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Age and environment of Miocene–Pliocene glaciomarine deposits, James Ross Island, Antarctica

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Abstract – Knowledge of the late Miocene–Pliocene climate of West Antarctica, recorded by sedimentary units within the James Ross Island Volcanic Group, is still fragmentary. Late Miocene glaciomarine deposits at the base of the group in eastern James Ross Island (Hobbs Glacier Formation) and Late Pliocene (3 Ma) interglacial strata at its local top on Cockburn Island (Cockburn Island Formation) have been studied extensively, but other Neogene sedimentary rocks on James Ross Island have thus far not been considered in great detail. Here, we document two further occurrences of glaciomarine strata, included in an expanded Hobbs Glacier Formation, which demonstrate the stratigraphic complexity of the James Ross Island Volcanic Group: reworked diamictites intercalated within the volcanic sequence at Fiordo Belén, northern James Ross Island, are dated by ^{40}Ar/^{39}Ar and ^{87}Sr/^{86}Sr at *c.* 7 Ma (Late Miocene), but massive diamictites which underlie volcanic rocks near Cape Gage, on eastern James Ross Island, yielded an Ar–Ar age of <3.1 Ma (Late Pliocene). These age assignments are confirmed by benthic foraminiferal index species of the genus *Ammoelphidiella*. The geological setting and *Cassidulina*-dominated foraminiferal biofacies of the rocks at Fiordo Belén suggest deposition in water depths of 150–200 m. The periglacial deposits and waterlain tills at Cape Gage were deposited at shallower depths (<100 m), as indicated by an abundance of the pectinid bivalve *'Zygochlamys' anderssoni* and the epibiotic foram *Cibicides lobatulus*. Macrofaunal and foraminiferal biofacies of glaciomarine and interglacial deposits share many similarities, which suggests that temperature is not the dominant factor in the distribution of late Neogene Antarctic biota. Approximately 10 m.y. of Miocene–Pliocene climatic record is preserved within the rock sequence of the James Ross Island Volcanic Group. Prevailing glacial conditions were punctuated by interglacial conditions around 3 Ma.

Keywords: Antarctica, stratigraphy, Ar/Ar, micropalaeontology, palaeoclimatology.

1. Introduction

The palaeoenvironmental and climatic history of West Antartica has been studied primarily in outcrops of sedimentary rocks on King George Island, South Shetland Islands, and in the James Ross Island group, northern Antarctic Peninsula. In particular, late Cenozoic strata have been the subject of intense investigation, as these document the onset of glaciation and the subsequent behaviour of the West Antarctic ice sheet. Whereas Oligocene and early Miocene strata on King George Island have thus far yielded the oldest evidence for glaciation in that part of the continent (Birkenmajer, 1990; Dingle & Lavelle, 1998), the younger glacial history has largely been reconstructed from Miocene–Pliocene rock sequences on James Ross, Seymour and Cockburn islands (e.g. Dingle, McArthur & Vroon, 1997; Pirrie *et al.* 1997*b*; Jonkers, 1998*a*). These younger sequences have considerable significance because their original stratigraphic context has been preserved (in most cases by overlying volcanic rocks). By contrast, climatic implications of deposits included in the Neogene Sirius Group in East Antarctica have been a hotbed of controversy, because of their confused stratigraphic context and therefore difficult age assessment (e.g. Webb & Harwood, 1991; Denton *et al.* 1993; Burckle & Potter, 1996; Webb, Mabin & McKelvey, 1996).

An accurate stratigraphy of the Neogene sedimentary rocks in the James Ross Island group, which as a rule occur in isolated outcrops, is essential for the reconstruction of the Antarctic climatic history over the past 20 million years, and consequently much effort has gone into dating of the various deposits. Isotopic dating has become increasingly important in this respect, particularly because the shallow-water deposits have mostly yielded meagre microfaunas, hampering age determination by traditional biostratigraphy (see review of their stratigraphy in Jonkers, 1998*b*). K–Ar datings of volcanic rocks associated with glaciomarine strata in the James Ross Basin were summarized by Sykes (1988),

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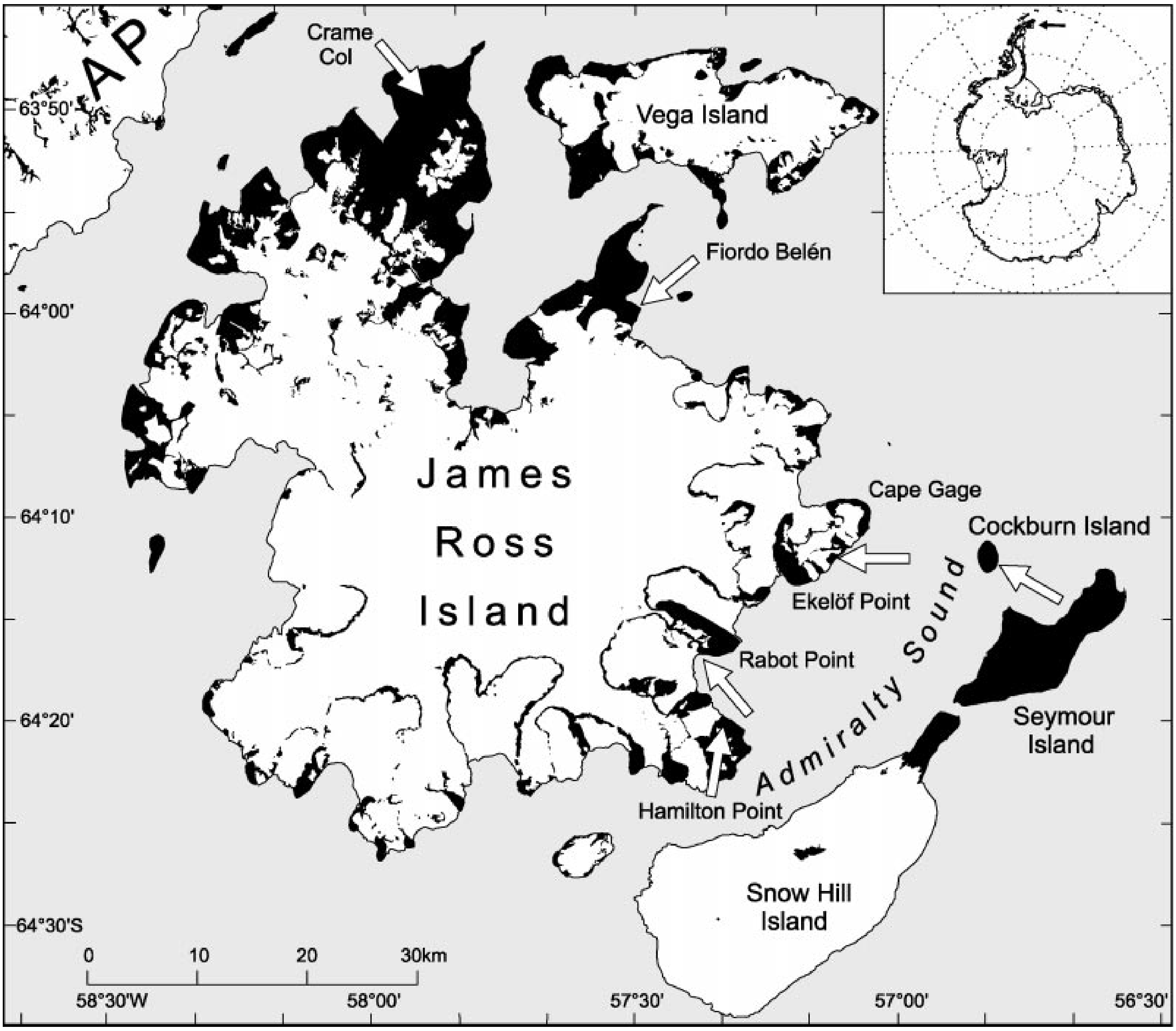

Figure 1. Map of the James Ross Island group, with localities of sedimentary units discussed in this paper indicated by arrows. Outcrop (largely Cretaceous–Lower Tertiary strata) is shown in black; ice-covered areas are white. AP – Antarctic Peninsula.

and supplemented by the first Ar–Ar datings by Jonkers & Kelley (1998). Sr-ages of skeletal carbonates from the area were given by Dingle, McArthur & Vroon (1997) and Dingle & Lavelle (1998). The K–Ar datings in particular have hinted at a complicated stratigraphy of volcanic and sedimentary facies (e.g. Smellie *et al.* 1988).

Late Neogene alkaline volcanic rocks of the James Ross Island Volcanic Group are exposed in the James Ross Island archipelago, on islands in the Antarctic Sound area, and on the Trinity Peninsula of northern Graham Land, Antarctic Peninsula (Nelson, 1975; Smellie *et al.* 1988). Sedimentary strata associated with these volcanic rocks are primarily known from James Ross and Cockburn islands, and may occur at the base of the James Ross Island Volcanic Group, as intercalations, or at the (local) top (for localities see Pirrie *et al.* 1997*b*; Jonkers, 1998*b*; Strelin *et al.* 1997). Although of limited thickness and lateral extent, these deposits yield important climatic signals, and their study significantly augments our currently fragmentary knowledge of Miocene–Pliocene palaeoclimate. Two sedimentary units have thus far been formally named: the Hobbs Glacier Formation, which includes glaciomarine deposits of late Miocene age at the base of the James Ross Island Volcanic Group (Pirrie *et al.* 1997*b*), and the Cockburn Island Formation, a late Pliocene interglacial deposit (Jonkers, 1998*a*).

This paper discusses the geological setting and biofacies of, and presents new Ar–Ar ages for, two sedimentary intervals that crop out at Fiordo Belén and near Cape Gage, on northern and eastern James Ross Island respectively (Fig. 1). Their stratigraphic relationships with previously named and dated sequences is discussed, and a stratigraphic framework for non-volcanic units within the James Ross Island Volcanic Group is proposed.

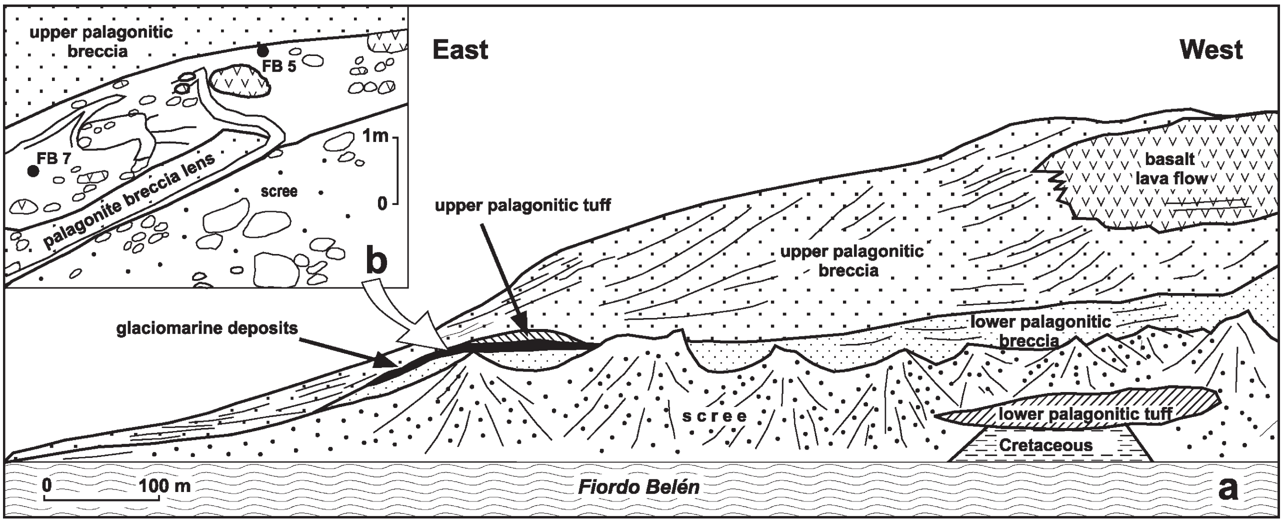

Figure 2. (a) Sketch of south side of Fiordo Belén, viewed from the north, showing distribution of lithofacies. (b) Sketch showing distorted bedding in glaciomarine deposits in eastern section of outcrop, and location of samples FB 5 and FB 7.

2. Geological setting

2.a. Fiordo Belén

Glaciomarine strata at Fiordo Belén (64°00′S, 57°30′W; Fig. 1) are exposed in a northeast-facing cliff, and were described in brief by del Valle *et al.* (1987) and Lirio & del Valle (1997). During subsequent fieldwork by JML in 1997 the stratigraphic relationships of the various lithofacies within the James Ross Island Volcanic Group at Fiordo Belén were resolved, and additional samples were obtained.

The volcanic sequence at Fiordo Belén unconformably overlies Cretaceous strata of the Marambio Group (Fig. 2a), and consists locally of palagonitic breccias and tuffs, and basaltic lavas. Two breccia units, a lower and an upper, are distinguished, which are both laterally continuous over several hundred metres. The upper unit, with a minimum thickness of 150 m, displays giant foresets with dips of 20°–40° and passes laterally into a basalt lava flow to the west. The glaciomarine deposits are sandwiched between these two palagonite breccias, and attain a maximum thickness of 5 m.

In the western part of the outcrop, where thickness of the glaciomarine unit is greatest, are several subhorizontally bedded, matrix-supported reworked diamictite beds, which are normally graded and which decrease in bed thickness; easterly dipping foresets occur in the sandy matrix. Subrounded olivine basalt clasts of up to 20 cm diameter are the most abundant abiogenic component, but sandstone (possibly derived from the Cretaceous sequence) and metamorphic rock clasts are also present. Scattered shell fragments of the extinct pectinid *'Zygochlamys' anderssoni* (Hennig, 1911) occur also (Fig. 3a). The uppermost strata, near

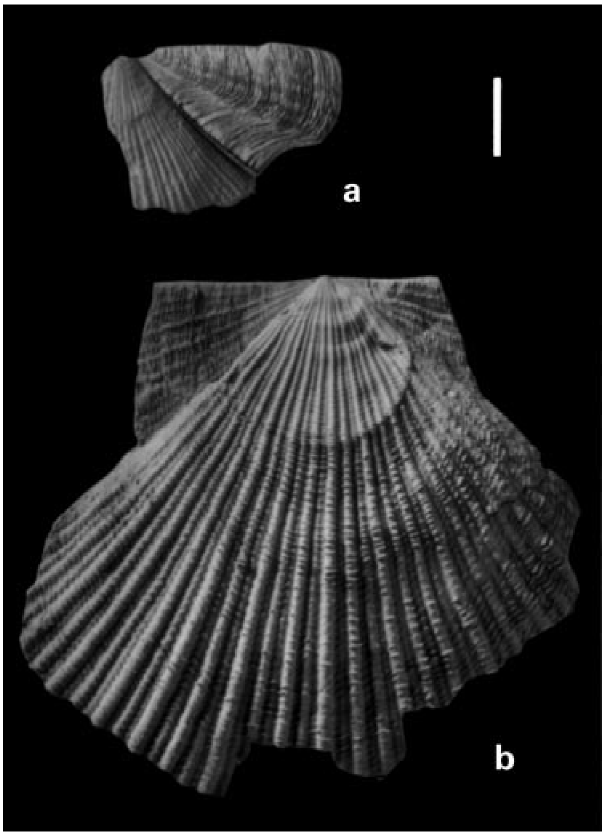

Figure 3. (a) *'Zygochlamys' anderssoni* (Hennig) from the Miocene of Fiordo Belén, right valve anterior auricle of thick-shelled specimen. (b) *'Z.' anderssoni* from the Pliocene of Cape Gage, thin-shelled left valve, which formed part of an articulated pair. Note distinct growth check in early ontogeny. In recent publications (e.g. Jonkers, 1998*a*,*b*) this species was assigned to *Zygochlamys* von Ihering (1907), but it will be demonstrated elsewhere (Jonkers, 2002) that it does not belong in that genus.

the contact with the overlying palagonitic tuff, are slightly deformed.

The glaciomarine unit thins eastward, and the contact with the lower palagonitic breccia dips at an angle of 20° in the eastern part of the outcrop (Fig. 2a). There, the strata are folded or broken up by synsedimentary loading of the overlying upper breccia (Fig. 2b). Poorly sorted, pebbly sandstone with indistinct parallel lamination at the base of the unit is overlain by a large block of palagonite breccia some 30 cm thick, encased within sediment and containing pectinid bioclasts. The upper 1.5 m consist of poorly sorted pebbly sandstone, with basalt clasts up to 30 cm diameter, and fossiliferous palagonite breccia. *'Z.' anderssoni* is more abundant and less fragmented at this site, and large thin-shelled specimens also occur. Shell fragments are mostly thick, and abraded as a result of transportation.

The fragmented and abraded nature of most pectinid shell material, together with an absence of encrusting organisms at Fiordo Belén, may point to a relatively deep water environment (see also Section 5). The stratigraphic position of the deposit, at the foot of steep-dipping foresets of hyaloclastite breccias (Fig. 2a), also suggests an appreciable depth of deposition. Careful analysis of sedimentary facies will be required for a more detailed interpretation of this glaciomarine deposit.

Samples FB 5 and FB 7, and a basalt clast for Ar–Ar dating, were taken from poorly sorted sandstone in the eastern section (Fig. 2b).

2.b. Cape Gage

Outcrops of Neogene glaciomarine strata between Cape Gage (64°10′S, 57°05′W) and Ekelöf Point (64°14′S, 57°12′W; Fig. 1), situated in cliffs facing Admiralty Sound, were logged and sampled by RAdV in 1997. The deposits are exposed in a vertical, and therefore inaccessible, cliff section at *c.* 100 m altitude, but just north of the high cliff, outcrops of the same sequence also occur much lower down, starting at about 5 m above sea-level. It is unclear if this lower sequence forms part of a separate fault block, or of a large land slide. However, the stratigraphic succession in the logged section appears intact. It comprises Cretaceous mudstones and sandstones of the Hamilton Point Member of the Santa Marta Formation (Pirrie *et al.* 1997*a*), which are unconformably overlain by at least 9 m of exposed glaciomarine deposits, and then by > 50 m of volcanic rocks. The exact thickness of the glaciomarine interval is not known, because some 20 m of stratigraphy above the exposed sequence is covered by debris.

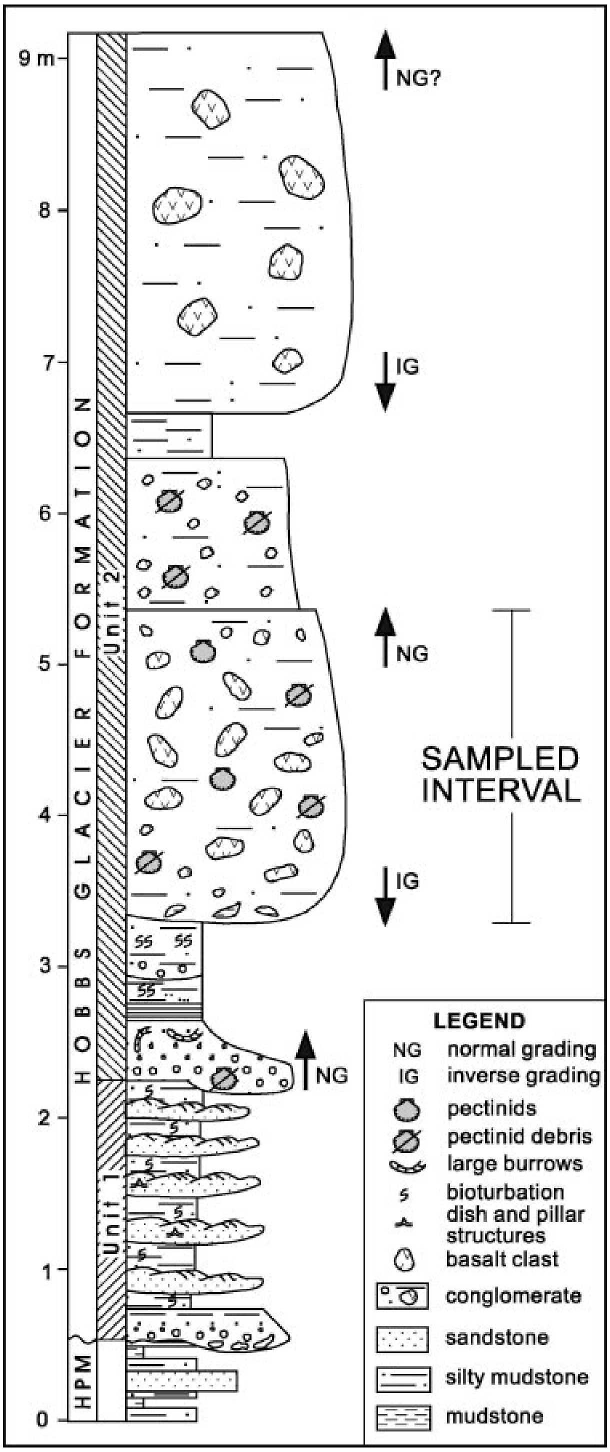

Figure 4. Lithological column of Hobbs Glacier Formation at Cape Gage. HPM – Hamilton Point Member.

Two distinct units are recognized within the glaciomarine interval: a lower, fine-grained clastic unit, nearly 2 m thick, with alternating mudstones and sandstones (Unit 1; Fig. 4), and an upper unit, some 7 m thick, in which massive diamictites predominate (Unit 2). At the base of the lower unit, a normally graded pebbly sandstone to mudstone rests with an erosive contact on Cretaceous strata and contains angular mudstone clasts, probably derived from the underlying sequence. The thin (10–20 cm) dark grey, tuffaceous sandstones in the overlying mudstone–sandstone succession have erosional bases and are

Table 1. Analytical data of ^{40}Ar/^{39}Ar dating

Step	^{40}Ar/^{39}Ar	^{38}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	cum.^{39}Ar%	^{40}Ar*/^{39}Ar	Age (Ma)	±
Fiordo Belén								
1	6.219	0.018	0.39	0.0222	3.0	–0.338	–7.3	2.0
2	3.403	0.016	0.39	0.0114	10.5	0.022	0.5	0.9
3	2.922	0.015	0.32	0.0093	13.5	0.182	3.9	2.0
4	4.738	0.017	0.61	0.0145	49.2	0.442	9.5	0.3
5	4.831	0.017	1.87	0.0149	63.1	0.428	9.2	0.8
6	4.818	0.018	3.75	0.0150	88.4	0.400	8.6	0.4
7	7.012	0.020	6.40	0.0205	93.3	0.944	20.3	1.6
8	14.625	0.026	9.36	0.0412	95.4	2.454	52.4	3.7
9	14.880	0.027	10.28	0.0432	96.7	2.109	45.1	5.9
10	15.526	0.026	10.73	0.0393	97.5	3.899	82.5	9.3
11	10.763	0.023	13.57	0.0285	99.8	2.352	50.2	3.2
Plateau age							9.2	0.3
Cape Gage								
1	1.433	0.016	2.99	0.0047	5.6	0.0548	1.2	0.7
2	1.767	0.015	1.67	0.0057	9.3	0.077	1.7	2.7
3	0.926	0.015	1.69	0.0025	11.8	0.195	4.3	3.9
4	0.647	0.016	2.25	0.0016	15.2	0.160	3.5	2.9
5	0.510	0.016	3.49	0.0013	26.3	0.139	3.1	0.4
6	0.443	0.015	7.50	0.0011	30.4	0.107	2.4	1.0
7	0.573	0.015	2.70	0.0015	53.4	0.123	2.7	0.4
8	0.441	0.015	3.28	0.0011	60.2	0.103	2.3	1.5
9	0.447	0.015	3.24	0.0010	87.8	0.163	3.6	0.4
10	0.514	0.015	5.573	0.0012	93.4	0.150	3.3	1.8
11	0.425	0.013	11.01	0.0009	100.0	0.166	3.7	2.7
Plateau age							3.1	0.3

Plateau ages are quoted at 2σ errors.

normally graded. Internally, these beds are frequently slumped and display dish and pillar structures; at the top of each bed are current ripples. The interbedded thin mudstones are intensely bioturbated.

Overlying matrix-supported conglomerates of the second, upper unit are initially of limited thickness (up to 40 cm), normally graded, and are well bioturbated with abundant large burrows; these beds contain isolated pectinid fragments. Two massive diamictites, 2–3 m thick, make up the bulk of the upper part of this interval. Inverse grading is seen at the erosive base of the lower bed. Sediment clasts in this layer may have been derived from the underlying mudstone bed; other, sub-angular clasts up to 25 cm diameter are predominantly of basaltic composition. Normal grading is present in the top part of this bed. Fossils of *'Zygochlamys' anderssoni* (Fig. 3b) occur in great abundance, their extremely thin shells orientated randomly. Complete valves and articulated pairs are not uncommon, suggesting either fossilization *in situ* or after minimal displacement. The uppermost diamictite is also inversely (bottom) to normally graded (top). Angular basaltic blocks in this bed are up to 55 cm in diameter. No pectinid remains were found within this interval.

The suite of lithologies of Unit 1 likely represents a distal turbidite facies, without much evidence of glacial conditions. The thick inverse to normally graded diamictites of Unit 2 could represent high concentration sediment gravity flows, but more depositional processes may have been involved. Again, this can only be resolved by a more detailed study.

It is interesting to note that in all sections of the Hobbs Glacier Formation described by Pirrie *et al.* (1997*b*) from other parts of eastern James Ross Island the sequences commence with glacially controlled deposition, followed by pro/periglacial delta sedimentation, but at Cape Gage the order is reversed. Such an alternation of depositional settings may attest to a dynamic tectonic history, or reflect the waxing and waning of shelf ice in the James Ross Island area (or perhaps both).

All samples from the section at Cape Gage were collected from the lower, massive fossiliferous diamictite bed (Fig. 4).

3. Ar–Ar dating

Basalt samples from Fiordo Belén and Cape Gage, one from each locality, were selected for ^{40}Ar/^{39}Ar dating. Since no samples were available from the volcanic strata proper, basaltic clasts from the sedimentary matrix at both localities were analysed to determine the maximum age of the deposits. Clasts were thin-sectioned prior to analysis to assess their suitability. Chips of two samples were cleaned with methanol and de-ionized water, and subsequently irradiated at McMaster reactor, Toronto, Canada. After cooling, whole rock irradiated samples were heated in 60 s heating steps, using a defocused multi-mode laser beam from a Nd-YAG laser running at the fundamental wavelength of 1064 nm. Released gas was gettered for five minutes and equilibrated into a MAP 215-50 noble gas spectrometer with a Johnston multiplier.

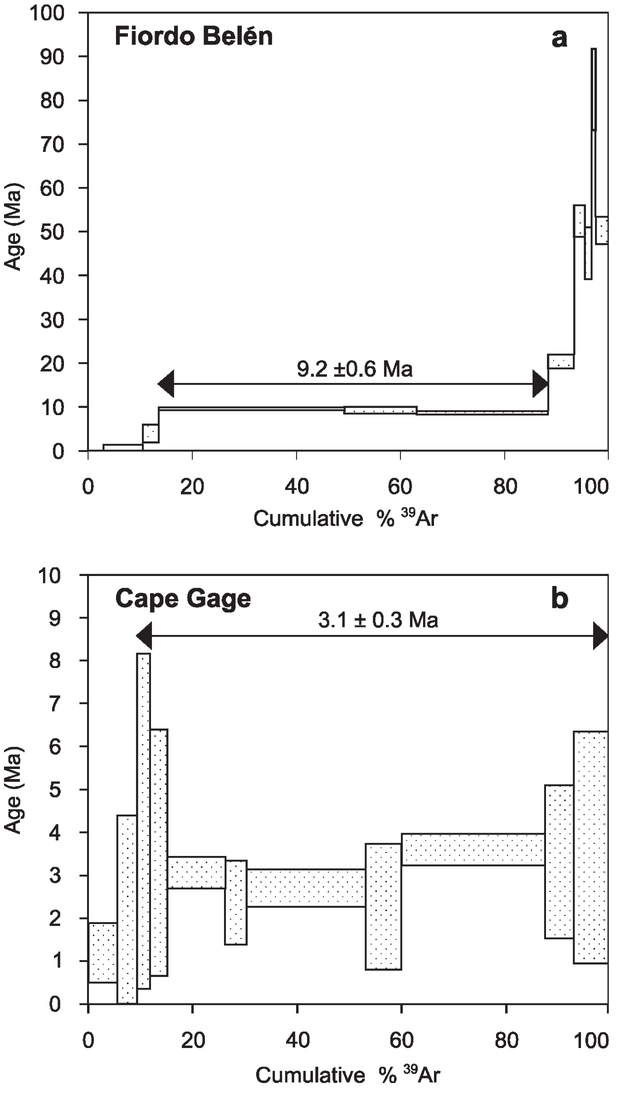

Figure 5. Incremental ^{39}Ar release spectra for basalt clasts from Fiordo Belén (a) and Cape Gage (b). Plateau ages are for 88.2% and 74.9% ^{39}Ar release, respectively.

Argon peaks were scanned ten times and peak heights were extrapolated back to the inlet time. Corrections were made for irradiation interference reactions and mass spectrometer discrimination. Calculated ages are based upon analysis of standard GA1550, with an assumed age of 97.9 Ma (McDougall & Harrison, 1988). A J-value of 0.01220±0.00006 was applied. Analytical data are given in Table 1. Both samples yielded meaningful plateaux (analysis within 2σ of the mean).

The Fiordo Belén basalt yielded a stable plateau, consisting of 74.9% of ^{39}Ar release, and an age of 9.2±0.3 Ma (Table 1; Fig. 5a). The high ages obtained during the last 11.6% of ^{39}Ar release are outside 2σ of the mean. Radiometric ages reported thus far for the James Ross Island Volcanic Group are almost exclusively based on K–Ar whole rock dating (Rex, 1972, 1976; Rinaldi *et al.* 1978; Webb & Andreasen, 1986; Sykes, 1988; Lawver *et al.* 1995), the exception being Ar–Ar ages of basalts on Cockburn Island (Jonkers & Kelley, 1998). Ages range from 7.13±0.49 Ma (Late Miocene; from a basalt clast in the Hobbs Glacier Formation at Crame Col; Fig. 1) to 1.27±0.08 Ma (Pleistocene). The oldest rocks of the regular volcanic sequence were dated at 6.45±0.60 Ma (Sykes, 1988). Thus, the ^{40}Ar/^{39}Ar age of 9.2±0.3 Ma reported here from Fiordo Belén is the oldest age obtained from volcanic rocks on James Ross Island to date, and further demonstrates that volcanism in the area commenced during early Late Miocene times. It also provides a maximum age for the glaciomarine sedimentary intercalation. Supporting evidence for a Late Miocene age comes from ^{87}Sr/^{86}Sr analysis of *'Zygochlamys' anderssoni* shell material from the deposit, which suggests 6.8 $^{+1.3}_{-0.5}$ Ma (Jonkers, 1998*b*), and from the absence of the Pliocene index foraminifer *Ammoelphidiella antarctica* (see Section 5). The Sr-age for Fiordo Belén is somewhat younger than the 9.9±0.97 Ma, yielded by barnacle plates from the type section of the Hobbs Glacier Formation at Rabot Point (Dingle & Lavelle, 1998).

The sample from Cape Gage produced an age of 3.1±0.3 Ma, its plateau consisting of 88.2% of ^{39}Ar release (Table 1; Fig. 5b). This Late Pliocene age is rather surprising, because the deposit is situated at the (local) base of the James Ross Island Volcanic Group, that is, in an identical lithostratigraphic position as the Late Miocene Hobbs Glacier Formation. A Pliocene age of the strata at Cape Gage is confirmed by abundant *Ammoelphidiella antarctica* (see Section 5). Our Ar–Ar age suggests a significantly younger volcanic sequence in the Cape Gage–Ekelöf Point area than on Cockburn Island, just across Admiralty Sound (Fig. 1), which was Ar–Ar dated at *c.* 4.8 Ma (Jonkers & Kelley, 1998).

4. Stratigraphy of the James Ross Island Volcanic Group

The stratigraphy of the James Ross Island Volcanic Group is still largely unresolved. Nelson (1975) proposed this name to encompass all volcanic rocks, as well as sedimentary strata that occur at the base of the volcanic sequence (his 'tuffaceous conglomerates'). Although he recognized five volcanic units, each consisting of basal palagonite breccias followed by olivine basalt flow lavas, which he thought were in stratigraphic superposition, he refrained from formally naming these. Subsequent radiometric datings of these units have not confirmed the stratigraphic succession suggested by Nelson (Smellie *et al.* 1988). Only two units within the James Ross Island Volcanic Group have been accorded formation status, both consisting of non-volcanic, sedimentary strata: the Hobbs Glacier Formation (Pirrie *et al.* 1997*b*) and the Cockburn Island Formation (Jonkers, 1998*a*). The former was defined for the basal sedimentary unit of the James

Ross Island Volcanic Group, and includes all glaciomarine strata overlying Cretaceous formations and underlying hyaloclastites or lavas of the James Ross Island Volcanic Group. Its maximum thickness in outcrop, at Rabot Point (Fig. 1), is only 4.3 m. On the basis of limited palynological evidence (presence of the dinoflagellate cysts *Bitectatodinium tepikiense* Wilson, *Lingulodinium* sp. and *Operculodinium* sp.) a late Miocene age was assigned to the unit (Pirrie *et al.* 1997*b*), which was later confirmed by Sr-dating (Dingle & Lavelle, 1998). The Cockburn Island Formation was proposed for interglacial deposits that occur exclusively on Cockburn Island, and which overlie the James Ross Island Volcanic Group. It has a unique stratigraphic position at the (local) top of the group, and is characterized by an entirely different lithofacies, in which diamictites and obvious ice-rafted debris are absent. Its age is somewhat controversial; Sr-dating of *'Zygochlamys' anderssoni* produced a mean age of 4.7 $^{+0.6}_{-1.2}$ Ma (Dingle, McArthur & Vroon, 1997), but fossil diatoms in the formation, especially *Actinocyclus actinochilus* (Ehrenberg) Simonsen and *Thalassiosira complicata* Gersonde, suggest an age close to 3 Ma (Jonkers & Kelley, 1998).

No names have as yet been proposed for sedimentary intercalations within the James Ross Island Volcanic Group, of which there are many (see Strelin *et al.* 1997). However, to formally name each of these as separate formations, with most such intercalations being barely mappable on a regional scale, would be impractical. Such action would result in a stratigraphic framework with a multitude of names, including many potential synonyms, since a unit's relative stratigraphic position cannot simply be gleaned from its lithostratigraphic relationships (Fig. 6). As it is perfectly conceivable that marine sedimentation was a continuous process, contemporaneous with volcanic activity in the James Ross Island area (at least some of the hyaloclastites were deposited in a marine environment; Skilling, 1991), we propose here to extend the concept of the Hobbs Glacier Formation to include all glaciomarine strata associated with the James Ross Island Volcanic Group, irrespective of their age or lithostratigraphic position.

The *c.* 3 Ma age of the Ar–Ar dated clast from Cape Gage is very similar to the diatom age of the Cockburn Island Formation, but we feel that the strata on both sides of Admiralty Sound cannot be correlated, because of their widely different lithologies and depositional environments. Since the clast indicates a maximum age, the Cape Gage deposits could be somewhat younger than the Cockburn Island Formation (Fig. 6).

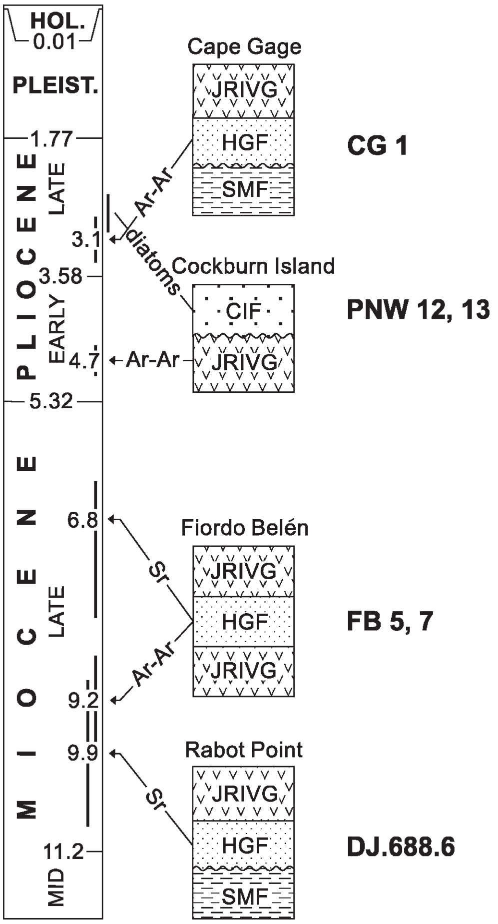

Figure 6. Schematic representation of lithostratigraphic relationships and age of rock units discussed in this paper. CIF – Cockburn Island Formation; HGF – Hobbs Glacier Formation; JRIVG – James Ross Island Volcanic Group; SMF – Santa Marta Formation. ^{40}Ar/^{39}Ar from Jonkers & Kelley (1998) and this paper; ^{87}Sr/^{86}Sr ages from Dingle & Lavelle (1998) and Jonkers (1998*b*); diatom ages from Jonkers & Kelley (1998).

5. Foraminiferal analysis

Four matrix samples, one from the type section of the Hobbs Glacier Formation at Rabot Point (DJ.688.6), two from Fiordo Belén (FB 5, FB 7) and one from Cape Gage (CG 1), were selected for micropalaeontological investigation. The sediment samples were disintegrated, using standard laboratory techniques, and washed over two sieves with mesh sizes of 595 and 125 μm. The residues were oven-dried and subsequently dry-sieved. The fauna in the size range 150–500 μm was analysed quantitatively. The results are presented in Table 2.

Because of the high abiogenic sand content, and consequently low foraminiferal yield of DJ.688.6, FB 5 and FB 7 (*c.* 16, 13 and 8 benthic forams per gram of residue, respectively), the residues of these samples were picked in their entirety. CG 1 produced a much higher foraminiferal abundance (227 forams/g residue), and a small split, containing at least 200 foraminifera, was obtained for analysis, using an Otto micro-splitter. The split was strewn onto a large picking tray with 45 fields, with care being taken to avoid size-sorting effects, and 200 foraminifera were picked

Table 2. Results of foraminiferal counts, with taxa listed in alphabetical order

Species	DJ.688.6	FB 5	FB 7	CG 1
Ammoelphidiella antarctica				28
Ammoelphidiella sp. nov.	8	22	3	
Angulogerina angulosa		5		1
Astrononion antarcticum				9
Cassidulina crassa/subglobosa	6	209	111	21
Cassidulinoides parkerianus	21	31	9	7
Cibicides lobatulus	1	11	3	48
Cribrononion sp.	4	6		24
Ehrenbergina glabra	1	4	2	
Epistominella vitrea	7	2		19
Fissurina laevigata	1	1		3
Fissurina spp.		4		1
Fursenkoina cf. *earlandi*	3			
Fursenkoina spp.		3	1	
Lagena spp.		2		
Lagena squamososulcata		1		
Lenticulina spp.		1	1	
Marginulina sp.			1	
Melonis spp.		23	2	16
Nonionella bradii	2			22
Nonionella turgida	1			
Rosalina araucana		1		
indeterminable benthics	2	13	2	1
Total no. benthics	57	339	135	200
No. benthics/g residue	15.6	12.6	8.0	226.5
No. benthic species	11	18	10	12 (29)*
No. planktonics		1	3	1

* The higher number is based on qualitative observation.

from randomly selected fields. All foraminifera were subsequently identified; the remaining residue of CG 1 was then scanned for a qualitative appreciation of its foraminiferal content. Foraminiferal pickings of DJ.688.6 are held at the British Antarctic Survey; those of FB 5, FB 7 and CG 1 are lodged at the Instituto Antártico Argentino.

Preservation in all samples is moderate to good, the best preservation being observed in CG 1. Foraminiferal tests in this sample look smooth and clean under the light microscope, but SEM study shows that the tests are thinly overgrown with mineral (probably calcitic) material, resulting in rugose surfaces (e.g. Fig. 11i, n). Tests in DJ.688.6 often have a chalky appearance.

Altogether, thirty-two foraminiferal taxa are recognized, and except for one large specimen of *Cyclammina*, all of these possess calcareous tests (see Appendix 1). Most species are common to all samples, but notable exceptions are the low trochospiral *Ammoelphidiella* sp. nov., which was only encountered in the Miocene samples DJ.688.6, FB 5 and FB 7, and the higher-spired *Ammoelphidiella antarctica*, which is exclusive to the Pliocene (CG 1). The latter species also occurs in abundance in the Pliocene Cockburn Island Formation (Gaździcki & Webb, 1996), and is recorded from various Pliocene deposits in East Antarctica, such as Prospect Mesa Gravels in Wright Valley, Victoria Land (Conato & Segre, 1974; Webb, 1974), and Larsemann Hills, Ingrid Christensen Coast (Quilty *et al.* 1990). Thus, these two species appear to be useful indicators of Miocene and Pliocene time, respectively.

All Miocene samples are dominated by cassidulinids (*Cassidulina crassa* and *Cassidulinoides parkerianus*), accounting for 47.5%, 71% and 89% in DJ.688.6, FB 5 and FB 7, respectively (Fig. 7). The faunas in the Fiordo Belén samples are very similar quantitatively, with a strong predominance of *C. crassa* in both; all other taxa constitute less than 10% of the benthic fauna. No such predominance is evident in the Pliocene sample from Cape Gage, in which altogether 28 taxa were recognized in the qualitative analysis. Here, *Cibicides lobatulus* is dominant (24%), followed by *Ammoelphidiella antarctica* (14%), *Cribrononion* sp. (12%), *Nonionella bradii* (11%) and *Cassidulina crassa* (10.5%).

Except for the species of the extinct genus *Ammoelphidiella*, all these taxa are still extant and commonly encountered in Antarctic waters. The faunas are typical of Antarctic shelf environments; none of the agglutinated or calcareous Antarctic deep-water species reported by Bandy & Echols (1964) are present. An association of cassidulinids (*Cassidulina crassa*, *C. subglobosa, Cassidulinoides parkerianus* and *Ehrenbergina glabra*), *Cibicides lobatulus*, *Angulogerina angulosa* and *Astrononion* was reported from the eastern continental shelf of the Weddell Sea, forming part of the 'Fresh Water Shelf Facies' of Anderson (1975), so named because of its association with cold (–1.5 to –1.9 °C), but relatively low salinity (less than 34.51 ‰) waters.

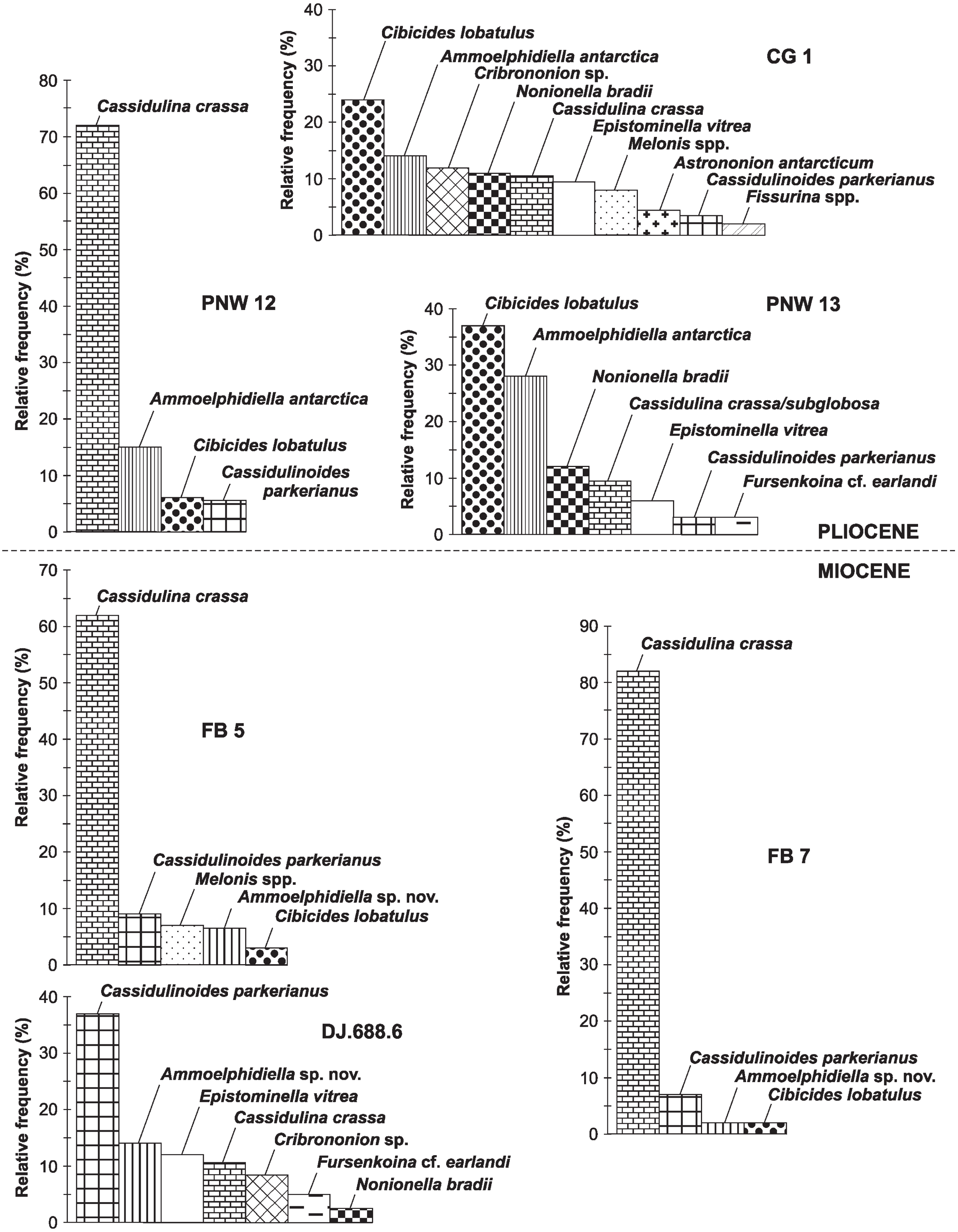

Figure 7. Quantitative distribution of benthic foraminiferal taxa in sedimentary units within the James Ross Island Volcanic Group. Only taxa that constitute > 2% of the assemblage are shown. DJ.688.6 is from the type section of the Hobbs Glacier Formation; FB 5 and FB 7 are from Fiordo Belén; CG 1 is from Cape Gage; PNW 12 and 13 are from Cockburn Island (data from Gaździcki & Webb, 1996). Stratigraphic positions of the samples are indicated in Figure 6.

Assemblages similar to those on James Ross Island were also reported from the Cockburn Island Formation by Gaździcki & Webb (1996). Two extreme assemblages from Cockburn Island, a low-diversity, *Cassidulina*-dominated fauna similar in composition to the Fiordo Belén faunas, and a more diverse, *Cibicides*-dominated assemblage, as in CG 1, are shown in Figure 7. The observed differences in diversity were interpreted by these authors to reflect varying degrees of transport and bioturbation, with low diversities resulting from selective removal of species during multiple phases of recycling. However, this does not explain, for example, the low numbers of *Cibicides lobatulus* (a robust species with a strong test) in such low-diversity assemblages. An alternative explanation might be that species diversity was influenced by fluctuation in environmental variables. Large-scale variation in species distribution and abundance within modern Antarctic calcareous shelf biofacies was described by Osterman & Kellogg (1979), but patterns of patchy species distribution on a much smaller scale have also been observed. Such small-scale patterns, in the modern shallow environment at Explorers Cove, McMurdo Sound, were shown to depend on substrate, as well as on oxygen content of bottom water and availability of organic matter (Bernhard, 1987). In the Cockburn Island Formation such parameters may have varied also, both laterally and over the time span during which the deposit formed. Physical evidence for repeatedly changing substrate is the vertical variation in lithology, which includes relatively 'clean' sandstones as well as coarse conglomerates, all with varying abundances of shell material. The abundance of bivalve shells in particular may account for fluctuations in the numbers of *Cibicides lobatulus*, of which living representatives settle preferentially on the circum-Antarctic scallop *Adamussium colbecki* (Smith) (Mullineaux & DeLaca, 1984), on which they graze algae and bacteria, and erode the shell to parasitize on the host's free amino acids (Alexander & DeLaca, 1987). This species also lives abundantly on other pectinid bivalves (e.g. on *Aequipecten opercularis* (Linnaeus): Haward & Haynes, 1976), and it is commonly fossilized in life position on shells of *'Zygochlamys' anderssoni* in the Cockburn Island Formation (Fig. 8). Thus, whereas *Cassidulina*-dominated faunas may reflect scallop-poor environments, *Cibicides*-rich assemblages may be found associated with abundant epibenthic bivalves.

Such a scenario could help to explain the faunistic differences on James Ross Island. In the deposit at Cape Gage, *'Z.' anderssoni* are plentiful, with many (near) *in situ* specimens, but their abundance in the Fiordo Belén intercalation is much lower; in addition, scallop shells at the latter site are much more fragmented, perhaps suggesting deposition some distance away from their habitat. Ultimately, the observed dominances may reflect differences in water depth: the position of the Fiordo Belén intercalation, near the base of giant foresets in the overlying palagonite breccia, suggests a water depth of at least 150–200 m. Depth of deposition of scallop-rich biofacies on Cockburn Island was interpreted to be no deeper than 100 m (Jonkers, 1998*a*); thus, water depth at Cape Gage probably did not exceed that figure. At Rabot Point the macrofauna is poor and only consists of barnacles and rare bivalves (Pirrie *et al.* 1997*b*). With scallops being absent *Cibicides lobatulus* consequently forms an insignificant part of the foram fauna (< 2 %).

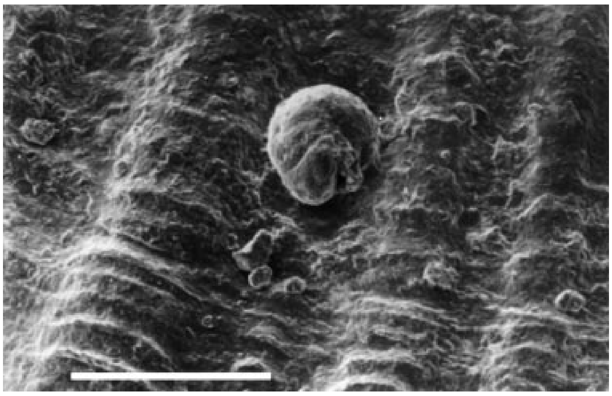

Figure 8. *Cibicides lobatulus* (Walker & Jacob), umbilical view of specimen fossilized in life position on shell of *'Zygochlamys' anderssoni* (DJ.854.47, Cockburn Island). Scale bar: 1 mm.

6. Conclusions

Dating by means of whole rock Ar–Ar laser-stepped heating and micropalaeontology of glaciomarine deposits associated with volcanic rocks on northern and eastern James Ross Island have demonstrated the stratigraphic complexity of the James Ross Island Volcanic Group. It is here proposed to expand the definition of the Hobbs Glacier Formation (James Ross Island Volcanic Group) to include all such deposits, whether at the base of or intercalated within the volcanic sequence.

The $^{40}Ar/^{39}Ar$ age of 9.2 ± 0.3 Ma, obtained from a basalt clast from the Hobbs Glacier Formation at Fiordo Belén, is the oldest age thus far reported for the James Ross Island Volcanic Group. This age confirms earlier reports of late Miocene volcanic activity and contemporaneous glaciomarine sedimentation in the James Ross Island area. Subsidence and volcanism may both be linked to major normal faulting resulting from post-subduction back-arc isostatic plate recovery (Smellie *et al.* 1988). The bathymetry of Admiralty Sound (cf. fig. 4A of Dingle, McArthur & Vroon, 1997) suggests that major faults now separate James Ross Island and the Seymour–Cockburn Island tectonic block. These faults may already have been differentially active during Pliocene times: uplift and erosion on the eastern side removed part of the early Pliocene (4.8 Ma) volcanic sequence of the James Ross Island Volcanic Group, with subsequent subsidence resulting in deposition of the interglacial Cockburn Island Formation (3 Ma) (Jonkers & Kelley, 1998). However, on the western side of Admiralty Sound, subsidence and ensuing glaciomarine deposition did not take place until later in Pliocene times (< 3 Ma), as suggested by the new Ar–Ar data. Uplift rates on Cockburn Island based on the elevation of 4.8 Ma subaerial lavas to a present-day altitude of 450 m, and of littoral conglomerates of 3 Ma to an altitude of 280 m, are both remarkably similar, being in the order of 9.4–9.3 cm × 10^{-3} years, but it is by no means certain that uplift was linear.

Macrofaunal and microfaunal biofacies of glaciomarine and interglacial deposits within the James Ross Island Volcanic Group are strikingly similar. The large pectinid bivalve *'Zygochlamys' anderssoni*, originally known only from interglacial deposits on Cockburn Island, evidently thrived just as well in environments with icebergs. The species' abundance in waterlain till indicates that this scallop may have lived near, or perhaps even beneath, floating shelf ice, as has been suggested also for the extant Antarctic scallop *Adamussium colbecki* (Hain & Melles, 1994). The habitat requirements of both species may have been rather similar, as the latter species also occurs in the interglacial Cockburn Island Formation (Jonkers, 1998*a*). *'Z.' anderssoni*'s occurrence in massive diamictites implies that this species cannot be considered as a reliable indicator of interglacial conditions, as was once thought (see discussion in Jonkers, 1998*a*). Its association with glacial deposits has important implications for the extinction of *Chlamys*-like scallops in Antarctica; this probably cannot simply be explained by assuming a temperature-dependent threshold beyond which precipitation of shells in these scallops became impossible, as suggested by Berkman & Prentice (1996), but that other environmental factors were responsible for their demise in Antarctica.

The strong similarity between late Neogene glaciomarine and interglacial foraminiferal biofacies, as demonstrated by quantitative analysis, is not surprising, given the fact that most taxa present in the Antarctic assemblages are cosmopolitan. This suggests once again that temperature does not primarily control distribution of benthic foraminiferal taxa, but that substrate and food supply are more important in this respect. The observed numerical compositional differences within and between facies may be explained by varying degrees of abundance of certain biota (especially scallops): *Cibicides lobatulus*-dominated assemblages may thus be associated with environments in which pectinids abound, and cassidulinid-dominated assemblages could indicate environments that are less conducive to sustain dense scallop populations. Such faunistic differences may ultimately reflect variation in water depth, or in rates of sediment supply.

Biostratigraphic analysis has reiterated the stratigraphic usefulness of species of the benthic foraminiferal genus *Ammoelphidiella*, of which a new species is recognized as a Late Miocene 'marker', and *A. antarctica* confirmed as an index for Pliocene time. As there is no simple relationship between lithostratigraphic position of the Hobbs Glacier Formation and age, it would appear that a rigid combination of isotopic dating and microfossil biostratigraphy is imperative to further resolve the stratigraphy of the James Ross Island Volcanic Group. A robust stratigraphic framework for sedimentary strata in the James Ross Island group, many of which are still undated, will contribute to a better understanding of late Neogene Antarctic palaeoclimate.

The present study has demonstrated that approximately 10 Ma of climatic record is preserved within the rock sequence on James Ross Island. Late Miocene–Late Pliocene sedimentary facies suggest that prevailing glacial conditions were punctuated by interglacial conditions around 3 Ma, as indicated by the deposits of the Cockburn Island Formation. In East Antarctica, marine diatoms of Pliocene age in the Sirius Group have been used as evidence of climatic amelioration around that time (Webb & Harwood, 1991; Jonkers & Kelley, 1998). Documenting more fully the history of Miocene–Pliocene Antarctic ice sheets in the northern Antarctic Peninsula requires detailed palaeoenvironmental analysis of other, as yet unstudied, occurrences of sedimentary deposits in the James Ross Island area.

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References

ALEXANDER, S. P. & DELACA, T. E. 1987. Feeding adaptations of the foraminiferan *Cibicides refulgens* living epizoically and parasitically on the Antarctic scallop *Adamussium colbecki*. *Biological Bulletin* **173**, 136–59.

ANDERSON, J. B. 1975. Ecology and distribution of foraminifera in the Weddell Sea of Antarctica. *Micropaleontology* **21**, 69–96.

BANDY, O. L. & ECHOLS, R. J. 1964. Antarctic foraminiferal zonation. *Antarctic Research Series* **1**, 73–91.

BERKMAN, P. A. & PRENTICE, M. L. 1996. Pliocene extinction of Antarctic pectinid mollusks. *Science* **271**, 1606–7.

BERNHARD, J. M. 1987. Foraminiferal biotopes in Explorers Cove, McMurdo Sound, Antarctica. *Journal of Foraminiferal Research* **17**, 286–97.

BIRKENMAJER, K. 1990. Geochronology and climatostratigraphy of Tertiary glacial and interglacial successions on King George Island, South Shetland Islands (West Antarctica). *Zentrallblatt für Geologie und Paläontologie*, Teil **1**, 141–51.

BRADY, H. B. 1881. Notes on some of the reticularian Rhizopoda of the Challenger Expedition, part 3. *Quarterly Journal of Microscopical Science* **21**, 31–71.

BRADY, H. B. 1884. Report on the foraminifera collected by H.M.S. Challenger during the years 1873–1876. *Reports on the Scientific Results of the Voyage of H.M.S. Challenger, Zoology* **9**, 1–814.

BURCKLE, L. H. & POTTER, N. 1996. Pliocene–Pleistocene diatoms in Paleozoic and Mesozoic sedimentary and igneous rocks from Antarctica: a Sirius problem solved. *Geology* **24**, 235–8.

CHAPMAN, F. 1916. Report on the Foraminifera and Ostracoda out of marine muds from soundings in the Ross Sea. *British Antarctic Expedition 1907–9, Geology* **2**, 57–78.

CHAPMAN, F. & PARR, W. J. 1935. Foraminifera and Ostracoda from soundings made by the trawler "Bonthorpe" in the Great Australian Bight. *Journal of the Royal Society of Western Australia* **21**, 1–7.

CONATO, V. & SEGRE, A. G. 1974. Depositi marini Quaternari e nuovi foraminiferi dell Antartide (Terre Victoria, Valle Wright). *Atti della Società Toscana di Scienze Naturali Resuidente in Pisa*, serie A **81**, 6–23.

CRESPIN, I. 1960. Some recent foraminifera from Vestfold Hills, Antarctica. *Science Reports of the Tohoku University, Sendai, Japan, second series (Geology), special volume* **4**, 19–31.

DE LA SAGRA, R. 1839. Foraminifères. *Histoire physique, politique et naturelle de l'Île de Cuba*. Paris: A. Bertrand, 224 pp.

DEL VALLE, R. A., MARSHALL, P. A., LIRIO J. M. & CAMERLINGO, E. 1987. Sobre la presencia del conglomerado con pecten en el fiordo Belen, isla James Ross. *Resúmenes, Primera Reunion de Comunicaciones sobre Investigaciones Antarcticas, Buenos Aires, 16 al 20 de Noviembre de 1987*. Buenos Aires: Dirección Nacional del Antártico. (1 p.; no pagination)

DE MONTFORT, D. 1808. *Conchyliologie systématique, et classification méthodique de coquilles*, vol. 1, pp. 1–410. Paris: F. Schoell.

DENTON, G. H., SUGDEN, D. E., MARCHANT, D. R., HALL, B. L. & WILCH, T. I. 1993. East Antarctic ice sheet sensitivity to Pliocene climatic change from a Dry Valleys perspective. In *The case for a stable East Antarctic ice sheet* (eds D. E. Sugden *et. al.*), pp. 155–204. Geografiska Annaler 75A.

DINGLE, R. V. & LAVELLE, M. 1998. Antarctic Peninsular cryosphere: Early Oligocene (*c.* 30 Ma) initiation and a revised glacial chronology. *Journal of the Geological Society, London* **155**, 433–7.

DINGLE, R. V., MCARTHUR, J. M. & VROON, P. 1997. Oligocene and Pliocene interglacial events in the Antarctic Peninsula dated using strontium isotope stratigraphy. *Journal of the Geological Society, London* **154**, 257–64.

D'ORBIGNY, A. 1826. Tableau méthodique de la classe des Cephalopodes. *Annales des Sciences Naturelles Paris* (série 1) **7**, 245–314.

D'ORBIGNY, A. 1839. Foraminifères. *Voyage dans l'Amérique Méridionale* **5**, 1–86. Paris: Pitois-Levrault.

D'ORBIGNY, A. 1846. *Foraminifères fossiles du Bassin Tertiaire de Vienne (Autriche)*. Paris: Gide et Comp., 312 pp.

FILLON, R. H. 1974. Late Cenozoic foraminiferal paleoecology of the Ross Sea, Antarctica. *Micropaleontology* **20**, 129–51.

GAŹDZICKI, A. & WEBB, P.-N. 1996. Foraminifera from the *Pecten* Conglomerate (Pliocene) of Cockburn Island, Antarctic Peninsula. *Palaeontologia Polonica* **55**, 147–74.

HAIN, S. & MELLES, M. 1994. Evidence for a marine molluscan fauna beneath ice shelves in the Lazarev and Weddell seas, Antarctica, from shells of *Adamussium colbecki* and *Nacella (Patinigera)* cf. *concinna*. *Antarctic Science* **6**, 29–36.

HAWARD, N. J. B. & HAYNES, J. R. 1976. *Chlamys opercularis* (Linnaeus) as a mobile substrate for foraminifera. *Journal of Foraminiferal Research* **6**, 30–8.

HENNIG, A. 1911. Le conglomérat Pleistocène à Pecten de l'Île Cockburn. *Wissenschaftliche Ergebnisse der Schwedischen Südpolar-Expedition 1901–1903* **3**, 1–72.

HERON-ALLEN, E. & EARLAND, A. 1922. Protozoa, Part II. Foraminifera. *British Antarctic ("Terra Nova") Expedition, Natural History Report (Zoology)* **6**, 25–268.

HERON-ALLEN, E. & EARLAND, A. 1932. Foraminifera, Part I. The ice-free area of the Falkland Islands and adjacent seas. *Discovery Reports* **4**, 291–460.

HOLLAND, R. 1910. The fossil foraminifera. *Wissenschaftliche Ergebnisse der Schwedischen Südpolar-Expedition 1901–1903* **3**, 1–12.

JONKERS, H. A. 1998*a*. The Cockburn Island Formation; Late Pliocene interglacial sedimentation in the James Ross Basin, northern Antarctic Peninsula. *Newsletters on Stratigraphy* **36**, 63–76.

JONKERS, H. A. 1998*b*. Stratigraphy of Antarctic late Cenozoic pectinid-bearing deposits. *Antarctic Science* **10**, 161–70.

JONKERS, H. A. 2002. *Late Cenozoic–Recent Pectinidae (Mollusca: Bivalvia) of the Southern Ocean and neighbouring regions*. Monographs of Marine Mollusca no. 5, pp. 1–125. Leiden: Backhuys Publishers. In press.

JONKERS, H. A. & KELLEY, S. P. 1998. A reassessment of the age of the Cockburn Island Formation, northern Antarctic Peninsula, and its palaeoclimatic implications. *Journal of the Geological Society, London* **155**, 737–40.

KANMACHER, F. 1798. *Adam's essays on the microscope; the second edition with considerable additions and improvements*, chapter 11, pp. 629–45. London: Dillon and Keating.

LAWVER, L. A., KELLER, R. A., FISK, M. R. & STRELIN, J. A. 1995. Bransfield Strait, Antarctic Peninsula – active extension behind a dead arc. In *Backarc basins, tectonics and magmatism* (ed. B. Taylor), pp. 315–42. New York, London: Plenum Press.

LECKIE, R. M. & WEBB, P.-N. 1986. Late Paleogene and early Neogene foraminifers of Deep Sea Drilling Project Site 270, Ross Sea, Antarctica. In *Initial Reports of the Deep Sea Drilling Project* **90** (eds J. P. Kennett, C. C. von der Borch *et al.*), pp. 1093–1142. Washington: U.S. Government Printing Office.

LIRIO, J. M. & DEL VALLE, R. A. 1997. Conglomerados con *Pecten* (Mioceno Superior y Plioceno Superior) en la isla J. Ross, Península Antártica. IV Jornadas de Investigaciones Antárticas, Instituto Antártico Argentino, Buenos Aires, 1–5 Septiembre, 1997, pp. 298–304. Buenos Aires: Dirección Nacional del Antártico.

McDougall, I. & Harrison, T. M. 1988. Geochronology and thermochronology by the ^{40}Ar/^{39}Ar method. *Oxford Monographs on Geology and Geophysics* **9**, 212 pp.

Montagu, G. 1803. *Testacea Britannica; or, natural history of British shells, marine, land, and fresh-water, &c.* London: J. White, 606 pp.

Mullineaux, L. S. & DeLaca, T. E. 1984. Distribution of Antarctic benthic foraminifers settling on the pecten *Adamussium colbecki. Polar Bio*logy **3**, 185–9.

Nelson, P. H. H. 1975 (for 1966). The James Ross Island Volcanic Group of north-east Graham Land. *British Antartic Survey Scientific Reports* **54**, 62 pp.

Osterman, L. E. & Kellogg, T. B. 1979. Recent benthic foraminiferal distributions from the Ross Sea, Antarctica: relation to ecologic and oceanographic conditions. *Journal of Foraminiferal Research* **9**, 250–69.

Parker, F. L., Phleger, F. B. & Peirson, J. F. 1953. Ecology of foraminifera from San Antonio Bay and environs, southwest Texas. *Cushman Foundation for Foraminiferal Research*, special publication **2**, 1–75.

Parr, W. J. 1950. Foraminifera. *British, Australian and New Zealand Antarctic Research Expedition Reports, series B (Zoology, Botany)* **5**, 235–392.

Pirrie, D., Crame, J. A., Lomas, S. A. & Riding, J. B. 1997*a*. Late Cretaceous stratigraphy of the Admiralty Sound region, James Ross Basin, Antarctica. *Cretaceous Research* **18**, 109–37.

Pirrie, D., Crame, J. A., Riding, J. B., Butcher, A. R. & Taylor, P. D. 1997*b*. Miocene glaciomarine sedimentation in the northern Antarctic Peninsula region; the Hobbs Glacier Formation, James Ross Island. *Geological Magazine* **136**, 745–62.

Quilty, P. G., Gillieson, D., Burgess, J., Gardiner, G., Spate, A. & Pidgeon, R. 1990. *Ammoelphidiella* from the Pliocene of Larsemann Hills, East Antarctica. *Journal of Foraminiferal Research* **20**, 1–7.

Reuss, A. E. 1849. Neue Foraminiferen aus den Schichten des österreichischen Tertiärbeckens. *Denkschriften der mathematisch–naturwissenschaftliche Klasse der Kaiserlichen Akademie der Wissenschaften* **1**, 365–90.

Rex, D. C. 1972. K–Ar age determinations on volcanic and associated rocks from the Antarctic Peninsula and Dronning Maud Land. In *Antarctic Geology and Geophysics* (ed. R. J. Adie), pp. 133–6. Oslo: Universitetsforlaget.

Rex, D. C. 1976. Geochronology in relation to the stratigraphy of the Antarctic Peninsula. *British Antarctic Survey Bulletin* **43**, 49–58.

Rinaldi, C. A., Massabie, A., Morelli, J., Rosenman, H. L. & del Valle, R. A. 1978. Geología de la isla Vicecomodoro Marambio. *Contribución del Instituto Antártico Argentino*, no. 217, pp. 1–37. Buenos Aires: Dirección Nacional del Antártico.

Skilling, I. P. 1991. Intraglacial eruptive environment of the Miocene–Recent, James Ross Island Group: evidence from palagonite and zeolite chemistry. *Abstracts, Sixth International Symposium on Antarctic Earth Sciences, Ranzan-machi, Saitama, Japan, September 1991*, p. 534. Tokyo: National Institute of Polar Research.

Smellie, J. L., Pankhurst, R. J., Hole, M. J. & Thomson, J. W. 1988. Age, distribution and eruptive conditions of Late Cenozoic alkaline volcanism in the Antarctic Peninsula and eastern Ellsworth Land: review. *British Antarctic Survey Bulletin* **80**, 21–49.

Strelin, J. A., Muñoz, C. E., Torielli, C. A., Carrizo, H. G. & Medina, F. A. 1997. Las diamictitas de la isla James Ross, Antártida: origen y probable relación con el "Conglomerado con *Pecten*". *IV Jornadas de Investigaciones Antárticas, Instituto Antártico Argentino, Buenos Aires, 1–5 Septiembre, 1997*, pp. 328–35. Buenos Aires: Dirección Nacional del Antártico.

Strong, C. P. & Webb, P. N. 1998. Lower Miocene foraminifera from CRP-1 drillhole. *Terra Antarctica* **5**, 515–20.

Sykes, M. A. 1988. New K–Ar age determinations on the James Ross Island Volcanic Group, north-east Graham Land, Antarctica. *British Antarctic Survey Bulletin* **80**, 51–6.

von Ihering, H. 1907. Les mollusques fossiles du Tertiaire et du Crétacé supérieur de l'Argentine. *Anales del Museo Nacional de Historia Natural de Buenos Aires* **14**, 1–611.

Walker, G. & Boys, W. 1784. *Testacea Minuta Rariora; a collection of the minute and rare shells lately discovered in the sand of the sea-shore near Sandwich by William Boys*. London: J. March, 25 pp.

Ward, B. L. & Webb, P.-N. 1986. Late Quaternary foraminifera from raised deposits of the Cape Royds–Cape Barne area, Ross Island. *Journal of Foraminiferal Research* **16**, 176–200.

Webb, P.-N., 1972. Paleontology of late Tertiary–Quaternary sediments, Wright Valley, Antarctica. *Antarctic Journal of the United States* **7**, 96–7.

Webb, P.-N. 1974. Micropaleontology, paleoecology and correlation of the Pecten gravels, Wright Valley, Antarctica, and description of *Trochoelphidiella onyxi* n. gen., n. sp. *Journal of Foraminiferal Research* **4**, 184–99.

Webb, P.-N. & Andreasen, J. E. 1986. Potassium/argon dating of volcanic material associated with the Pliocene *Pecten* Conglomerate (Cockburn Island) and Scallop Hill Formation (McMurdo Sound). *Antarctic Journal of the United States* **21**, 59.

Webb, P.-N. & Harwood, D. M. 1991. Late Cenozoic glacial history of the Ross Embayment, Antarctica. *Quaternary Science Reviews* **10**, 215–23.

Webb, P.-N., Mabin, M. G. C. & McKelvey, B. C. 1996. A marine and terrestrial Sirius Group succession, middle Beardmore Glacier–Queen Alexandra Range, Transantarctic Mountains, Antarctica. *Marine Micropalaeontology* **27**, 273–97.

Williamson, W. C. 1858. *Recent Foraminifera of Great Britain*. London: The Ray Society, 107 pp.

Appendix 1. Faunal reference list

Wherever possible we have followed Gaździcki & Webb (1996) in their specific identifications.

Ammoelphidiella antarctica Conato & Segre, 1974, p. 12; Quilty *et al.* 1990, p. 5, pl. 1, fig. 21; Gaździcki & Webb, 1996, p. 164, fig. 7, pl. 37, figs 5–7, pl. 38, figs 1–10; *Rotalia beccarii* (Linnaeus) *sensu* Holland, 1910, pt. 9, p. 11, pl. 2, figs 11, 12; *Buccella* n. sp., Webb, 1972, pt. 6, fig. 2; *Trochoelphidiella onyxi* Webb, 1974, pt. 4, p. 196, pl. 1, figs 1–12, pl. 2, figs 1–10, pl. 3, figs 1–6, pl. 4, figs 1–6, pl. 5, figs 1–6. Figure 12o–q.

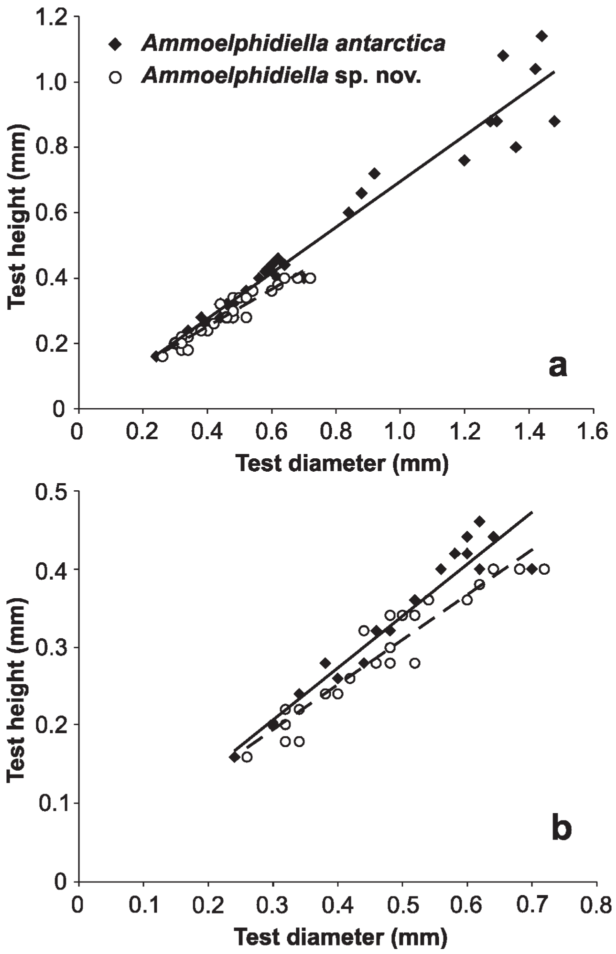

Figure 9. Bivariate plot of test height and test diameter of *Ammoelphidiella antarctica* and *Ammoelphidiella* sp. nov. (a) Total size range of *A. antarctica*, (b) total size range of *Ammoelphidiella* sp. nov. Solid lines: axes of linear regression for *A. antarctica*; dashed lines: axes of linear regression for *A.* sp. nov.

Remarks. This is the only known Pliocene species of *Ammoelphidiella*.

***Ammoelphidiella* sp. nov.** Figure 12l–n.

Remarks. The test of this species is similar to that of *A. antarctica*, but its maximum size is smaller (up to *c*. 0.7 mm versus 1.5 mm diameter; Fig. 9a). In the same size range it generally has a lower spire, but a few high-spired specimens were found in DJ.688.6; conversely, low trochospiral *A. antarctica* occur rarely in the Pliocene Cape Gage assemblage (Fig. 9b). The mean H/D ratio is 0.624 ± 0.001 (n = 26); of *A. antarctica* in the same size range this is 0.681 ± 0.011 (n = 19; mean H/D over the total range is similar: 0.691 ± 0.011 [n = 30]).

This new species occurs in all of the Miocene samples examined (DJ.688.6, FB 5, FB 7); it is absent from the Pliocene. Other pre-Pliocene species of *Ammoelphidiella* are *A. pustulosa* Leckie & Webb (upper Oligocene–lower Miocene section of DSDP Site 270; Leckie & Webb, 1986), *A. uniforamina* d'Agostino (early–mid Miocene), and two unnamed, early Miocene taxa similar to *A. pustulosa*, from DSDP Site 270 (Leckie & Webb, 1986) and CRP-1 drill hole, southwestern Ross Sea (Strong & Webb, 1998). Tests of these taxa are much smaller (0.2–0.3 mm diameter) and more compressed than those of the species from James Ross Island.

Leckie & Webb (1986) considered mid-Miocene *A. uniforamina* the species most closely related (and possibly ancestral) to *A. antarctica* (their *A. onyxi*), differing chiefly in its single row of sutural foramina, which are elongate parallel to the sutures. Late Miocene *Ammoelphidiella*, documented here for the first time, possess a double row of sutural pores (Fig. 12m), as in Pliocene *A. antarctica*, suggesting that the new species from James Ross Island is probably directly ancestral to *A. antarctica*.

Angulogerina angulosa (Williamson); Gaździcki & Webb, 1996, p. 162, pl. 34, figs 8–10; *Uvigerina angulosa* Williamson, 1858, p. 67, pl. 5, fig. 140; Brady, 1884, p. 576, pl. 74, figs 15–18; Chapman, 1916, pt. 2, p. 32, pl. 3, fig. 22; Heron-Allen & Earland, 1932, p. 397, pl. 12, figs 32–39; *Uvigerina striata* d'Orbigny; Heron-Allen & Earland, 1932, p. 397, pl. 12, fig. 31. Figure 10r, s.

***Astacolus* sp.**

Remarks. Qualitative observation only. Figure 10j–l.

Astrononion antarcticum Parr, 1950, p. 371, pl. 15, figs 13, 14 (as '*antarcticus*'); Crespin, 1960, p. 26, pl. 2, fig. 9; Fillon, 1974, p. 139, pl. 6, figs 4–6. Figure 11j, k.

Cassidulina crassa d'Orbigny, 1839, p. 56, pl. 7, figs 18–20; Brady, 1884, p. 429, pl. 54, figs 4, 5; Holland, 1910, pt. 9, p. 7, pl. 2, figs 2, 5; Heron-Allen & Earland, 1932, p. 357, pl. 9, figs 26–33; Crespin, 1960, p. 29, pl. 3, figs 12, 13; Gaździcki & Webb, 1996, p. 161, pl. 35, figs 1–3; *Globocassidulina subglobosa* (Brady) *sensu* Gaździcki & Webb, 1996, pl. 35, fig. 7. Figure 11f–h.

Remarks. Gaździcki & Webb (1996) figured a specimen of *C. subglobosa* which is indistinguishable from *C. crassa*, being of similar size and having a laterally compressed test. In their description (p. 162), the test of *C. subglobosa* is said to be tightly enrolled and much smaller than that of *C. crassa*.

Cassidulina subglobosa Brady, 1881, p. 60; Brady, 1884, p. 430, pl. 54, fig. 17.

Remarks. Only a few cassidulinids in our samples are referable to *C. subglobosa*. These are of comparatively small size, with a less compressed test than *C. crassa*. It is possible that these specimens represent extremes in the variation of *C. crassa*, or that they are juveniles of *Cassidulinioides*. Figure 11i.

Cassidulinoides parkerianus (Brady); Parr, 1950, pt. 6, p. 344, pl. 12, fig. 25; Fillon, 1974, p. 139, pl. 4, fig. 5; Ward & Webb, 1986, p. 190, pl. 4, fig. 9; Gaździcki & Webb, 1996, p. 161, pl. 35, figs 4–6; *Cassidulina parkeriana* Brady, 1881, p. 59; Brady, 1884, p. 432, pl. 54, figs 11–16; Chapman, 1916, pt. 2, p. 30, pl. 2, fig. 13; Heron-Allen & Earland, 1932, p. 359, pl. 9, figs 22–25; *Cassidulinoides* cf. *parkerianus* (Brady); Quilty *et al.* 1990, p. 3, pl. 1, fig. 10. Figure 11d.

Cibicides lobatulus (Walker & Jacob); Gaździcki & Webb, 1996, p. 163, pl. 36, figs 1–3; Osterman & Kellogg, 1979, p. 264, pl. 1, figs 1–3; *Nautilus lobatulus* Walker & Jacob, *in* Kanmacher, 1798, p. 642, pl. 14, fig. 36; *Truncatulina lobatula* (Walker & Jacob); Brady, 1884, p. 660, pl. 92, fig. 10, pl. 93, figs 1, 4, 5; Holland, 1910, pt. 9, p. 10; *Cibicides refulgens* de Montfort, 1808, p. 121, text-fig. 31; Osterman & Kellogg, 1979, p. 264, pl. 1, figs 4, 5; Quilty *et al.* 1990, p. 3, pl. 1, fig. 17; Gaździcki & Webb, 1996, p. 162, pl. 36, figs 4–6; *Truncatulina refulgens* (de Montfort); Brady, 1884, p. 659, pl. 92, figs 7–9; Holland, 1910, pt. 9, p. 10, pl. 2, figs 1, 7.

Remarks. Holland (1910) considered *C. refulgens* a mere 'variety' of *C. lobatulus*, but nonetheless kept them separ-

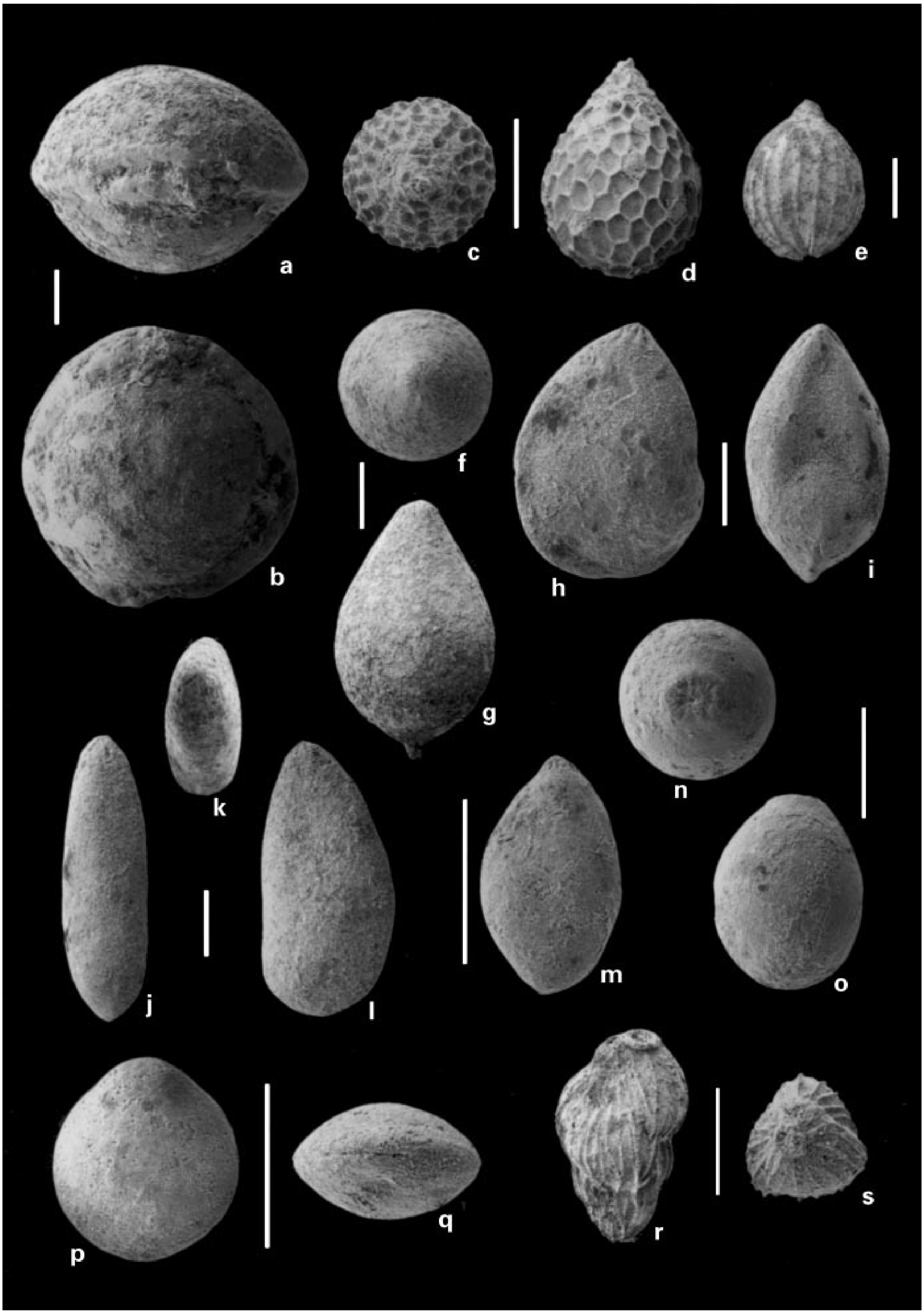

Figure 10. (a, b) *Pyrgo fornasinii* Chapman & Parr, top (a) and front (b) view of same specimen (× 50). (c, d) *Lagena* sp. 1, top (c) and side (d) view of same specimen (× 100). (e) *Lagena* sp. 2, side view (× 55). (f, g) *Pseudonodosaria* sp., top (f) and side (g) view of same specimen (× 60). (h, i) *Lenticulina* sp., side (h) and front (i) view of same specimen (× 75). (j–l) *Astacolus* sp., front (j), top (k) and side (l) view of same specimen (× 60). (m) *Polymorphina* sp. (× 150). (n, o) *Oolina globosa* (Montagu), top (n) and side (o) view of same specimen (× 100). (p, q) *Fissurina laevigata* Reuss, side (p) and top (q) view of same specimen (× 150). (r, s) *Angulogerina angulosa* (Williamson), side (r) and (s) top view of same specimen (× 100). All specimens from CG 1. Scale bars: 200 μm.

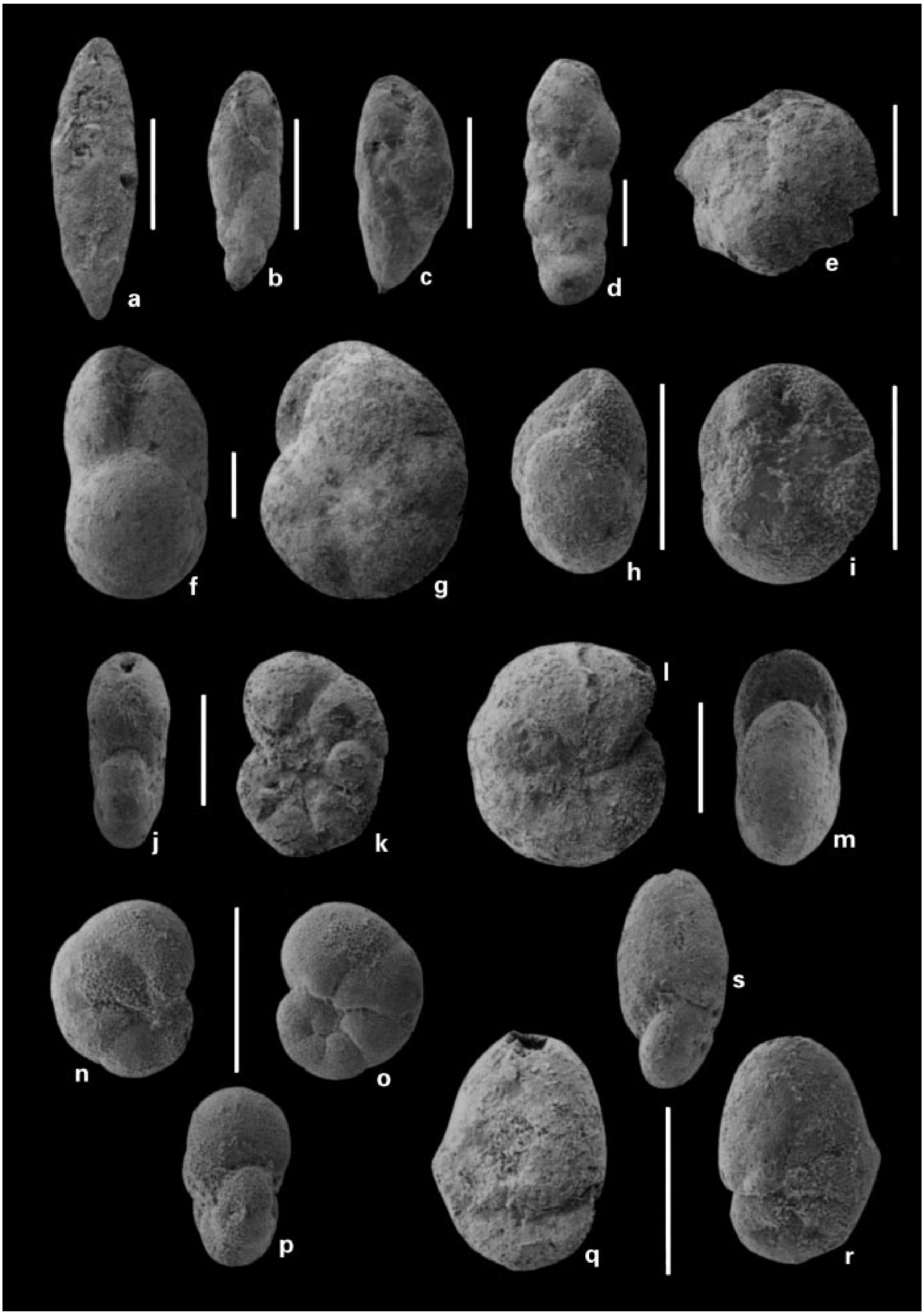

Figure 11. (a, b) *Fursenkoina* cf. *earlandi* (Parr), side views (× 100). (c) *Fursenkoina* sp., side view (× 100). (d) *Cassidulinoides parkerianus* (Brady), side view (× 60). (e) *Ehrenbergina glabra* Heron-Allen & Earland, front view (× 100). (f–h) *Cassidulina crassa* d'Orbigny, front (f) and side (g) view of same specimen (× 60), (h) front view of small specimen (× 150). (i) *Cassidulina subglobosa* Brady, front view (× 150). (j, k) *Astrononion antarcticum* Parr, front (j) and side (k) view of same specimen (× 100). (l, m) *Melonis* sp., side (l) and front (m) view of same specimen (× 100). (n–p) *Nonionella bradii* (Chapman), side (n, o) and front (p) view of same specimen (× 150). (q–s) *Nonionella turgida* (Williamson), side (q, r) and front (s) view of same specimen (× 150). All specimens from CG 1. Scale bars: 200 µm.

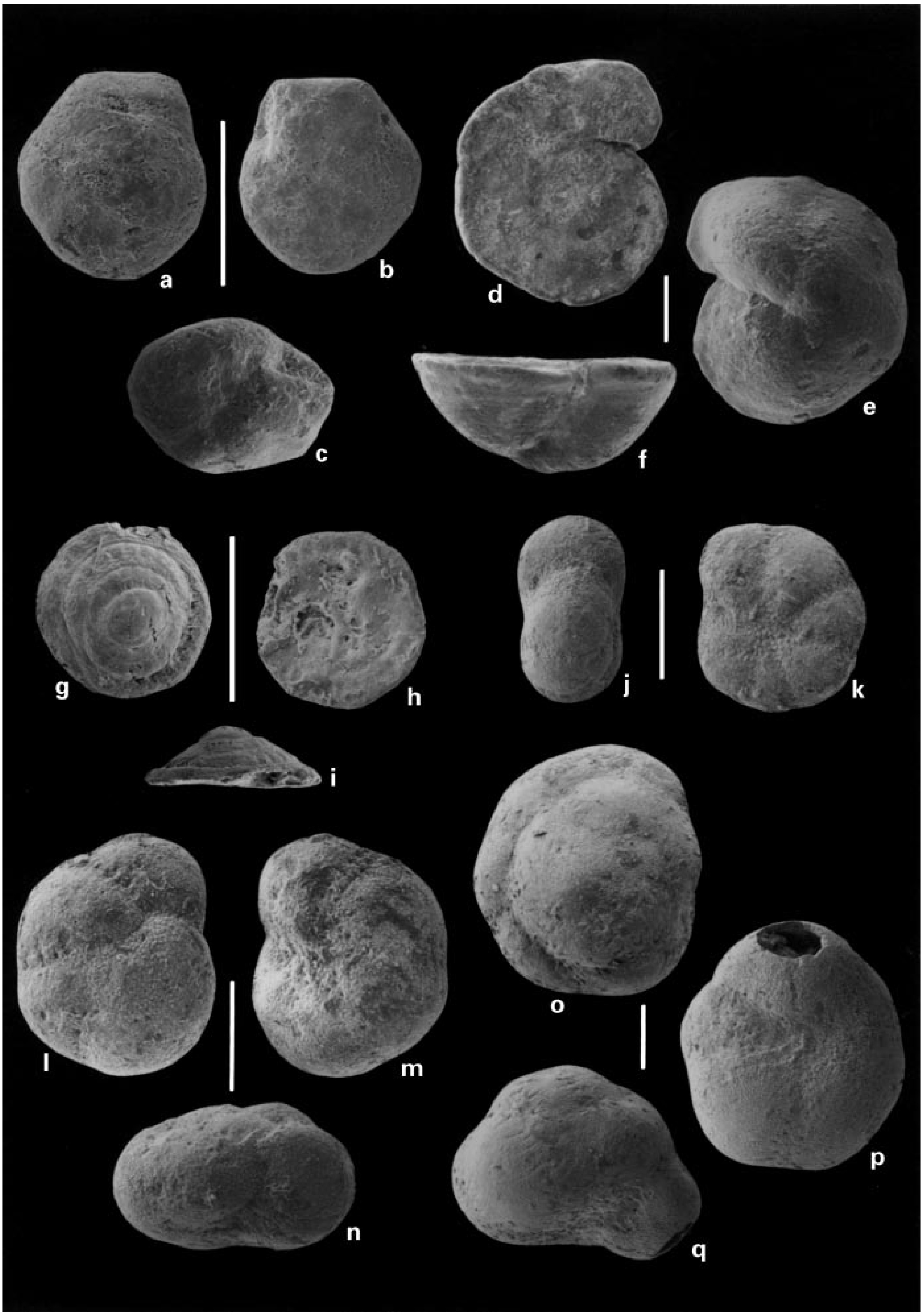

Figure 12. (a–c) *Epistominella vitrea* Parker, Phleger & Peirson, spiral (a), umbilical (b) and oblique side (c) view of same specimen (× 150). (d–f) *Cibicides lobatulus* (Walker & Jacob), spiral (d), umbilical (e) and side (f) view of same specimen (× 60). (g–i) *Patellina corrugata* Williamson, spiral (g), umbilical (h) and side (i) view of same specimen (× 150). (j, k) *Cribrononion* sp., front (j) and side (k) view of same specimen (× 100). (l–n) *Ammoelphidiella* sp. nov., spiral (l), umbilical (m) and side (n) view of same specimen (× 100). (o–q) *Ammoelphidiella antarctica* Conato & Segre, spiral (o), umbilical (p) and side (q) view of same specimen (× 60). (l–n) From DJ.688.6, all other specimens from CG 1. Scale bars: 200 µm.

ate. Many later authors have upheld both, but the gradual characters they used to recognize these 'species' (e.g. the degree of convexity of both the spiral and umbilical sides; cf. Gaździcki & Webb, 1996) only allow recognition of extremes and distinction is rather arbitrary. Both names are clearly being used for a single, variable taxon in which the degree of convexity (particularly of the spiral side) seems to be dependent upon the substrate to which the animal is attached. Figure 12d–f.

Cibicides ungerianus (d'Orbigny); *Rotalina ungeriana* d'Orbigny, 1846, p. 157, pl. 8, figs 16–18; *Truncatulina ungeriana* (d'Orbigny); Brady, 1884, p. 664, pl. 94, fig. 9; Holland, 1910, pt. 9, p. 10, pl. 2, fig. 10.

Remarks. The test of this species is usually biconvex, but planoconvex or concavoconvex (as in Holland's fig. 10) also occur.

***Cyclammina* sp.**

Remarks. A single large specimen (0.6 mm diameter) was seen in DJ.688.6.

Dentalina ?filiformis (d'Orbigny); *Nodosaria (Nodosaire) filiformis* d'Orbigny, 1826, p. 253.

Remarks. Only a two-chambered fragment is available.

Ehrenbergina glabra Heron-Allen & Earland; Fillon, 1974, p. 139, pl. 5, figs 9, 10; Osterman & Kellogg, 1979, p. 264, pl. 1, fig. 4; Ward & Webb, 1986, p. 194, pl. 6, figs 9–11; Quilty *et al.* 1990, p. 3, pl. 1, fig. 11; *Ehrenbergina hystrix* var. *glabra* Heron-Allen & Earland, 1922, pt. 2, p. 140, pl. 5, figs 1–6, 11; Heron-Allen & Earland, 1932, p. 360. Figure 11e.

Epistominella vitrea Parker, Phleger & Peirson, 1953, p. 9, pl. 4, figs 34–36; Quilty *et al.* 1990, p. 3, pl. 1, figs 12, 13; Gaździcki & Webb, 1996, p. 162, pl. 35, figs 10, 11. Figure 12a–c.

Fissurina laevigata Reuss, 1849, p. 366, pl. 46, fig. 1; Leckie & Webb, 1985, p. 1112, pl. 18, figs 11, 12; Quilty *et al.* 1990, p. 2, pl. 1, fig. 3; *Lagena laevigata* (Reuss); Brady, 1884, p. 473, pl. 114, fig. 8. Figure 10p, q.

***Fissurina* sp.**

Remarks. The test of this species is more elongate than that of *F. laevigata*, and has two basal keels (these are broken off). Only found in FB 5.

Fursenkoina* cf. *earlandi (Parr); Gaździcki & Webb, 1996, p. 162, pl. 35, figs 8, 9; *Fursenkoina earlandi* Anderson, 1975, pt. 1, pl. 10, fig. 10; Ward & Webb, 1986, p. 194, pl. 6, fig. 8.

Remarks. Our specimens (and those in the references given) differ from *Bolivina earlandi* Parr (1950, pt. 6, p. 339, pl. 12, figs 16a, b) in their more fusiform test, which is distinctly twisted, and in more elongate chambers. Figure 11a, b.

***Fursenkoina* sp.**

Remarks. The test of this species is shorter than that of *Fursenkoina* cf. *earlandi*, and bears a basal spine; the chambers are more inflated. It was observed in FB 5 and CG 1. Figure 11c.

***Lagena* sp. 1.**

Remarks. This species superficially resembles *Lagena hexagona* (Williamson, 1858), but the reticulate ornamentation is less regular, resulting in a pattern of randomly arranged pentagons and hexagons. Figure 10c, d.

***Lagena* sp. 2**; *Lagena* sp. of Quilty *et al.* 1990, p. 2, pl. 1, fig. 2.

Remarks. Only a single specimen was recovered from CG 1, which closely resembles that illustrated by Quilty *et al.* (1990). As these authors remarked, this foram may well be a juvenile of a species that belongs in a multi-chambered genus. Figure 10e.

Lagena squamososulcata Heron-Allen & Earland, 1922, p. 151, pl. 5, figs 15, 19 (as '*squamoso-sulcata*'); *Oolina squamososulcata*; Ward & Webb, 1986, p. 187, pl. 2, figs 12–14.

Lenticulina gibba d'Orbigny; Gaździcki & Webb, 1996, p. 160, pl. 34, fig. 6; *Cristellaria gibba* d'Orbigny *in* de la Sagra, 1839, p. 63, pl. 7, figs 20, 21; Brady, 1884, p. 546, pl. 69, figs 8, 9; Holland, 1910, pt. 9, p. 8, pl. 2, fig. 3.

Remarks. Present only in the sample from Cape Gage.

***Lenticulina* spp.**

Remarks. Besides *L. gibba*, at least two more unidentified species were found in CG 1. The specimen in FB 5 (Table 2) consists of an umbonal part only, which precludes specific assignment. Figure 10h, i.

***Marginulina* sp.**

Remarks. Just a single specimen in FB 7.

***Melonis* sp.**; Gaździcki & Webb, 1996, p. 163, pl. 37, figs 1, 2. Figure 11l, m.

Nonionella bradii (Chapman); Fillon, 1974, p. 140, pl. 5, figs 12, 13; Gaździcki & Webb, 1996, p. 163, pl. 36, figs 7, 8; *Nonionina ?scapha* (von Fichtell & von Moll); Brady, 1884, p. 730, pl. 109, fig. 16; *Nonionina scapha* var. *bradii* Chapman, 1916, pt. 3, p. 71, pl. 5, fig. 42. Figure 11n–p.

Nonionella turgida (Williamson); *Rotalina turgida* Williamson, 1858, p. 50, pl. 4, figs 95–97; Brady, 1884, p. 731, pl. 109, figs 17–19.

Remarks. Only two specimens were found in CG 1. Figure 11q–s.

Oolina globosa (Montagu); Gaździcki & Webb, 1996, p. 161; *Serpula (Lagena) laevis globosa* Walker & Boys, 1784, p. 3, pl. 1, fig. 8; *Vermiculum globosum* Montagu, 1803, p. 523; *Lagena globosa* (Montagu); Holland, 1910, pt. 9, p. 8, pl. 2, fig. 9. Figure 10n, o.

Patellina corrugata Williamson, 1858, p. 46, pl. 3, figs 86–89; Brady, 1884, p. 634, pl. 86, figs 1–7; Parr, 1950, pt. 6, p. 352; Ward & Webb, 1986, p. 194, pl. 5, figs 13, 14; *?P. antarctica* Parr, 1950, pt. 6, p. 352, pl. 13, figs 19–21; Fillon, 1974, p. 140, pl. 5, figs 1, 2. Figure 12g–i.

Remarks. A single, small specimen was recorded in CG 1.

***Polymorphinidae* spp.**

Remarks. Two specimens of species of the genera *Guttulina* and *Polymorphina* (Figure 10m) are present in CG 1.

***Pseudonodosaria* sp.**; Gaździcki & Webb, 1996, p. 160, pl. 34, figs 4, 5. Figure 10f, g.

Pyrgo fornasinii Chapman & Parr, 1935, p. 5; Gaździcki & Webb, 1996, p. 159, pl. 34, figs 1–3; *Biloculina ringens* (de Lamarck); Holland, 1910, pt. 9, p. 5, pl. 1, figs 5–8. Figure 10a, b.

Rosalina araucana d'Orbigny, 1839, p. 44, pl. 6, figs 16–18; *Discorbina araucana* (d'Orbigny); Brady, 1884, p. 645, pl. 86, figs 10, 11.