuum mode was activated. Foraminiferal specimens collected are deposited in the collections of the British Geological Survey, Keyworth-Nottingham. The taxonomic composition of the foraminifera in the core analysed has been described in Chapter 2.

4.1.2 Foraminiferal palaeoecology

The main distinction in benthic foraminiferal microhabitat characteristics is that between epifaunal and infaunal (Jorissen et al. 1995). The depth in the sediment down to which most organisms can live is determined by oxygen availability (except in the case of active anaerobic taxa), and in the presence of oxygen, the vertical distribution of organisms is controlled by food availability (see chapter 3; TROX-model: Jorissen et al. 1995). Linke and Lutze (1993) proposed that foraminiferal microhabitats are not

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necessarily static; benthic foraminifera generally inhabit several deep superficial sediment layers. Various terms have been used to categorise these microhabitats. For example: epifaunal (0–1 cm), shallow infaunal (0–2 cm), intermediate infaunal (1–4 cm), transitional (0–4 cm) and deep infaunal (>4 cm) (Corliss 1991; Rathburn and Corliss 1994; Rathburn et al. 1996; Mackensen 1997). These groupings may reflect different strategies for survival (acquiring food, avoiding predation, and reproduction) within a diverse benthic environment that can extend from centimetres above the sediment-water interface to centimetres into the sea floor (McCorkle et al. 1997). The absolute penetration depth of foraminiferal distribution probably also reflects a series of environmental and ecological factors (i.e. oxygen penetration depth and food supply) that are likely to differ from site to site, and possibly as a function of time at a given site in response to the changing flux of organic matter to the sea floor. This depth-range includes the complete range from well oxygenated to strongly dysoxic conditions. However, some deep infaunal taxa are not limited by the zero oxygen level, but may be involved in anaerobic pathways of organic matter remineralisation at several centimetres depth in the sediment (see also Chapter 3).

The most important factors controlling deep-sea benthic foraminifera are organic matter influx from surface primary productivity, oxygenation of bottom waters, and bottom water carbonate corrosiveness (Gooday and Rathburn 1999). Although the ecology of benthic foraminiferal assemblages is controlled by multiple environmental factors, the organic carbon flux to the sea floor is thought to be the predominant environmental parameter controlling the composition of assemblages, and the oxygen concentration becomes limiting when it reaches a critical level for a species (e.g. see Kaiho 1994; Jorissen et al. 1995). Oxygen can only be considered as the main factor for the majority of species when oxygen levels are very low (<1 ml/l), and the percentage occurrence of deep infauna is high (Jorissen et al. 1995; Altenbach et al. 1999; van der Zwaan et al. 1999; De Rijk et al. 2000; Wollenburg and Kuhnt 2000; Murray 2001; Szarek et al. 2007; Mojtahid et al. 2010: see also Chapter 3). Kitazato and Ohga (1995) have shown in feeding experiments that shallow infaunal species are likely to respond to deposition of fresh phytodetritus.

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According to Jorissen et al. (1998) and Licari et al. (2003), intermediate infaunal species probably inhabit the nitrate reduction zone, while deep infaunal species survive in the sulphate reduction zone. This means that the species average living depth (0-8 cm) and down core distribution patterns used by Bubenshchikova et al. (2008) are not sufficient enough to differentiate the intermediate and deep infaunal groups. For example, species of *Nonionella, Fursenkoina, Chilostomella* and *Globobulimina* genera have been found deep in the sediments within or below the oxic-anoxic interface and are deep infaunal in many meso-eutrophic settings (e.g., Corliss 1991; Corliss and Emerson 1990; Bernhard 1992; Kitazato 1994; Rathburn and Corliss 1994; McCorkle et al. 1997; Fontanier et al. 2002; Licari et al. 2003). Benthic foraminiferal microhabitats in Core U1342 must have depended on the temporal variation in organic matter flux, oxygenation, and redox conditions for their survival. Kaiho (1994) only considered dissolved oxygen content in modern oceans in his benthic foraminiferal oxygen index study; other factors that may relate to benthic foraminifera microhabitat occupancy such as carbon influx, temperature, salinity, wave action, sediment type and current (Murray 1991) were not considered in assigning the deep sea benthic species into various oxygen indicator groups. However, as outlined above, many species also respond to organic carbon flux, food type, and are able to use anaerobic pathways for respiration. This limitation makes Kaiho's (1994) oxygen proxy (Benthic Foraminiferal Oxygen Index) difficult to utilise for this study.

An examination of the faunal data down core in this study indicates that taxa can be assigned to five categories (see Table 4.1; Plate 4.1), based on key previous studies such as Bubenshchikova et al. (2008) in the Okhotsk Sea (nearby to the Bering Sea), and other studies where there are generic affiliation and close morphologic similarity to taxa in this study (e.g. Corliss and Chen 1988; Thiel et al. 1989; Corliss 1985; 1991; Steinsund et al. 1994; Kitazato 1994; Smart et al. 1994; Thomas and Gooday 1996; Gooday 1988, 1993; Kitazato and Ohga 1995; Polyak et al. 2002; Fontanier et al. 2002; Licari et al. 2003; Sun et al. 2006; Ivanova et al. 2008; Kender et al. 2008 and Alve 2010; Bubenshchikova et al. 2008). Other species (~33% of the total counts) with uncertain affiliation were not assigned to any microhabitat / oxygen-level group (Table 4.1). Most of the taxa examined are cosmopolitan (see also Chapter 2) and have been

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recorded previously from faunas in the oxygen minimum zone (OMZ) of the Okhotsk Sea (Bubenschikova 2008, 2010), and from the Pacific Ocean and its environs including the North Pacific (Butt 1980; Dowsett and Ishman 1995), Northwestern Pacific (Ohkushi et al. 2000), Equatorial Pacific (Akimoto 1994), Southeast Pacific (Schönfeld 1995), Japan Sea (Kato 1992) and Arctic Ocean (Scott and Vilks 1991).

4.1.2.1 Deep infaunal species

These are benthic foraminifer species with microhabitat preference that is >4-10 cm below the sea-sediment interface, in normal marine settings (i.e. not in OMZs). These species are thought to be able to survive low oxygen, and have been designated as "dysoxic" by Kaiho (1994, 1999). These benthic foraminifera includes *Globobulimina affinis, Chilostomella oolina* (Corliss, 1985); *Globobulimina* spp., *Brizalina pacifica, Fursenkoina* spp. *Nonionella digitata, Globobulimina auriculata, Chilostomella ovoidea* (Corliss and Emerson 1990; Corliss 1991; Bernhard 1992; Kitazato 1994; Rathburn and Corliss 1994; Kitazato and Ohga 1995; McCorkle et al. 1997; Fontanier et al. 2002; Licari et al. 2003, Bubenshchikova et al. 2008); Kender et al. (2008) placed *Martinottiella* aff. *communis* and *Martinottiella* sp. in the deep infauna group based on the morpho-group categories of Van den Akker et al. (2000), and Kender and Kaminski (submitted) found it to occur within the modern OMZ of Bowers Ridge. *Bolivina spissa* has been placed in various microhabitat preference groups by different authors: intermediate infauna (Bubenshchikova et al. 2008), deep infauna (Bubenshchikova et al. 2010) and as shallow infauna (Glock et al. 2011). As noted in Chapter 3, detailed analysis suggests that this species had a range of oxygen tolerances.

4.1.2.2 Intermediate infaunal species

These are benthic species with microhabitat preference that range from ~1.8 to 4.0 cm below the sea-sediment interface (Bubenshchikova et al. 2008) in typical marine settings (i.e. not the OMZ). They are probably not able to survive extremely low oxygen levels, and are probably responding mainly to changes in the type and regularity of organic carbon flux into the ocean. They were termed the "suboxic" group by Kaiho (1994, 1999b). These species includes *Melonis barleeanum* and *Pullenia simplex*

(Corliss 1991); *Bolivina spissa, Nonionella labradorica* (Bubenshchikova et al. 2008); *Takayanagia delicata* (Ohkushi et al. 2003).

4.1.2.3 Shallow infaunal species

These are benthic species with microhabitat preference that ranges from 0.5 to 1.7 cm (Bubenshchikova et al. 2008) in typical marine settings (i.e. not the OMZ). These benthic species also are probably not able to survive very low oxygen levels, and are probably responding mainly to changes in the type (quality) and seasonality of organic carbon flux into the ocean. They were also termed the "suboxic" group by Kaiho (1994, 1999). Benthic foraminifer species classified as shallow infauna includes *Lenticulina* spp. (Corliss 1991); *Islandiella norcrossi, Uvigerina* spp., *Quinqueloculina* spp. and *Takayanagia delicata* (Bubenshchikova et al. 2008); *Uvigerina peregrina, Uvigerina hispida, Bulimina mexicana* (Licari et al. 2003, Kender et al. 2008); *Eggerella* spp. (Fontanier et al. 2002); *Fursenkoina* sp. *Uvigerina* spp. and *B. spissa* (Kitazato and Ohga 1995).

4.1.2.4 Epifaunal species

These are benthic foraminiferal taxa with typical microhabitat preference from 0–1 cm. They were termed the "oxic" group by Kaiho (1994; 1999), and here include: *Hoeglundina elegans, Cassidulina laevigata* and *Cassidulina teretis* (Licari et al. 2003); *Triloculina* spp. (Corliss 1985; Corliss and Chen 1988, Corliss 1991; Gooday et al. 1992; Kitazato 1994); *Oridorsalis umbonatus, Cibicidoides* sp. and *Globocassidulina subglobosa* (Kender et al. 2009); *Alabaminella weddellensis* and *Epistominella exigua* (also phytodetritivores: Gooday 1988, 1993; Sun et al. 2006). Some other epifaunal species are: *Pyrgo murrhina, Triloculina frigida, Epistominella exigua, Lenticulina* spp. and *Oridorsalis umbonatus* (Corliss and Chen 1988); *Triloculina* sp. (Kitazato and Ohga 1995); *Triloculina frigida* (Corliss and Chen 1988); *Planulina ariminensis* and *Cibicidoides wuellerstorfi* (Kitazato 1994).

4.1.2.5 Phytodetritivores

These are benthic foraminiferal species that are known to respond to marked seasonality in food supply to the ocean. These include: *A. weddellensis* which is regarded as an opportunistic species, blooming at times of high seasonal phytodetrital flux to the sea floor (Gooday 1988, 1993; Gooday et al. 1990; Thomas and Gooday 1996; Smart et al. 1994); *Epistominella exigua* and *A. weddellensis* (Gooday 1988; Thiel et al. 1989; Gooday et al. 1990; Gooday 1993; Smart et al. 1994; Kitazato and Ohga 1995; Sun et al. 2006); and *Islandiella norcrossi* (Steinsund et al. 1994; Polyak et al. 2002; Ivanova et al. 2008). Alve (2010) showed that living *Cassidulina laevigata* is a phytodetritivore, since it disappeared when there was a halt in the supply of fresh phytodetritus. Gooday (1996) classified some other benthic foraminifer as species that are associated with phytodetritus; these include *Adercotryma glomeratum, Alabaminella weddellensis, Epistominella exigua, Fursenkoina* sp., *Globocassidulina subglobosa, Oridorsalis umbonatus, Tinogullmia riemanni* and *Trochamminacean* sp. 1. In this study, only *A. weddellensis, C. laevigata* and *I. norcrossi* are considered as phytodetritivores based on their consistent classification as such by different authors.

4.2 Analytical criteria for foraminifera

In order to broadly examine the distribution patterns of benthic foraminiferal fauna down core in this study, plots of the 14 most common species representing 92.07% of the total fauna counted were initially made (Fig. 4.5). For the purpose of assemblage Interval demarcation, the 6 most numerically abundant species (for images see Plate 4.1) representing 71.04% of the total fauna counted were plotted down core and used. Their microhabitat preferences are based on previous studies outlined above (Corliss and Chen 1988; Gooday 1988; Thiel et al. 1989; Corliss 1991; Steinsund et al. 1994; Kitazato and Ohga 1995; Licari et al. 2003; Ivanova et al. 2008; Bubenshchikova et al. 2008, 2010; Alve 2010). These taxa are *A. weddellensis, I. norcrossi, T. delicata, C. laevigata, B. exilis and U. bifurcata.*

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Benthic foraminifera fauna recorded from Core 1342 (~20.60 m-ccsf)	Deep infauna (Dysoxic): >4 to 10 cm below sea-sediment interface	Intermediate infauna (Suboxic): ~1 to 4 cm below sea-sediment interface	Shallow infauna (Suboxic): 0-2 cm below sea-sediment interface	Epifauna (Oxic): 0-1 cm	Phytodetritivores	Unassigned
Alabaminella weddellensis				X	X	
Angulogerina angulosa						X
Bolivina sp. 1	X					
Bolivina sp. 2	X					
Bolivina sp. 3	X					
Bolivina spissa	X	X				
Brizalina alata	X					
Brizalina earlandi	X					
Bulimina exilis	X					
Bulimina mexicana	X	X	X			
Cassidulina laevigata				X	X	
Cassidulina reniforme			X			
Cassidulina teretis				X		
Cassidulinoidies parkerianus						X
Cibicidoides sp.			X	X		
Cushmanina striatopunctata						X
Dentalina ittai.						X
Eggerella sp. 1			X			
Ehrenbergina sp.						X
Elphidium sp. 1			X			
Elphidium sp. 2			X			
Elphidium sp. 3			X			
Elphidium ustulatum			X			
Epistominella exigua				X	X	
Epistominella pulchella						X
Fissurina crebra			X			
Fissurina minima			X			
Fursenkoina aff. *texturata*	X					
Globobulimina auriculata	X					
Globobulimina pacifica	X					
Globocassidulina subglobosa		X	X	X	X	
Gyroidina sp. 1						X
Gyroidina sp. 2						X
Hoeglundina elegans				X		
Islandiella norcrossi			X		X	

Table 4.1 continues on the next page

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Benthic foraminifera species microhabitat group (from previous studies)						
Benthic foraminifera fauna recorded from Core 1342 (~20.60 m-ccsf)	Deep infauna (Dysoxic): >4 to 10 cm below sea-sediment interface	Intermediate infauna (Suboxic): ~1 to 4 cm below sea-sediment interface	Shallow infauna (Suboxic): 0-2 cm below sea-sediment interface	Epifauna (Oxic): 0-1 cm	Phytodetritivores	Unassigned
Karreriella sp.						X
Lagena hispida						X
Lagena nebulosa						X
Lagena sp. 1						X
Lagena sp. 2						X
Lagena sp. 3						X
Lagena sulcata						X
Lenticulina rotulata			X			
Lotostomoides calomorphus						X
Martinottiella communis	X					
Melonis barleeanus		X				
Moncharmontzeiana petaloskelts						X
Nonionella digitata	X					
Nonionellina labradorica		X				
Oolina hexagona						X
Oridorsalis umbonatus				X	X	
Planulina ariminensis				X		
Planulina wuellerstorfi				X		
Procerolagena gracilis						X
Procerolagena gracillima						X
Pullenia simplex			X			
Pyrgo murrhina				X		
Quinqueloculina sp.				X		
Reussoolina apiculata						X
Stainforthia fusiformis						X
Takayanagia delicata			X			
Triloculina frigida				X		
Uvigerina bifurcata		X	X			
Uvigerina hispida		X	X			
Uvigerina peregrina		X	X			
Uvigerina senticosa		X				
Uvigerina sp. 1		X				
Valvulineria araucana						X

Table 4.1 Benthic foraminifer microhabitat preference in accordance with consistent groupings in selected studies: Corliss and Chen 1988; Gooday 1988; Thiel et al. 1989; Corliss 1991; Steinsund et al. 1994; Kitazato and Ohga 1995;

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Licari et al. 2003; Ivanova et al. 2008; Bubenshchikova et al. 2008, 2010; Alve 2010. Some ~ 33% of the species (23 species) examined could not be assigned to a category.

4.3 Analysis of ice rafted debris (IRD)

Expedition 323 Scientists (2011) described the colour of the sediment from Site U1342 to generally range from very dark greenish grey and dark grey, to biogenic-rich olive grey to olive, with dark grey to black or shades of light grey to white ash layers. In this study, lithic fragments are considered to be ice-rafted-debris (IRD), as there is no other way that they could have easily reached this location. IRD is sediment released from melting ice in the ocean and deposited on the sea floor (Knudsen et al. 2004). Whenever ice is in contact with terrigenous debris (i.e clay, sand, gravel, boulder clay etc.), there is the potential for entrainment and enclosure of the lithic debris (Bischof 2000). Site U1342 is located at the highest point of Bowers Ridge, which is ~800 m below sea level today. Aiello and Ravelo (2012) suggest that as Bowers Ridge is below sea level, most of the siliciclastics present in samples from Bowers Ridge were likely derived from sea icebergs. IRD (rock and mineral fragments) are classified into 2 broad groups; these are considered useful for the purpose of assessment of the sedimentological (i.e laminated intervals vis-à-vis the ice drafted debris) context of the foraminiferal assemblages, possible links with productivity, determination of sediment provenance and other environmental signatures prevailing at site U1342, Bowers Ridge. LR04 data (Lisiecki and Raymo 2005) and the age/depth tie points from detailed benthic foraminiferal oxygen isotope ($\delta^{18}O$) analyses carried out on *Uvigerina* sp. in the same samples by Knudson and Ravelo (personal communication), are also used in this study for interpretation.

Specific minerals and grains, i.e. crystals (mainly quartz), rock fragments, and altered volcanics showing signs of abrasion, were counted and examined in the >62 μm size fraction sample. IRD from 158 samples out of the 160 samples from ~20.60 m interval studied (no available sample at two depths: Appendix 1) were analysed. Grains

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were identified based on physical properties. Using the same procedures as for the benthic foraminiferal analysis, a minimum of 300 individual fragments were picked from each sample into reference slides, using a micro hand-splitter where needed (half, quarter, one-eighth sizes). The number of individual specimens picked (i.e. >300) from each of the 158 samples gives a good representation of all the fragment types (rock and mineral) present in the aliquot of a sample.

Fragments were classified into two broad groups, i) rock and ii) mineral fragments, based on physical characteristics (colour, texture, shape etc.) as observed under the binocular microscope. The 2 broad classifications are considered useful for the purpose of determination of provenance of the fragments. These two categories were further qualified using textural form (size and shape). As a way to standardize IRD measurements in this study, dimensions of ten of the largest grains (both rock and mineral) were determined per sample. Maximum and minimum diameters of these 10 fragments (measuring 20 dimensions from rock and mineral fragments) per sample were measured, and the average dimensions of the largest grains per sample for each group were determined and used for analysis. These values are plotted against other parameters down core. Fragment sizes were classified based on Wentworth (1922) and shapes classified into 3 broad classes: very angular to angular, sub-angular and rounded to well-rounded. A few fragments of sponge spicules are also present. Due to practicalities, IRD analysed are predominantly sand size (very fine sand, fine sand, medium sand and coarse sand), even though silt may form part of the IRD (Aiello and Ravelo 2012). The average maximum diameter for rock fragments ranges from 0.30-0.85 mm, and average minimum diameter ranges from 0.20-0.57 mm; while the average maximum diameter of mineral fragments ranges from 0.21-0.60 mm, and the range for the average minimum mineral diameter is 0.18-0.57 mm (Appendix 10). Average dimensions for a total of 6320 fragments (3160 each of rock and mineral fragments) measured were plotted against other parameters, such as the sedimentological log, benthic foraminiferal oxygen isotope record, species abundances, and species diversity. Various rock and mineral fragments examined from the IRD study consist of different shades of quartz fragments, ranging from clear/glassy, frosted (with shades ranging

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from light green, light brown, grey to black) and few black, brown and glassy rock fragments, and few mica sheets.

4.4 Reconstructing the time interval of the sampled core

The total core length retrieved at Site U1342 is 41.35 m (CCSF) spans the last ~1.2 Ma (middle Pleistocene to Holocene), although the majority of the Holocene was not recovered (Expedition 323 Scientists 2011). The age/depth tie points used in the study are derived from detailed benthic foraminiferal oxygen isotope δ^{18}O analyses carried out on *Uvigerina* sp. on the same samples by Knudson and Ravelo (paper in review). This isotope stratigraphy was matched to the global isotope curve (LR04) of Lisiecki and Raymo (2005), where they found a correlation coefficient of 0.64. The average sedimentation rate down the ~20.60 m interval is determined as ~0.0373 m/ka, although is variable (Table 4.2; Fig. 4.2). The interval analysed (~20.60 m) corresponds to ~597 ka. A sedimentary core log based on the core photographs of Site U1342 was made by carefully analysing the photographs (Fig. 4.3). In this study, samples have been taken at ~13 cm spacing (an average time resolution of ~3 ka between each sample).

SN	1342 depth (CCSF-A)	LR04 (ka)	Sedimentation Rate (m/ka)
1	0.02	0.00	0.0126
2	0.20	14.70	0.1018
3	0.55	18.10	0.0337
4	1.16	36.11	0.0422
5	2.23	61.64	0.0516
6	3.28	82.00	0.0205
7	3.55	95.18	0.0348
8	4.50	122.29	0.0264
9	4.96	139.94	0.0353
10	6.56	185.11	0.0263
11	7.97	239.00	0.0362
12	9.63	284.81	0.0630
13	12.41	328.83	0.0333
14	14.83	401.72	0.0667
15	15.39	410.00	0.0144
16	15.72	433.20	0.0395
17	18.01	491.29	0.0263
18	19.61	552.00	0.0261
19	20.29	578.19	0.0185
20	21.26	630.70	0.0205

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Table 4.2 Age model for top ~21.26 m of Site U1342 (Knudson, and Ravelo personal communication) SN = sample number; CCFS-A (m) = core composite depth below seafloor in meters; LR04 = global Pliocene-Pleistocene benthic d^{18}O stack (Lisiecki and Raymo 2005); m/ka = metre per thousand years.

4.5 Sedimentological analysis

Site U1342 is at a water depth that lies within the modern OMZ, and core-sediments retrieved display a relatively low sedimentation rate (Table 4.2: average of ~0.0373 m/ka; see also Fig. 4.2), which are the lowest sedimentation rates among the other Expedition 323 sites (see Chapter 1: Fig. 1.3) (Expedition 323 Scientists 2011). The sedimentology comprises biogenic (mainly diatom frustules with varying proportions of calcareous nannofossils, foraminifera, silicoflagellates, and radiolarians), siliciclastic (mainly silt and very fine sand, and also isolated clasts of pebble to cobble size), and volcaniclastic materials (mainly fine ash) (see Expedition 323 Scientists 2011). There are variations in the sedimentation rate down core at Site U1342 (Table 4.2; Fig. 4.2). The highest sedimentation rate is recorded at ~15 Ka (0.1018 m/ka) and the lowest at the top of the core (0.02 m-CCSF = top of the core). According to Aiello and Ravelo (2012), grain size analysis shows that sediment at Bowers Ridge is generally coarser when compared with sediments from other Bering Sea slope sites; the average mean size being fine silt and sand-size particles. As Bowers Ridge is below sea level, Aiello and Ravelo (2012) suggest that siliciclastics were likely derived from sea icebergs formed in the winter months. According to Aiello and Ravelo (2012), diatom ooze has been considered as the dominant lithology at the two other sites (U1343 and U1344) on the Bowers Ridge, where other lithologies include authigenic carbonates (dolomite and aragonite) and sulphide (Expedition 323 Scientists 2011).
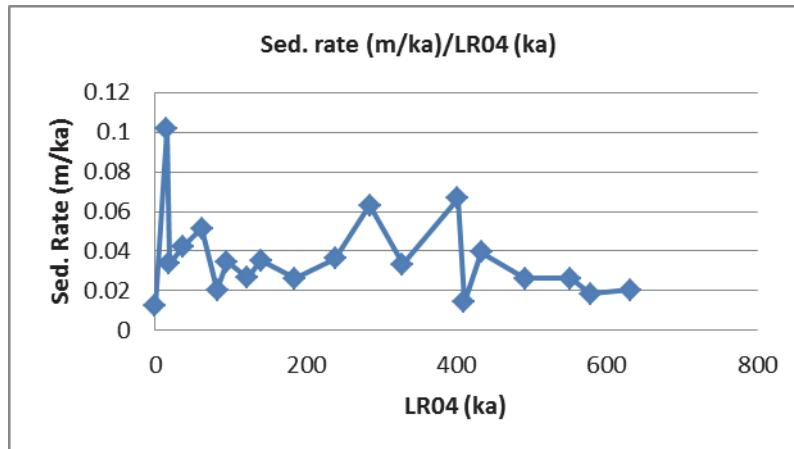
Figure 4.2 Sedimentation rate at Site U1342, Bowers Ridge (Note that total interval of this study is ~20.60 m = ~ 597 Kyr). The sedimentation rate is based on matching oxygen isotopes with the global composite LR04, and was provided by Knudson and Ravelo (in review).

The most prominent sedimentary features in the core from Site U1342 are decimetre to metre scale bedded alternations of sediment colour and texture, reflecting alternations in lithology that are predominantly parallel laminated (Fig. 4.3), but occasionally cross-laminated (Expedition 323 Scientists 2011). Fine-scale lamination preserving alternations between millimetre-scale laminae of biogenic and terrigenous material were also present. Sediments were bioturbated at some intervals between 3.60 and 3.70 m; 5.00 and 5.20 m; 5.80 and 5.96 m; 8.90 and 9.20 m; 10.14 and 10.28 m (CCSF), while this is less obvious through other intervals (see Fig. 4.3).

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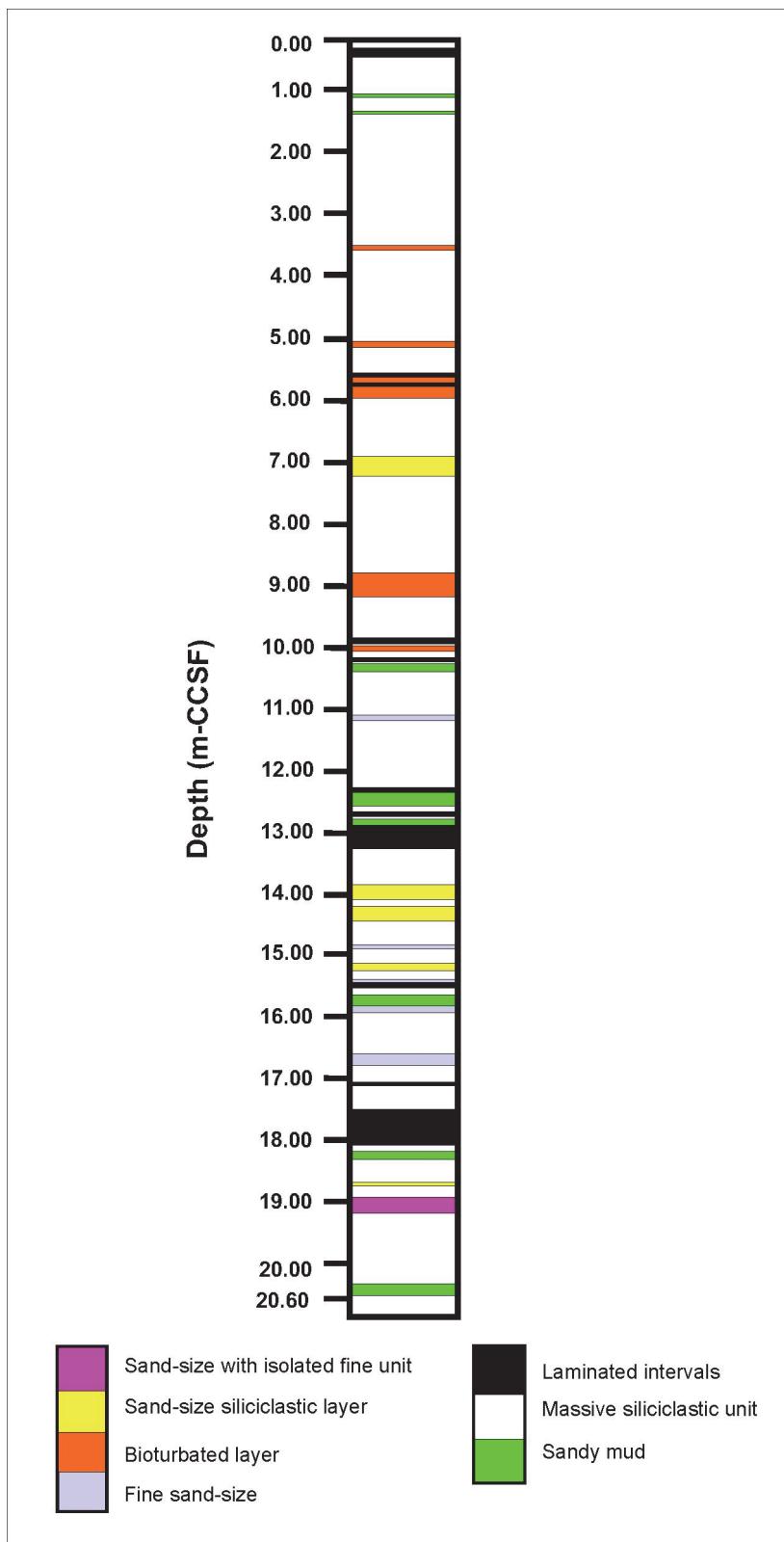
Figure 4.3 Simplified sedimentary log of Site U1342, Bowers Ridge (Total depth is ~20.60 m: see Appendix 11).

In general, the colour of the sediment ranges from very dark greenish grey and dark grey, to biogenic-rich olive-grey to olive, with dark-grey to black or shades of light grey to white volcaniclastic ash layers (Expedition 323 Scientists 2011). Expedition 323 Scientists (2011) reported rare cross-bedding indicative of bottom water currents. Substrate disturbance therefore cannot be completely ruled out as a possible control on benthic foraminiferal assemblages at some horizons in the Bering Sea.

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4.6 Results

A total of 35,465 benthic foraminiferal specimens were recovered from the sampled interval, from the >62 μm fraction sample (Appendix 1). Abundance, diversity and taxonomic composition of these benthic foraminifera vary substantially (see Figs. 4.5 – 4.7). In all, 68 species of benthic foraminifera have been documented, most being calcareous, with the exception of the agglutinated *Eggerella* sp. and *Martinottiella communis*. Of these, 52 species were identified to species level (see Chapter 2), while 16 species were identified only to generic level. Some 52 of the 158 samples analysed contained counts that have greater than 300 benthic foraminifera; 49 samples contained counts that have less than 100. These last sets of counts are thought not significant enough for precise ecological interpretations, and as such, are used only where necessary (i.e. as ancillary data to support the identification of a particular ecology within the succession). Overall, faunal assemblages are dominated by shallow infaunal species (e.g. *Islandiella norcrossi*, *Uvigerina bifurcata*, *Uvigerina peregrina*, *Ehrenbergina* spp.); deep infaunal species (e.g. *Bulimina exilis, B. spissa, Brizalina alata* and *Brizalina earlandi*), which occur in relatively high numbers sporadically down core, and phytodetritivores (e.g. *A. weddellensis* and *I. norcrossi*). Others are rare occurrences of epifauna (e.g. *Oridorsalis umbonatus*, *Cibicidoides* sp., *Hoeglundina elegans, Triloculina frigida*).

There is a weak correlation ($R^2 = 0.53$) between the total abundance of fauna and its species diversity down core (Fig. 4.4). However, this figure shows generally that after about 200 specimens are counted, the faunal diversity does not significantly increase, thus 200 specimens appears to capture the true diversity in most cases.

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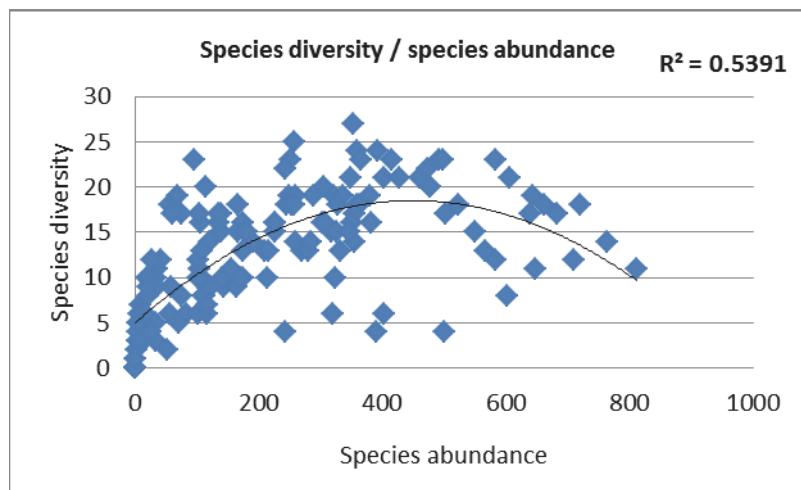
Figure 4.4 Polynomial plot showing species abundance of fauna versus species diversity; there is a weak correlation (R^2 = 0.53) between abundance of fauna and its species diversity down core. The plot shows a generally increasing numbers of species encountered up to about 200 specimens counted.

Species with overall relative abundance between 1.26 and 21.16% (a total of 14 species: *Globocassidulina subglobosa*, *Uvigerina peregrina*, *Cassidulina reniforme*, *Cassidulina laevigata*, *Gyroidina* sp., *Valvulineria araucana*, *B. spissa*, *Brizalina earlandi*, *Ehrenbergina* sp., *Takayanagia delicata*, *Uvigerina bifurcata*, *Islandiella norcrossi*, *Alabaminella weddellensis* and *Bulimina exilis*) down core are considered common (Fig. 4.5). These common taxa make a total of 92.07% of the total specimens counted from the studied interval. Out of these, 6 key species (numerically the most abundant: Fig. 4.6) with overall down core abundance > 9 % (*T. delicata*: 21.16%; *U. bifurcata*: 17.21%; *I. norcrossi*: 10.10%; *A. weddellensis*: 9.66% *B. exilis*: 9.09%) and *C. laevigata* which has > 200 specimens in some samples; *C. laevigata* has a total of 3.82% of all specimens recorded down core. These 6 species are considered significant for the recognition of discrete assemblage intervals (see Figs. 4.5 - 4.8). Percentage abundances of these taxa comprise 71.04 % of the total specimens counted, and so capture the majority of the species changes and by inference the ecological changes.

Common benthic foraminifera to abundant benthic foraminifera are recorded in most of the samples, with medium to relatively good preservation. There are no available samples for 2 horizons (7.44 m and 9.97 m-CCSF) out of the 160 horizons analysed, and these may have been missed during the original sample collection (by Expedition 323 Scientists), while 3 other samples (5.13 m, 15.29 m and 15.44 m-CCSF) were barren of foraminifera. Generally, samples showing highest abundance of foraminifera are closer to the bottom of the sampled interval of the core (15.69-19.92 m-CCSF) with the exception of a few samples within this range that have low abundances (i.e. at 17.72 and 20.44 m-CCSF).

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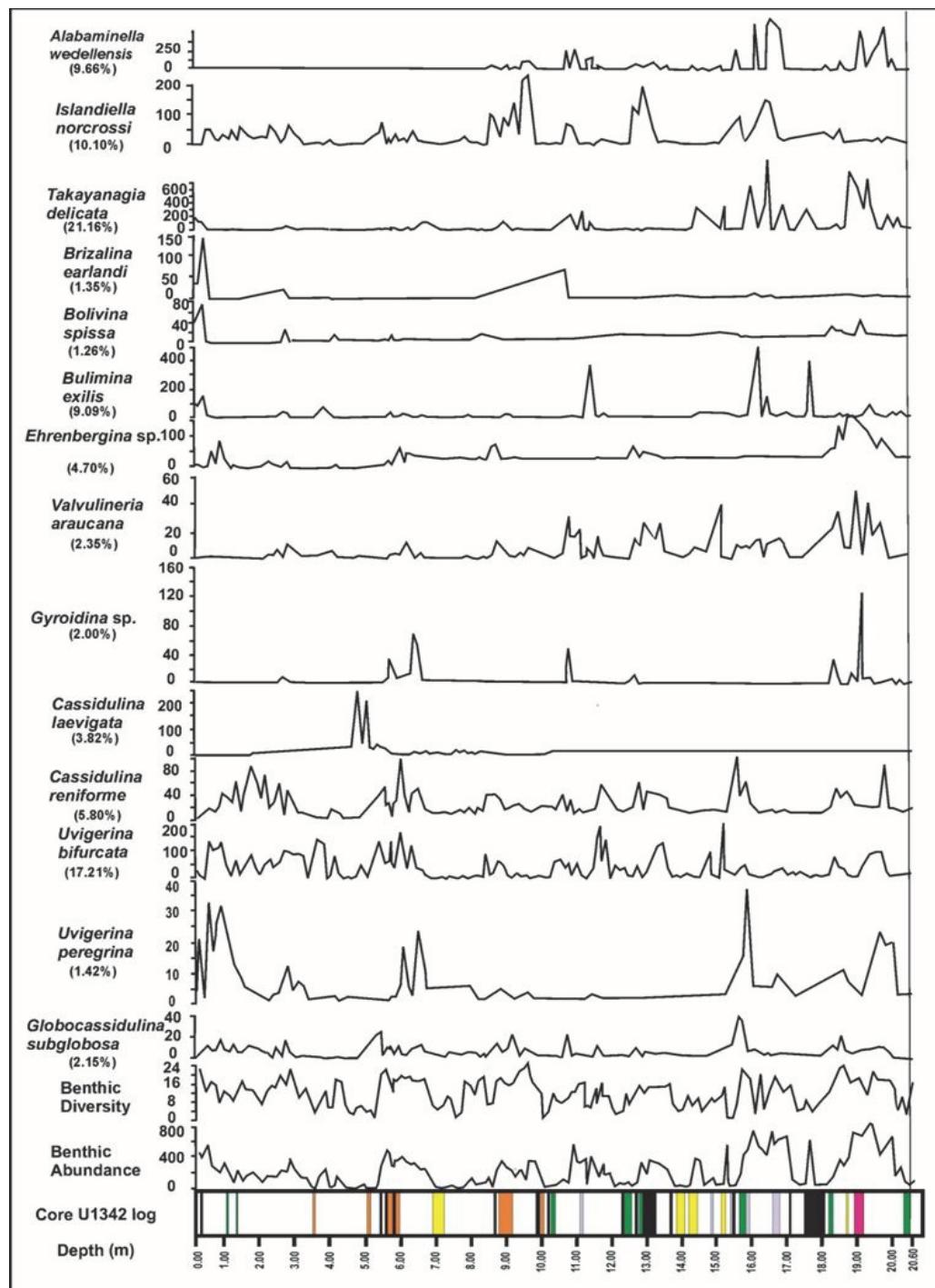
Figure 4.5 Down core abundance plots showing the 14 most common species representing 92.07% of the total benthic foraminiferal fauna counted from Site U1342, Bering Sea (see also Appendix 9)

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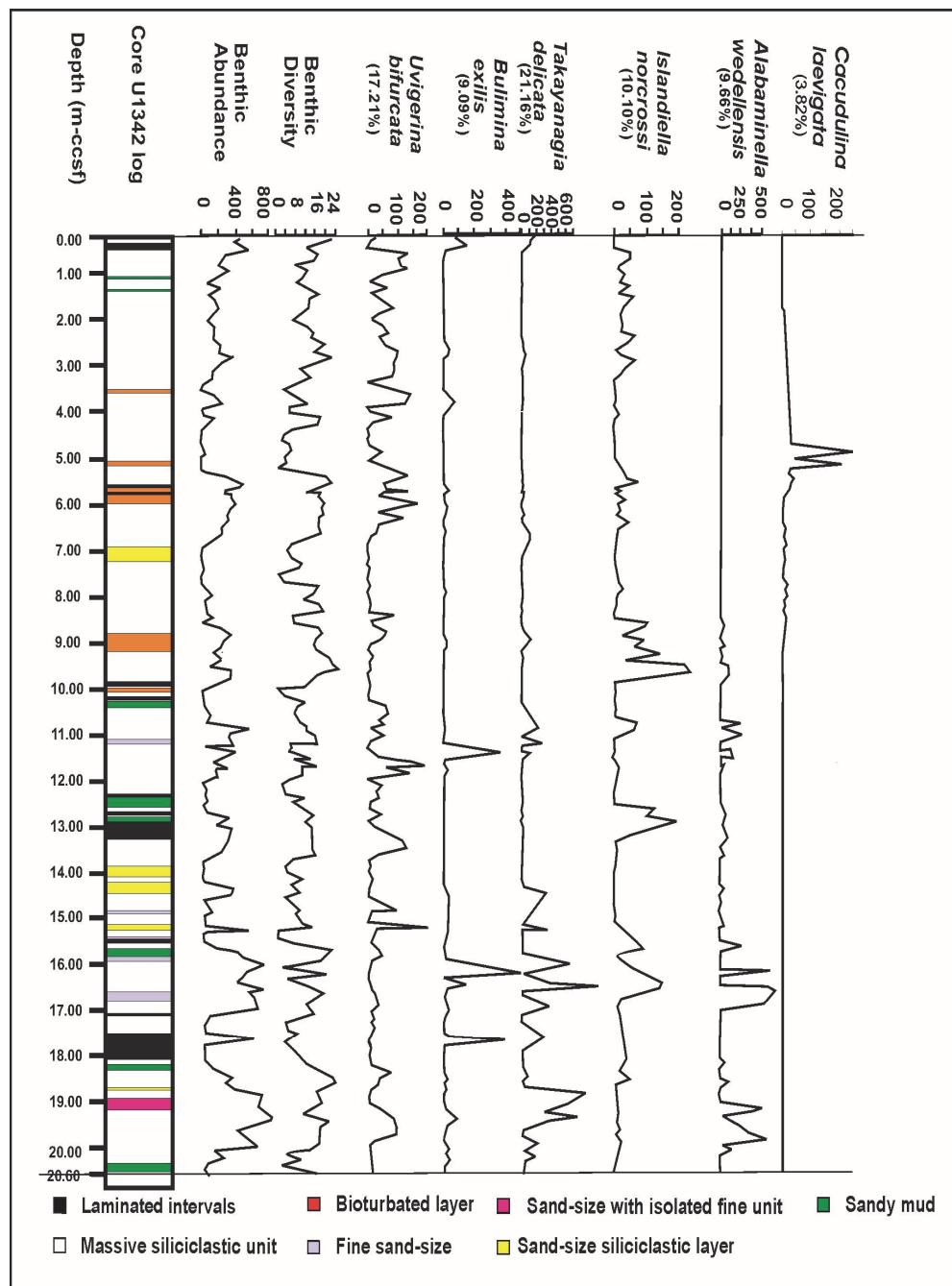
Figure 4.6 Abundance plots of the 6 species down core, comprising of the five most abundant taxa together with *Cassidulina laevigata* which has over 200 specimens in one sample; the 6 species represents ~ 71.04% of the total benthic foraminiferal fauna recorded down core from Site U1342, Bowers Ridge.

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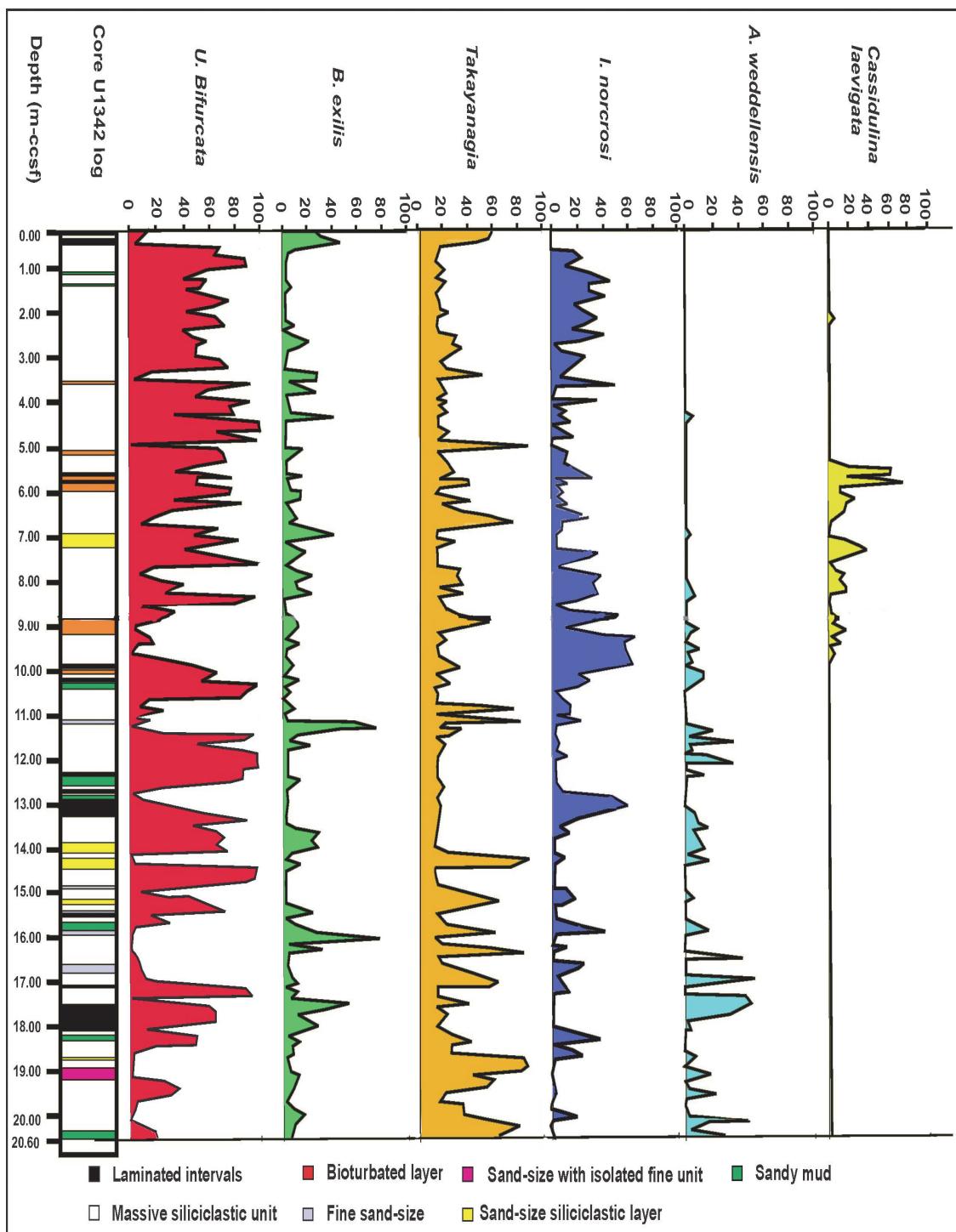
Figure 4.7 Percentage plots of the 6 key taxa against the sedimentary succession; these 6 species represent ~ 71.04% of the total benthic foraminiferal fauna recorded from Site U1342 studied core interval of ~ 20.60 m.

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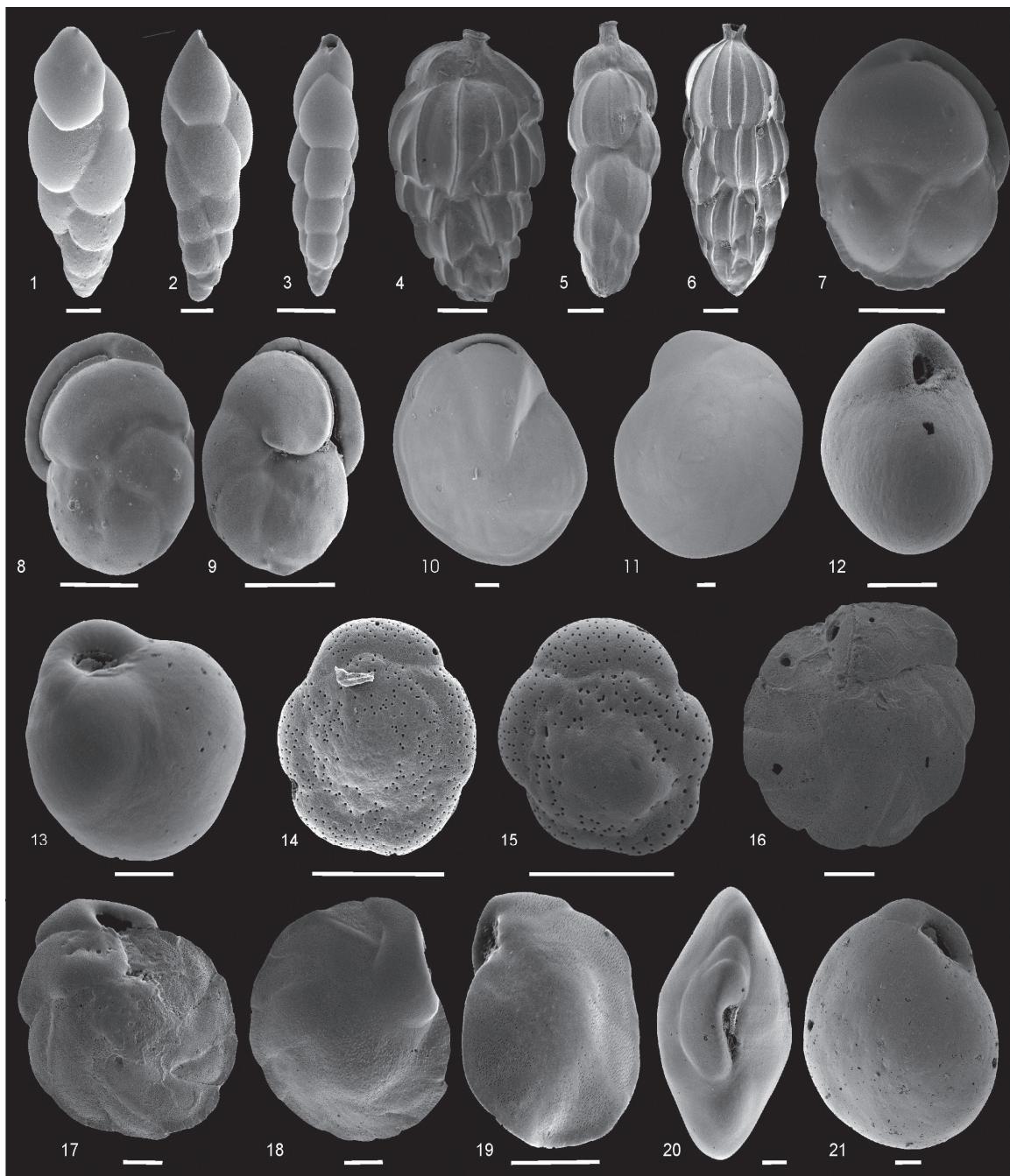
Plate 4.1 The six key species of benthic foraminifera from Core 1342 used in the determination of benthic foraminifera assemblages down core; these species are also used in microhabitat classification: Species: 1-3. *Bulimina exilis* **(Deep infauna); 4-6:** *Uvigerina bifurcata* **(Intermediate infauna); 7-9:** *Takayanagia delicata* **(Shallow infauna); 10-11:** *Hoeglundina elegans* **(Epifauna); 12-13:**

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***Globocassidulina subglobosa* (Epifauna); 14-15: *Alabaminella weddellensis* (Phytodetritivores and Epifauna); 16-18: *Cassidulina laevigata* (Phytodetritivores and Epifauna); 19-21: *Islandiella norcrossi* (Phytodetritivores and Shallow infauna)*. **Scale bars =100 μm.**

4.6.1 Changes in benthic foraminiferal abundances down core

Eight discrete intervals were defined from the ~20.60 m-CCSF long core from Site U1342 based on the abundances of key species (see Appendices 1 and 7). The eight intervals are identified from youngest to oldest (down core) as: 1) *Uvigerina bifurcata*, 2) *Cassidulina laevigata*, 3) *Uvigerina bifurcata / Takayanagia delicata,* 4) *Islandiella norcrossi*, 5) second *Uvigerina bifurcata,* 6) *Takayanagia delicata / Alabaminella weddellensis,* 7) second *Uvigerina bifurcata / Takayanagia delicata* and 8) *Takayanagia delicata.*

4.6.1.1 Uvigerina bifurcata dominated interval: 0 - ~5.40 m-CCSF (0~151 Ka)

The total number of specimens recorded through this interval is 7078; these accounts for ~19.96% of the total fauna down core (see Appendix 7). *U. bifurcata* (the eponymous species) accounts for ~31.07% of the fauna through this interval. Other common benthic species are *Ehrenbergina* sp., *Uvigerina peregrina, Angulogerina angulosa, Islandiella norcrossi, Bolivina spissa, Brizalina earlandi and Takayanagia delicata.* Relatively high proportions of *T. delicata, Bolivina exilis, B. spissa, Brizalina earlandi* and *Bolivina* spp. are present (Appendix 1, Fig. 4.8). Few specimens of *A. weddellensis* are recorded throughout this interval. Species diversity fluctuates between 2 and 25 species per sample. *U. bifurcata* has its highest abundance at depth 3.48 m-CCSF; with a total of 145 specimens (~89% of total fauna recorded at that depth). The sedimentology of the interval includes laminated sedimentary deposits, sandy mud units, sand-size siliciclastics and massive siliciclastic units interrupted with bioturbated layers. Some 7 out of 41 samples from this interval have foraminiferal counts that are more than 300 specimens per sample.

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4.6.1.2 Cassidulina laevigata dominated interval: 5.40 - ~ 6.50 m-CCSF (~151 - 180 Ka)

A relatively short interval (~1.1 m), with the total number of specimens recorded through this interval being 4425; this number accounts for ~12.48% of the total fauna down core (see Appendix 7). *Cassidulina laevigata* (the eponymous species) accounts for ~23.23% of the fauna through this interval. Other common benthic species are *Uvigerina bifurcata, Bolivina exilis, Takayanagia delicata, Islandiella norcrossi, Ehrenbergina* sp. and *Angulogerina angulosa.* Few specimens of *A. weddellensis* are recorded throughout this interval. Species diversity is relatively high, and fluctuates between 13 and 23 species per sample. *C. laevigata* has its highest abundance (238 specimens in a sample) at 5.41 - 5.46 m-CCSF; with an average of ~86 specimens in samples from this interval. Some 10 out of 12 samples from this interval have foraminiferal counts that are more than 300 specimens per sample (up to 499 at 5.41 m). The sedimentology of this interval includes laminated sedimentary deposits, sandy mud units, sand-size siliciclastics and massive siliciclastic units interrupted with bioturbated layers.

4.6.1.3 Uvigerina bifurcata / Takayanagia delicata dominated interval: ~ 6.50-9.00 m-CCSF (~180 - 265 Ka)

The total number of specimens recorded through this interval is 2044; these accounts for ~5.76% of the total fauna down core (see Appendix 7). *U. bifurcata* and *T. delicata* (the eponymous species) accounted for ~18.79% and ~22.60% respectively of the fauna through this interval. Other common benthic species are *Bolivina exilis, Islandiella norcrossi, Cassidulina reniforme, Cassidulina laevigata, Ehrenbergina* sp. and *Angulogerina angulosa.* Few specimens of *A. weddellensis* are recorded throughout this interval. Species diversity is relatively high, and fluctuates between 3 and 19 species per sample. *Takayanagia delicata* has highest abundance (up to 122 specimens in a sample at 8.86 m-CCSF), while *U. bifurcata* has its highest occurrence (up to 90 specimens at 8.34 m-CCSF); *U. bifurcata* and *I. norcrossi* are abundant through this interval. Only one sample (at 8.72 m) out of 20 samples from this interval has a foraminiferal count

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that is more than 300 specimens (up to 365 in a sample). The sedimentology of the interval includes laminated sedimentary deposits, massive siliciclastic units and bioturbated layer at the base of the interval.

4.6.1.4 Islandiella norcrossi dominated interval: ~9.00-10.40 m-CCSF (~265 - ~298 Ka)

In this assemblage (~1.40 m thickness of core), a total of 1562 specimens (4.40% of the total count down core) were recorded. Species diversity fluctuates between 3 and 27 species per sample; there are 11 samples analysed from this interval that includes laminated deposits at depth 9.92 and 10.25 m-CCSF (~288 and ~295 ka). Two of the samples have more than 300 specimens (up to 356 specimens in one sample: Appendices 1 and 7). The interval is dominated by relatively high proportions of *I. norcrossi*, comprising approximately 48.53% of the total fauna recorded in this interval (see Appendix 7); other commonly associated benthic foraminifer species are *Takayanagia delicata, Ehrenbergina* sp., *Valvulineria araucana, Globobulimina auriculata, Cassidulinoides parkerianus,* and fewer numbers of *Alabaminella weddellensis.* The sedimentology at this interval comprises laminated and bioturbated deposits with a small unit of sandy mud (Figs. 4.3, 4.8).

4.6.1.5 Second Uvigerina bifurcata dominated interval: ~10.40-15.79 m-CCSF (~298 - ~458 Ka)

In this interval, a total of 7517 specimens were recorded (~21% of the total count down core: Appendix 7). Diversity ranges between 2 and 22 species per sample. Some 13 out of 41 samples contain well above 300 specimens (i.e up to 567 specimens at 10.78 m-CCSF). The most abundant species in this interval is the eponymous species, which makes up 26.49% of the total specimens recorded. Associated benthic foraminifera species are *A. weddellensis, B. exilis, B. earlandi, C. parkerianus, V. araucana* and *G. auriculata.* There is a wide numerical range in the abundance of the 6 key species recorded from samples in this interval (between 5 and 567 specimens in a sample: Appendix 7). The sedimentology is marked by episodes of massive siliciclastic units,

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sand-size siliciclastic layers, laminated units and sandy mud with an isolated fine sand unit (Figs 4.3, 4.8).

4.6.1.6 Takayanagia delicata / Alabaminella weddellensis dominated interval: ~15.79 - 16.90 m-CCSF (~458 - ~490 Ka)

In this assemblage, a total of 4572 specimens were recorded (~13% of the total count down core: Appendix 7). All samples (8) of this interval contain well above 300 specimens (up to 721 specimens at 15.95 m-CCSF); there is a wide range of species diversity (between 4 and 23 species per sample) through this interval. The interval is characterised by relatively high abundance, key amongst which are *T. delicata* and *Alabaminella weddellensis* (34.69% and 26.82% respectively of the total specimens recorded through this interval: Appendix 7). Other common species include *A. weddellensis, U. bifurcata, C. reniforme* and *I. norcrossi. Valvulineria araucana* has a low to medium occurrence (between 2 and 16 specimens per sample), but with a consistent occurrence through this interval. Stratigraphically, the upper part of this assemblage interval is characterised by a sudden decrease in the abundance of *B. exilis* from 488 specimens to as low as 6 specimens in a sample (Appendices 1 and 7). The sedimentology is marked by massive siliciclastic units, fine sand-sized units, and a laminated interval.

4.6.1.7 Second Uvigerina bifurcata / Takayanagia delicata dominated interval: ~16.90-18.67 m-CCSF (~490 - ~541 Ka)

In this assemblage, a total of 2034 specimens were recorded (~6% of the total count down core: Appendix 7). Some 3 out of 12 samples in this interval contain above 300 specimens (up to 610 at depth 17.57 m-CCSF); the range of species diversity is relatively wide, between 3 and 25 species per sample (Appendices 1 and 7). This interval is recorded through 1.77 m-CCSF of the core studied. This interval is characterised by relatively high abundances, being dominated by *U. bifurcata* and *T. delicata*: each accounting for ~21% of the total fauna. Other common species include *A. weddellensis, U. peregrina, Ehrenbergina* sp., *Cassidulina reniforme, Globocassidulina subglobosa, Oridorsalis umbonatus, Valvulineria araucana, B. exilis* and *B. spissa.* At

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17.57 m-CCSF, there is a sudden and short-lived increase in the abundance of *B. exilis* (up to some 390 specimens: ~19% of total fauna in this interval) and *T. delicata* (up to some 197 specimens: ~10% of total fauna in this interval). This interval includes laminated deposits at 17.09 m-CCSF (~490 Ka) and between 17.45-18.07 m-CCSF (~505 and ~520 Ka), massive siliciclastic units, episodic fine sand, and units of sandy mud towards the base of the interval (see Figs 4.3).

4.6.1.8 Takayanagia delicata dominated interval: ~18.67-20.59 m-CCSF (~541 - ~597 Ka)

The last interval in the section studied produced a total of 6233 specimens (18% of the total count down core: Appendix 7). Some 9 out of 14 samples through this interval contain above 300 specimens; the range of species diversity is relatively wide, between 1 and 23 species per sample (see Appendices 1 and 7). This interval is recorded through 1.92 m-CCSF of the core studied; it is characterised by relatively high abundances, being dominated by *T. delicata* (~43% of the total faunal recorded through this interval: Appendix 7). Other common species include *A. weddellensis, U. bifurcata, Valvulineria araucana* and *Bulimina exilis.*

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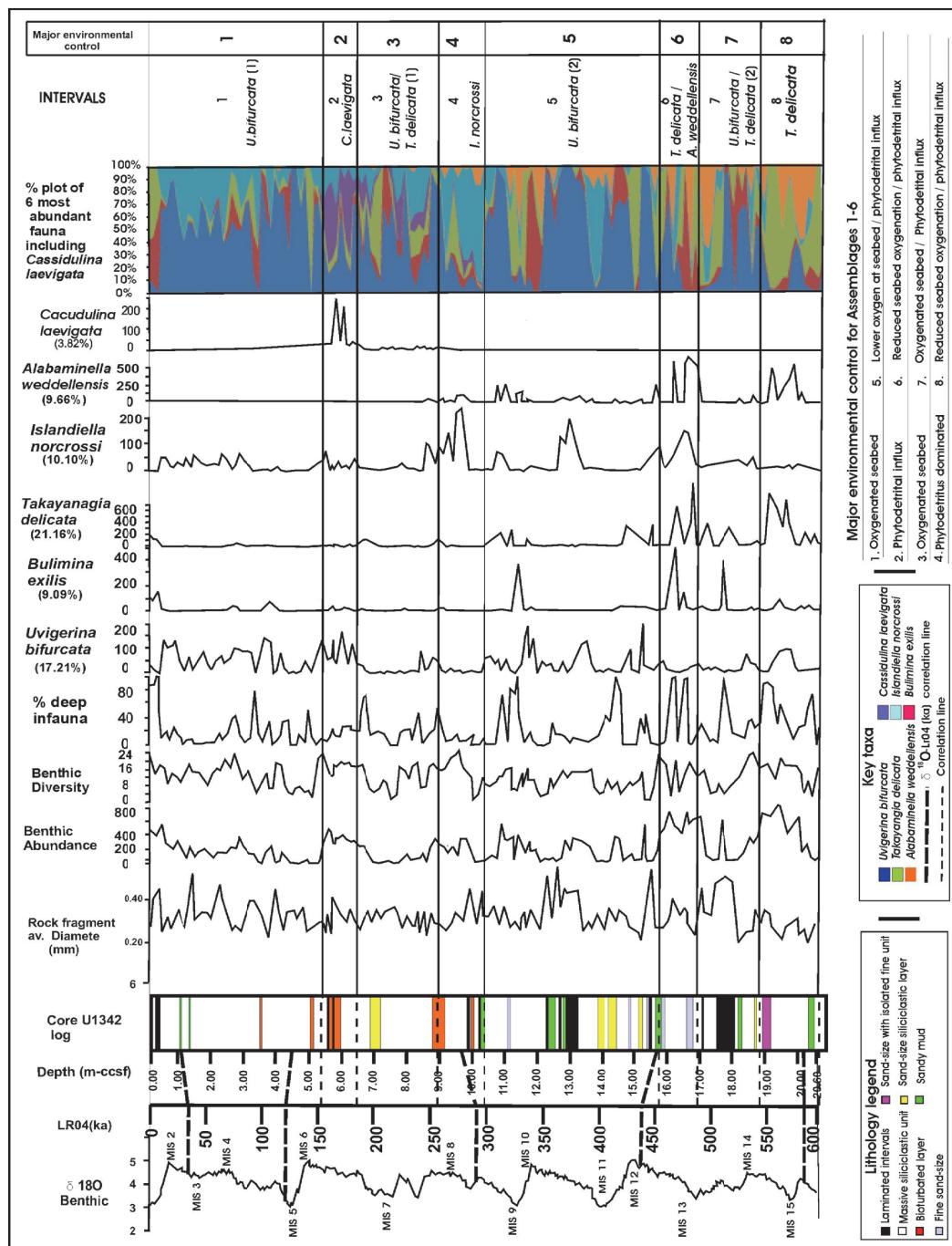
Figure 4.8 Species abundances for 6 key taxa in the core, representing ~71.04 % of the total benthic foraminifer fauna. The overall diversity, abundance, benthic oxygen isotope data for U1342 (from Knudson and Ravelo personal communication, correlated to the oxygen isotope dataset of Lisiecki and Raymo (2005, = LR04 (ka) column in figure), and IRD value is represented down core

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against the sedimentary log. Eight temporally discrete benthic foraminiferal intervals are distinguished down core for Site U1342 based on the dominance of one or more taxa.
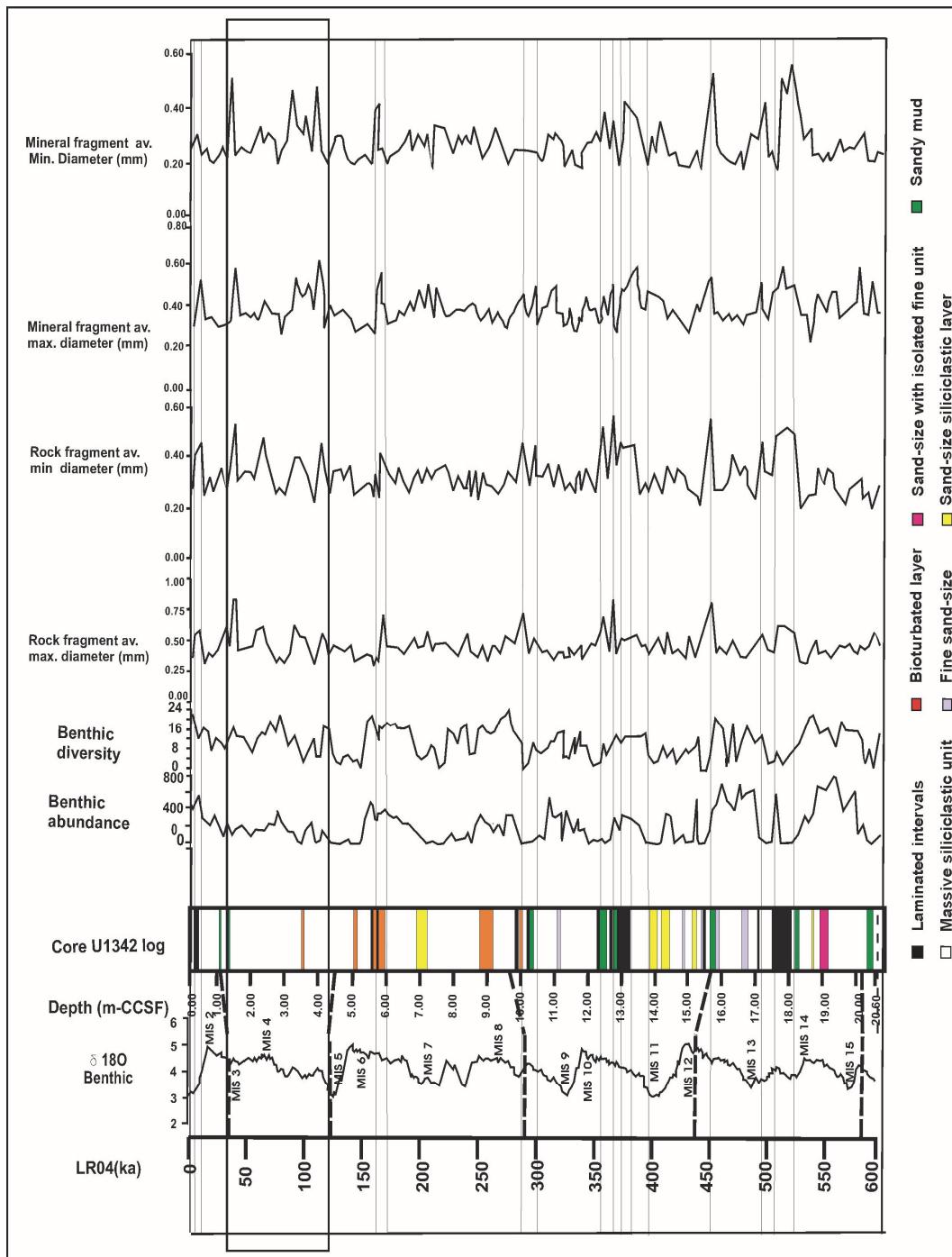
Figure 4.9 Benthic foraminiferal abundances and diversities, sedimentary log, benthic foraminiferal oxygen isotope data for U1342 (from Knudson and Ravelo

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personal communication, correlated to the oxygen isotope dataset of Lisiecki and Raymo (2005, = LR04 (ka) column in figure), and IRD values (total depth is ~20.60 m). Faint lines show correlation between peak of average IRD size dimensions and the laminated intervals down core. Inside the rectangle (in the top part of the core) are the only 3 bioturbated intervals (with siliciclastic units) which correlate with the peak of IRD size dimensions (see also Appendix 10).

4.6.2 Ice rafted debris (IRD) distribution patterns

Plots of IRD data (Fig. 4.9: diameter, dimensions) against depths for both rock and mineral fragments (i.e. average maximum and minimum dimensions) generally show the same size pattern (Fig. 4.9). All the plots peak in size dimensions through the laminated intervals down core (Fig. 4.13); the only exceptions being at three intervals near the top part of the core: at ~1.28, ~3.24, ~3.77 m-CCSF. Larger IRD (average rock fragments: up to 0.85 mm and average mineral fragments up to 0.53 mm) were recorded in the laminated intervals, while smaller IRD fragments were recorded through other bioturbated intervals down core. Simple polynomial correlation plots (of IRD average dimensions versus benthic foraminiferal abundance; IRD versus benthic foraminiferal diversity and percentage deep infauna) show correlations that are not statistically significant (see Figs. 4.10 - 4.12)

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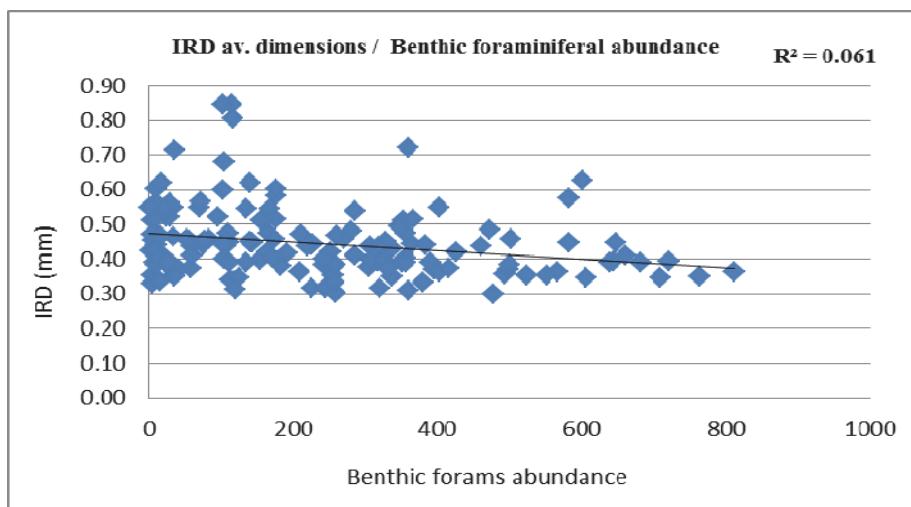
Figure 4.10 Polynomial plot showing average dimensions of ice rafted debris (IRD) versus benthic foraminifera abundance. Correlation is not statistically significant (R^2 = 0.06).
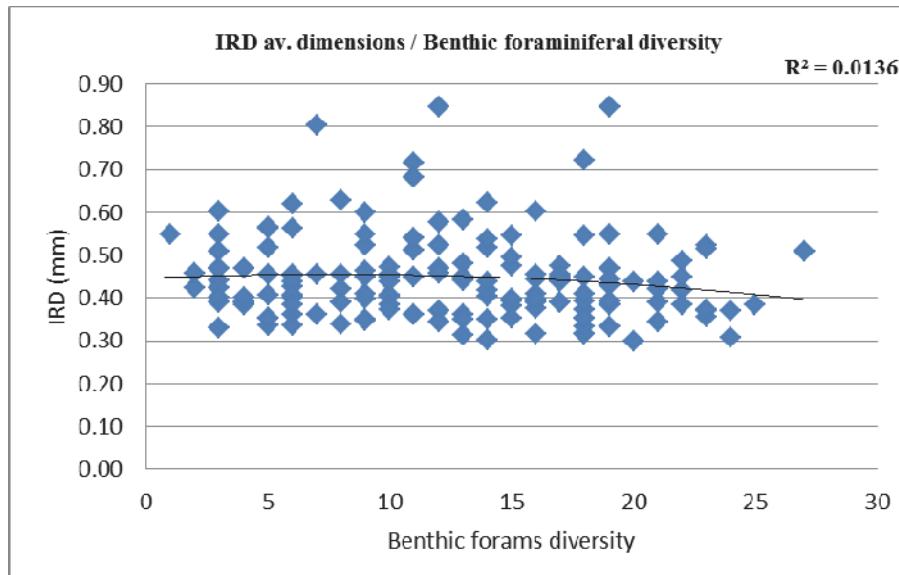
Figure 4.11 Polynomial plot showing average dimensions of ice rafted debris (IRD) versus benthic foraminifera diversity. Correlation is not statistically significant (R^2 = ~ 0.01).

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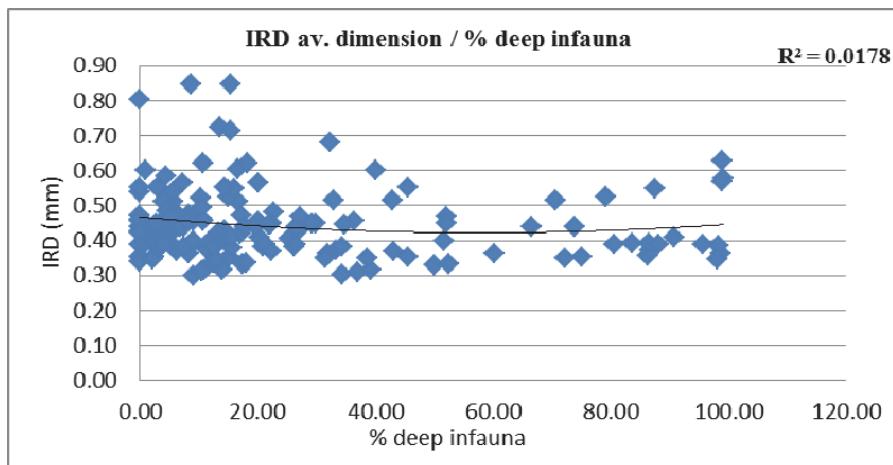
Figure 4.12 Polynomial plot showing average dimensions of ice rafted debris (IRD) versus percentage deep infauna. Correlation is not statistically significant ($R^2 = \sim 0.01$).
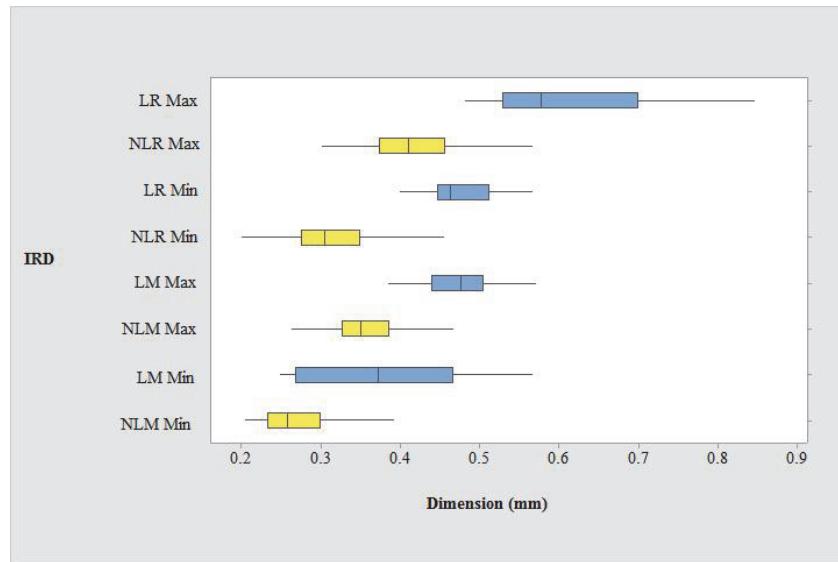
Figure 4.13 Box and whisker plot showing the relationship between the average dimensions of IRD (rock and mineral: mm) in laminated and non-laminated intervals; blue boxes represent fragments in laminated intervals, while yellow boxes represent fragments in non-laminated intervals. Average maximum and minimum dimensions of rock fragments in laminated intervals (LR Max; LR Min), average maximum and minimum dimensions of rock fragments in non-laminated intervals (NLR Max; NLR Min), average maximum and minimum dimensions of mineral fragments in laminated intervals (LM Max; LM Min) and average maximum and minimum dimensions of mineral fragments in non-laminated intervals (NLM Max; NLM Min). Generally, the average dimensions of IRD in laminated intervals are larger than in the non-laminated intervals.
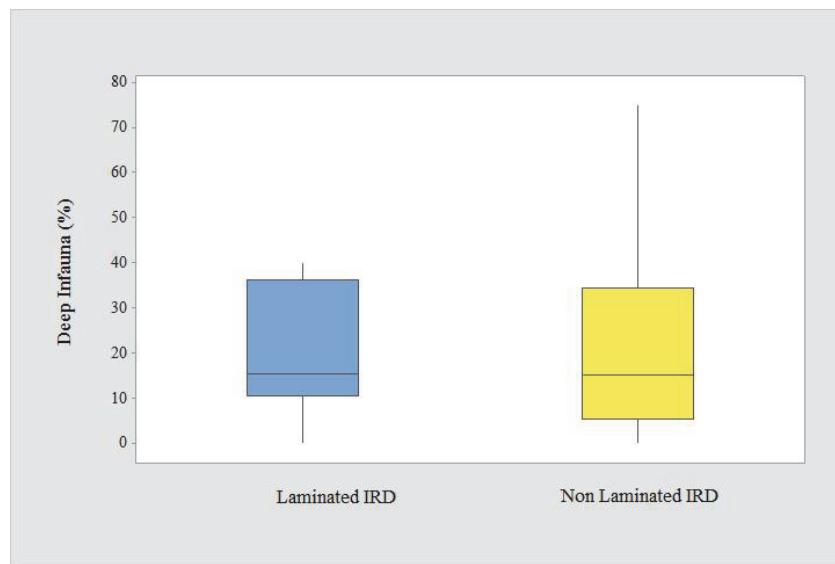
Figure 4.14 Plot showing the relationship between percentage deep infauna, average dimensions of IRD in laminated and non-laminated intervals; blue box represent fragments in laminated intervals, while yellow box represents fragments in non-laminated intervals. Box (specimens abundance) and whisker (specimens over-all occurrence range) plots statistically and visually show that laminated intervals do not always contain deep infaunal foraminifer (i.e. the range of 'whiskers' on the blue box being short when compared with 'whiskers' on the yellow box) and also contain less deep infauna (i.e. position of the 50th percentile on the blue box). The position of the 50th percentile and the span of the blue box show that laminated intervals do not always contain deep infaunal foraminifera. Laminated IRD = IRD in laminated intervals; non-laminated IRD = IRD in non-laminated interval

4.7 Discussion

4.7.1 Possible environmental significance of the eight foraminiferal intervals

At Site U1342, the biostratigraphical ranges of the 68 foraminiferal taxa identified to species level are known in all cases to exceed that of the interval studied (~597 Kyr), and therefore changes in assemblage structure down core (see Appendix 1 and Fig. 4.8)

are thought primarily to reflect environmental parameters and not extinction or origination events. Through much of the interval studied, the faunal assemblage suggests bottom waters were not dysoxic (Fig. 4.8) and comprise of a mixture of taxa that are epifaunal, infaunal (shallow, intermediate and deep) and phytodetritivore epifaunal (for definitions see Table 4.1). The eight intervals distinguished possibly suggest down core changes in seabed oxygen level (sometimes coinciding with laminated intervals) and input of phytodetritus. It should be noted that each interval indicates considerable variation in seabed conditions. Of the 6 key species out of 68 benthic foraminifera species analysed, *A. weddellensis* and *Cassidulina laevigata* are classified as phytodetritivore epifauna; *Islandiella norcrossi* as phytodetritivores; *Takayanagia delicata* as shallow infauna; *Uvigerina bifurcata* as intermediate depth infauna, and *Bulimina exilis* as deep infauna (see Table 4.1). For the purpose of determination and identification of the benthic foraminiferal assemblages down core, these 6 taxa (Plate 4.1; Figs. 4.6 and 4.7: *Takayanagia delicata*: 21.16%; *Uvigerina bifurcata*: 17.21%; *Islandiella norcrossi*: 10.10%; *Alabaminella weddellensis*: 9.66% *Bulimina exilis*: 9.09% and *Cassidulina laevigata*: 3.82%) have proved most useful, based on their individual percentage abundances (between 3.82 and 21.16%) totalling 71.04% of the total benthic foraminifera counted (see Appendices 1 and 7). Other less common benthic foraminifer in the core with abundances between 0.01- 3.82% have been used for ecological interpretations where they can be clearly assigned to a specific benthic foraminiferal ecology.

4.7.1.1 Interval 1, Uvigerina bifurcata dominated interval: 0 - ~5.40 m-CCSF (0~151 Ka)

This interval is characterised by the consistent abundance of its eponymous shallow infaunal species and *I. norcrossi*, which here is used to infer the predominance of high seasonal organic carbon flux to the seabed (Katsuki and Takahashi 2005) and oxygen levels above dysoxic (Kaiho 1994, Bubenshchikova et al. 2008) through the 151 Kyr of this interval (see Table 4.1). The overall species complement of the *U. bifurcata* dominated interval (Appendix 1; Figs. 4.8) includes a mixture of taxa found in various microhabitat groups (phytodetritivore, deep infaunal, intermediate infaunal, shallow

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infaunal and epifaunal; see Table 4.1), signalling that seabed environmental conditions were generally not dysoxic. The uppermost part of the *U. bifurcata* interval is located in laminated mud between 0.10-0.25 m-CCSF depths (~3 to ~7 Ka) characterised by the highest abundances of infaunal *Bulimina exilis*, *Bolivina spissa, Brizalina earlandi, Islandiella norcrossi* and *Takayanagia delicata* (Appendix 1; Fig. 4.8). The *Bulimina* and *Bolivina* species suggest intermittent high organic carbon flux (Steinsund et al. 1994; Polyak et al. 2002; Ivanova et al. 2008) an low oxygen at the seabed (possibly below ~1 ml/l; see Bubenshchikova et al. 2008; Kuhnt et al. 2013). This is consistent with the sedimentary motif of the laminated mudstones.

The abundance of *I. norcrossi* throughout this interval possibly indicates the importance of seasonal phytodetritus flux to the seabed. The sudden change at 5.40 m-CCSF to *Cassidulina laevigata* (Fig. 4.8) suggests a sustained change in phytodetritus delivery to the seabed that defines the next foraminiferal interval down core.

4.7.1.2 Interval 2, Cassidulina laevigata dominated: ~5.40 - ~6.50 m-CCSF (~151 - ~180 Ka)

This interval spans ~29 Kyr. It is characterised by sudden and high abundance of its eponymous species, this distinguishes it from intervals above and below (Appendix 1; Fig. 4.8). Some studies in the Arctic Ocean and North Sea shows that species of *Cassidulina* do not occur below ~1°C (Østby and Nagy 1981; Klitgaard-Kristensen et al. 2002); species of this genus are thought to be relatively sensitive to bottom water temperature. A laboratory experiment (Alve 2010) showed that living *C. laevigata*, in contrast to many other species, disappeared from the assemblage after a halt in the supply of fresh phytodetritus for a period of two years, indicating that this species requires an input of fresh phytodetritus to survive. At site U1342, changes in the supply of phytodetritus input to the seabed are suggested by the sudden dominance of *C. laevigata* between 5.40 and 6.50 m-CCSF (~151 - ~180 ka: Figs. 4.5, 4.6, 4.7 and 4.8), this is interpreted to indicate elevated levels of phytodetritus to the seabed with no long-term halt in supply within this interval (see Alve 2010); the dominance of shallow infaunal taxa (*U. bifurcata, Cassidulina reniforme, I. norcrossi, Ehrenbergina sp. G. subglobosa* and *U. bifurcata*) within the *Cassidulina laevigata* dominated interval at

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depths 5.62 and 5.74 m-CCSF (equivalent to an interpreted age of ~163 and ~167 ka) does not suggest low seabed oxygen (see also Chapter 3).

The sudden and high abundance of *Cassidulina laevigata* through this interval is therefore interpreted to mean input of fresh phytodetritus to the seafloor. The genus *Cassidulina* has been grouped as suboxic (Kaiho 1994).

4.7.1.3 Interval 3, Uvigerina bifurcata / Takayanagia delicata dominated interval: ~ 6.50 - 9.00 m-CCSF (~180 - 265 Ka)

This interval spans ~85 Kyr. It is characterised by the sudden high abundance of *T. delicata* through its uppermost stratigraphical interval, and also at the base of this interval (*T. delicata*: up to 114 in a sample), and the relative dominance of *U. bifurcata* toward the base of the interval (see Appendix 7). This variation in the abundance of the two eponymous species is inferred to signal dynamic seabed conditions with respect to changes in phytodetrital influx to the seabed. *Takayanagia delicata* shows closer distributional patterns to other deep infaunal species down core, thus it is thought that *T. delicata* may indicate very high organic carbon flux, and/or have an oxygen tolerance intermediate between suboxic and dysoxic conditions indicating intermittent low oxygen sea bed conditions through this interval. In contrast, *U. bifurcata* has a relatively low abundance through this interval.

Intervals that show abundant *U. bifurcata* suggests the seabed was oxygenated (Kaiho 1994; Bubenshchikova et al. 2008), whilst others dominated by intermittent abundance of infaunal *T. delicata* indicate periods of probable increase in organic carbon flux although this interpretation is tentative due to the lack of modern data on *T. delicata*.

4.7.1.4 Interval 4, Islandiella norcrossi dominated interval: ~9.00-10.40 m-CCSF (~265 - ~298 Ka)

This interval spans ~33 Kyr. It is characterised by the consistently high abundance of its eponymous species, which is interpreted as a phytodetritivore (see Table 4.1). This suggests that an overall characteristic of this interval that distinguishes it from those above and below (Appendix 1; Fig. 4.8) was marked seasonality in the phytodetritus

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flux to the seabed. Studies on the Arctic shelf have shown high proportions of *I. norcrossi* coincide with seasonal sea ice and summer ice edge productivity (Steinsund et al. 1994; Polyak et al. 2002; Ivanova et al. 2008). Co-occurrence of opportunistic phytodetritus taxa such as *Alabaminella weddellensis* (Loubere and Fariduddin 1999; Thomas and Gooday 1996; Gooday 1993) and *Globocassidulina subglobosa* (Gooday 1996) in this assemblage are inferred to signify periods of particularly high seasonal phytodetrital flux to the sea floor (Thomas and Gooday 1996; Smart et al. 1994), which is mostly associated with seasonal surface water stratification possibly from sea ice-related processes (Katsuki and Takahashi 2005). The sudden change at 8.86 m-CCSF to *Islandiella norcrossi*-dominated assemblages (Fig. 4.8) suggests a sustained change in phytodetritus delivery to the seabed that defines the next foraminiferal interval down core. Other key taxa present in this interval are *Globobulimina auriculata* and *Takayanagia delicata.*

Down core at depth 10.36 m-CCSF, the shallow infaunal species *U. bifurcata* once again becomes dominant. This interval also includes abundant *T. delicata*, but perhaps more importantly it includes abundant phytodetritivores (*I. norcrossi* and *A. weddellensis*), and thus suggests a different overall environmental regime to that of the uppermost *U. bifurcata*-dominated interval in U1342 (see interval 1, above).

4.7.1.5 Interval 5, Second Uvigerina bifurcata dominated interval: ~10.40-15.79 m-CCSF (~298 - ~458 Ka)

This interval lasted some ~163 Kyr. It is characterised by the consistent abundance of its eponymous species that suggests a seabed that was not dysoxic, together with sustained influx of phytodetritus to the sea floor. The upper interval of this assemblage is located in a massive siliciclastic unit between 10.40-12.25 m-CCSF (~301 to ~355 Ka) punctuated by sandy mud deposits; this upper interval is characterised by abundance of the eponymous species. Dominance of *U. bifurcata* at levels between 11.47-11.81, 13.46-13.60 and 15.19 m-CCSF (equivalent to an interpreted age of ~332-~342, ~390-~395 and ~440 Ka) and co-occurrence of deep infaunal taxa such as *Bulimina exilis, Brizalina alata, Brizalina earlandi* and *Takayanagia delicata* between

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10.78 and 11.81 m-CCSF (equivalent to an interpreted age of ~312 to ~342 Ka: Appendix 1; Figs. 4.8) indicate possible switches from typical seabed conditions (at ~298 to ~312 Ka) to lower oxygen conditions with higher organic carbon flux (~312 to ~342 Ka).

Down core from depth 15.79 m-CCSF (~458 Ka), *U. bifurcata* once again shows reduced abundance.

4.7.1.6 Interval 6, Takayanagia delicata / Alabaminella weddellensis dominated interval: ~15.79-16.90 m-CCSF (~458 - ~490 Ka)

This interval spans ~32 Kyr. The high abundance of the eponymous species coupled with the occurrence of some deep infaunal species such as *Brizalina earlandi* and *Bolivina* sp. 1, and the low abundance of shallow infauna such as *U. bifurcata* is interpreted to infer the dominance of low oxygen conditions at the seabed with high organic carbon flux. The intermittent high abundance of *Alabaminella weddellensis* (up to 347 specimens per sample: Appendices 1 and 7; Fig. 4.8) and *Islandiella norcrossi* (up to 142 specimens per sample) also suggests times of strong seasonal phytodetrital input to the seabed (Katsuki and Takahashi 2005) that may be associated with seasonal sea ice and probable summer sea ice edge productivity (Steinsund et al. 1994; Polyak et al. 2002; Ivanova et al. 2008).

Down core from 16.90 m-CCSF (~490 Ka), there is a sudden decrease in the abundance of *T. delicata.*

4.7.1.7 Interval 7, Second Uvigerina bifurcata / Takayanagia delicata dominated interval: ~16.90- 18.67 m-CCSF (~490 - ~541 Ka)

This interval spans 51 Kyr. Overall species documented here are a mixture of taxa present in various microhabitat groups (see Table 4.1; Appendix 1); which signal seabed conditions may have been dynamic with respect to changes in oxygen level and phytodetrital influx to the seabed. Some intervals show abundant *U. bifurcata* that suggests the seabed was not dysoxic, whilst others are dominated by intermittent abundance of *T. delicata*, indicating periods of probable increase in organic carbon flux. As stated above, it is inferred from the co-occurrence of *U. bifurcata* and *T. delicata*

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(and its co-occurrence with other deep infaunal i.e. *B. exilis*) that *T. delicata* may have an oxygen tolerance intermediate between shallow and deep infaunal species. Intermittent occurrences of phytodetritivores such as *A. weddellensis* and *I. norcrossi* are inferred to signify seasonal phytodetrital blooms (Katsuki and Takahashi 2005). The sudden increase in abundance of *B. exilis* (up to 390 specimens) at 17.72 m-CCSF is short-lived. It is interpreted to infer a short period of low oxygen conditions and high organic carbon flux to the seabed.

4.7.1.8 Interval 8, Takayanagia delicata dominated interval: ~18.67-20.59 m-CCSF (~541 - ~597 Ka)

This interval lasted some 56 Kyr. It is characterised by high but fluctuating abundance of the eponymous species (up to 540 specimens at its peak; and as low as 8 in another sample) through this interval. This suggests variations in organic carbon flux and oxygen seabed conditions (i.e. inferred from the association of *Takayanagia delicata* with deep infaunal species down core), whilst the relatively high abundance of *A. weddellensis* (up to over 260 specimens in two different samples) suggests a strong seasonal phytodetrital influx to the seabed. Other conspicuous taxa through this interval include *Bulimina exilis, Valvulineria araucana* and *Cassidulina reniforme.*

Down core from ~20.40 m-CCSF there is rapid increase in the abundance of *T. delicata* that defines the lower boundary of this interval.

4.8 Relationship of IRD, laminated intervals and foraminiferal species diversity

Analysis of the glacial-interglacial cycles (LR04), age/depth tie points and the sedimentary log of Core U1342 (~20.59 m-CCSF) shows that most of the laminated intervals correlate with glacial intervals (9 out of 11intervals: i.e. within MIS 6:~135 to ~185 Ka, MIS 8:~250 to ~310 Ka, MIS 10:~340 to ~390 Ka, MIS 12:~425 to ~460 Ka and MIS 14: ~510 to ~570 Ka; see Appendix 10, Figs. 4.9, 4.13 and 4.14). Only in the first laminated interval (~ 6 to ~8 Ka) and also towards the base of the studied interval (~475 Ka) was there no correlation. Box and whisker plots were constructed to

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statistically and visually analyse the data spread (i.e Figs. 4.13 and 4.14): average dimensions of IRD in laminated intervals have larger dimensions than in the non-laminated intervals (Fig. 4.13). Comparing IRD data with laminated and glacial periods, laminated intervals mostly correlate with largest diameter IRD (with the exception of two IRD peaks at ~30 and ~120 Ka: see Fig. 4.9); therefore, sedimentation within this interval at site U1342 suggests a link with glaciations in the last ~ 597 Ka. This is in line with the assertion of Aiello and Ravelo (2012) in a study on the marine sedimentation in the Bering Sea, where a negative correlation between diatoms and coarser siliciclastic materials is significant, indicating that the delivery of coarser siliciclastic particles occurred mainly during glacial phases. Rock and mineral fragments (IRD) with different shades of quartz fragments ranging from clear/glassy, frosted (with shades ranging from light green, light brown, grey to black), fine grained, black rock fragments (possibly basalt), few glassy rock fragments (possibly obsidian), and a few micas recovered from this site point to a volcanic provenance. All the sediments reported from the Bowers Ridge (Site U1342) were deposited at water depths of around 818 m; the clear separation between the Site U1342 topographic high and the Bering Sea Shelf is thought to minimize the influence of reworked sediments from nearby shelf areas (Takahashi et al. 2011): a source from reworking by storm events is therefore unlikely. One implication of coarser rock fragments during the majority of laminated intervals (Fig. 4.13) is that current winnowing caused the removal of fine grains, and that current action may therefore be the cause of the lamination (or bedding) rather than low oxygen. Nevertheless, three of the laminated intervals (e.g. including the uppermost one, Fig. 4.9) may have been associated with low oxygen as they are characterised by deep infaunal benthic foraminifera.

Deep infaunal foraminiferal species have generally been interpreted to indicate low oxygen levels (Corliss 1991; Kaiho 1994; Bernhard et al. 1997; Jorissen et al. 1995; Jorissen 1999; Gooday 2003), and low oxygen conditions are expected to cause a reduction in the species diversity of benthic foraminiferal faunas. Cross plots show that laminated intervals do not always contain deep infaunal foraminifera (see Fig. 4.14) and this is consistent with a sedimentological-winnowing-origin for some of these horizons. Indeed, if the laminated intervals are interpreted as dominantly low-oxygen intervals,

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then species diversities are not significantly lower than in bioturbated (presumed oxygenated) intervals (i.e. between ~60 and ~85 Ka): substantial reduction in species diversity is recorded in only two out of the eleven laminated intervals (~445 and ~505 to ~ 520 Ka: Appendix 1). Another possibility is that other factors (i.e. type and supply of organic carbon) aside from oxygen-level may be the overriding control on benthic foraminiferal species diversity at Bowers Ridge (see also Chapter 3).

4.9 Conclusions

Benthic foraminiferal assemblages for the past ~597 Kyr at IODP Site U1342 show that abundance, diversity and taxonomic composition vary substantially down core. Some 68 species have been identified, which are thought to denote five main benthic living positions/lifestyles (phytodetritivore epifaunal, epifaunal, shallow infaunal, intermediate infaunal and deep infaunal), with tolerance of high organic carbon and decreasing oxygen-level reflected in the transition from shallowest to deepest habitat. Down core changes in the abundance of key selected species identify eight temporally discrete intervals in U1342, which appear to reflect broad changes in seabed oxygen levels and phytodetritus flux. In some instances, these may relate to changes in sea ice extent in the Bering Sea through time, though there is no clear relationship between the different intervals and the global glacial - interglacial oscillations over the past 597,000 years. Although benthic foraminifera are thought to respond strongly to changes in seabed oxygen levels and the flux of phytodetritus, the relationships at Bowers Ridge are complex, and no clear pattern can be established in this study. On the whole, seabed conditions for the past ~597 Kyr appear to have been dominantly oxygenated, though interspersed with intervals when the flux of phytodetritus appears to have increased. Occasionally, strongly-laminated intervals appear to have been caused by either low oxygen (according to the dominance of infaunal benthic foraminifera), or by current winnowing (causing a reduction in fine terrigenous IRD material).

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5. Conclusions

The specific aims of this study were: 1) to provide a detailed taxonomic appraisal of the late Quaternary benthic foraminifera from Site U1342, Bowers Ridge, in the Bering Sea; 2) assess the down core changes in morphology (especially pore density) of the species *Bolivina spissa* as a proxy for sea bed oxygen level; and 3) assess down core changes in the benthic foraminiferal assemblage structure. An overarching aim of the work is to provide a detailed appraisal of the late Quaternary Bering Sea benthic foraminifera that can be used in other studies of this region and the North Pacific.

Taxonomic assessment of the benthic foraminiferal assemblages from 160 samples at ~13 cm intervals from the 20.59 m interval identifies 68 benthic species from 41 genera and 22 families. Of these 68 species, 52 were identified to species level, while 16 are described in open nomenclature. The species are calcareous, with the exception of *Eggerella* sp. and *Martinottiella communis,* which are agglutinated. The diversity and abundance of the foraminiferal assemblages varies greatly throughout the studied core length. Biogeographical assessment shows that most of the species are known mainly from the Pacific Ocean and its neighbouring seas. The morphological inventory of several key species has been enhanced, most notably for the species *Uvigerina peregrina, Uvigerina bifurcata* and *Bolivina spissa.* Efforts have been made to quantify morphological variability of the test within assemblages of species studied such as *U. peregrina, U. bifurcata* and *B. spissa.*

Working on the premise of some studies that equates benthic foraminiferal species morphology with seabed oxygen level (i.e Kaiho 1994), and more recent studies (i.e. Glock et al. 2011; Glock et al. 2012; Kuhnt et al. 2013) that reported a link between foraminiferal test pore density (PD) and bottom water dissolved oxygen content (BW-O_2), the relationship between PD and interpreted sea BW-O_2 in the tests of the calcareous benthic foraminifer *Bolivina spissa* (Cushman) have been assessed. BW-O_2 estimates were made using a combination of benthic foraminiferal assemblage structure (especially percentage of deep infaunal taxa), in conjunction with the recognition of laminated intervals that may indicate lower oxygen level. Calculated PD values show no apparent correlation with interpreted BW-O_2. Thus, it is inferred that changes in oxygen level may not be the primary or sole driver of PD for *B. spissa*, or that methods used for

assessing seabed oxygen level are imprecise. Furthermore, time averaging of the samples analysed and the lifestyle of *B. spissa* may have obscured primary signals. Factors such as mixing of assemblages by *in-vivo* migration of foraminiferal assemblages between microhabitats, or post-mortem sediment transport and bioturbation may have obscured the primary PD signal and may be responsible for non-correlation of the PD and interpreted BW-O_2. This study questions the use of PD analysis in *B. spissa* for determining BW-O_2 where accompanying sedimentological and/or palaeontological data are unclear, or where precise lamination-by-lamination sampling is impossible and taphonomic processes are not obvious.

Analysis of benthic foraminiferal assemblages' down core in chronological order (at ~13 cm intervals) through the last ~597 Kyr (~20.60 m composite core depth) at Bowers Ridge identifies assemblages of benthic foraminifera that comprisess dominantly shallow infaunal taxa such as *Uvigerina* spp., *Islandiella norcrossi* and *Cassidulina* spp. Some deep infaunal taxa such as *Bolivina spissa, Nonionella digitata, Fursenkoina* spp., *Brizalina pacifica* and *Bolivina* spp. are also recorded. The proportion of deep infaunal species was used as a proxy for low oxygen conditions at the seabed, whilst shallow infaunal species are used as a proxy for a better-oxygenated sea bed. Eight temporally discrete intervals are distinguished down core by the percentage abundances of six key species: Interval 1, *Uvigerina bifurcata*-dominated; Interval 2, *Cassidulina laevigata*-dominated; Interval 3, *Uvigerina bifurcata / Takayanagia delicata* -dominated; Interval 4, *Islandiella norcrossi*-dominated; Interval 5, second *Uvigerina bifurcata*-dominated; Interval 6, *Takayanagia delicata / Alabaminella weddellensis*-dominated; Interval 7, second *Uvigerina bifurcata / Takayanagia delicata*-dominated; and Interval 8, *Takayanagia delicata*-dominated. Three of the intervals signal a well-oxygenated sea bed, whilst the other five intervals suggest strong influence of phytodetritus flux to the seabed coupled with varying dissolved oxygen levels at the seabed. Down core changes in the abundance of selected key species may reflect broad changes in phytodetritus flux through time that may relate to changes in sea ice extent. The relationship between ice rafted debris with laminated interval and glacial periods within the study interval at site U1342 suggests a link with glaciations in the last ~597 Kyr. However, there is no clear relationship between the different intervals and the glacial-interglacial oscillation at the site over this period.

Coarser clastic grains (interpreted as IRD) in some of the laminated intervals, as opposed to unlaminated ones, coupled with an absence of abundant deep-infaunal foraminifera and occasional cross-bedding, indicates some of the laminated intervals may have been caused by strong current winnowing rather than low oxygen *per se*.

Appendices

APPENDICES

A CD-ROM containing benthic foraminifer data from 160 samples recovered from core samples at Site U1342, Bowers Ridge, Bering Sea

Appendix 1. Excel file containing overall downcore abundance and diversity of benthic foraminifer in the 160 samples from Site U1342

Appendix 2. Microsoft word file containing list of benthic foraminifera species (listed in suprageneric order of classification: Loeblich and Tappan 1987) from Site U1342

Appendix 3a. Excel file containing morphometric data of *Uvigerina bifurcata*

Appendix 3b. Excel file containing morphometric data of *Uvigerina peregrina*

Appendix 3c. Excel file containing morphometric data of *Uvigerina hispida*

Appendix 3d. Excel file containing data of *Bolivina spissa* used for morphometric analysis.

Appendix 4a. Excel file containing inferred oxygen level (based on % deep infaunal species used as a proxy for low oxygen conditions at the seabed, and % shallow infaunal species used as a proxy for a well-oxygenated seabed) of *Bolivina spissa* specimens selected at intervals with inferred different oxygen level; PD were determined for each of the megalospheric specimens at the selected intervals

Appendix 4b. Excel file containing pore density (PD) counts from pre-determined area on each *Bolivina spissa* specimen used

Appendix 4c. Excel file containing *Bolivina spissa* PD data used for box and whisker plot; and correlation plots (i.e. *B. spissa* specimens from laminated and non-laminated intervals).

Appendix 5. Excel file containing benthic foraminifer data from Site U1342 used for fragmentation analysis

Appendix 6. Excel file containing percentage abundance data of the 6 most abundant benthic foraminifer species used in the demarcation of eight discrete benthic foraminiferal intervals.

Appendix 7. Excel file containing benthic foraminifera data used in the demarcation of eight discrete benthic foraminiferal intervals in the study.

Appendix 8. Excel file containing percentage and abundance plots of 6 most abundant species used in the demarcation of eight discrete benthic foraminiferal intervals.

Appendix 9. Excel file containing overall abundance and diversity plots and individual plots of most abundant species used in the demarcation of eight discrete benthic foraminiferal intervals.

Appendix 10. Excel file containing overall downcore dimensions of Ice rafted debris (IRD) from Site U1342

Appendix 11. File containing Site U1342 sedimentary Core log photographs

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