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Stratigraphy of Antarctic late Cenozoic pectinid-bearing deposits

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Abstract: Antarctic late Cenozoic pectinid-bearing sedimentary strata are chiefly confined to localities in the northern part of the Antarctic Peninsula, in the McMurdo Sound area, and Marine Plain, East Antarctica. Ages of these deposits range from Oligocene to Holocene. *Chlamys*-like scallops, which are absent from today's Southern Ocean, thrived in Antarctic waters during both glacial and interglacial episodes, but disappeared during the Late Pliocene. Their extinction is believed to result from the combined effects of increased carbonate solubility, habitat loss and limitations in food availability, associated with major cooling.

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Introduction

Outcrops of coarse-grained Late Cenozoic sedimentary rocks with fossil representatives of the Family Pectinidae (Mollusca, Bivalvia) in the Antarctic are comparatively few and far between (Fig. 1). The pectinid-bearing deposits are characteristically of limited thickness and areal extent, and are found chiefly in coastal localities of the northern Antarctic Peninsula and McMurdo Sound regions. Their fossil scallops have until recently nearly all been assigned to *Chlamys* Röding, a genus of Pacific origin with living representatives currently thought to be confined to the North Atlantic and North Pacific (Waller 1991). Morphologically similar-valved species occurring elsewhere are now being systematically removed from this taxon. High-latitude *Chlamys*-like scallops have demonstrated great sensitivity to climate change. For example, the southern New Zealand *Zygochlamys delicatula* (Hutton), one of the species now living closest to Antarctica, is known to have migrated considerably northward during cold periods in the Late Pliocene and Early Pleistocene (e.g. Beu 1995). Since chlamydinids are lacking from today's Southern Ocean south of the Antarctic Convergence (Powell 1965), their occurrence in Neogene strata in Antarctic and subantarctic regions is of considerable interest to the study of the Late Cenozoic glacial history of the continent. Another important aspect of the pectinid-bearing sediments is their relevance to the study of the evolution of high-latitude molluscan faunas, with species diversities of modern Antarctic faunas being well below those in lower latitudes (Clarke & Crame 1992).

Pliocene Antarctic pectinid-bearing strata have almost invariably been associated with interglacial conditions: for example by Andersson (in Buckman 1910) for those on Cockburn Island, James Ross Island group, by Speden (1962) for the Scallop Hill Formation in the McMurdo Sound region, for the Prospect Mesa Gravels of Wright Valley, Victoria Land (Nichols 1964, Webb 1974), and by Pickard *et al.* (1988) for scallop-containing deposits in the Vestfold Hills, Ingrid Christensen Coast. By contrast, the pectinid-bearing rocks of the Oligocene Polonez Cove Formation on King George Island, South Shetland Islands (Birkenmajer 1982), and late Miocene deposits on James Ross Island, which were recently incorporated in the Hobbs Glacier Formation, are believed to have accumulated during a prevailing glaciomarine regime (Pirrie *et al.* 1997).

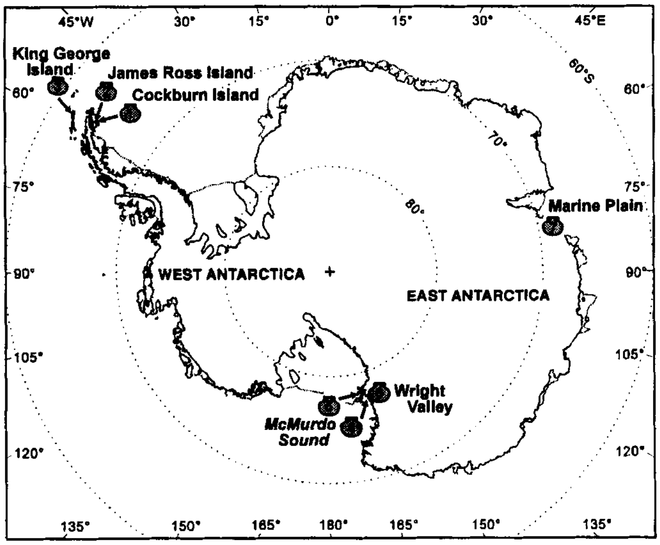

Fig. 1. Location map of late Cenozoic Antarctic pectinid-bearing deposits. 1: Cockburn Island Formation, Cockburn Island; 2: Hobbs Glacier Formation, Obelisk Col, Ulu Peninsula, and near Cape Gage; scallop-rich conglomerate of del Valle *et al.* (1987), Fiordo Belén, James Ross Island; 3: Polonez Cove Formation, Lions Rump, King George Island, South Shetland Islands; 4: Taylor Formation, New Harbour, Ross Island and Minna Bluff, McMurdo Sound area; 5: Scallop Hill Formation, Ross, Black and White islands and Brown Peninsula, McMurdo Sound area; 6: Prospect Mesa Gravels, Prospect Mesa, Wright Valley, Victoria Land; 7: Unnamed sedimentary strata in Marine Plain, Vestfold Hills, Ingrid Christensen Coast.

In this account, a summary of the respective distributions, lithologies and palaeontology of these various occurrences is given, together with a critical review of relative ages. New data gathered during field work on Cockburn Island and King George Island in January and February 1996 are incorporated.

West Antarctica

Cockburn Island

The oldest-known Antarctic pectinid-bearing deposit is on Cockburn Island, in the James Ross Island group (Fig. 2). Until recently referred to as the "*Pecten*-conglomerate" (Andersson 1906), this rock unit is now formally defined as the Cockburn Island Formation (Jonkers in press). The strata occur at altitudes between about 190 and 280 m above sea level and overlie volcanic rocks of the Miocene–Pliocene James Ross Island Volcanic Group.

The scallop-rich facies, with a maximum thickness of more than 10 m, forms a wedge-shaped sedimentary body which rests upon a bench-like feature in the eastern and southern part of the island. The rocks of this facies type are rusty-brown sandstone and conglomerate of which the pebbly matrix was exclusively derived from the James Ross Island Volcanic Group. The extinct *Zygochlamys anderssoni* (Hennig) (Fig. 3a), *Adamussium* sp. cf. *A. colbecki* (Smith) (Fig. 3b) and *Laternula* spp. are the dominant fossil macroinvertebrates. From field evidence it is concluded that water depth of this facies did not exceed 100 m (Jonkers in press). Proximal boulder conglomerate of the Cockburn Island Formation occurs near the western limits of the island and were deposited in a nearshore environment adjacent to a palaeo-cliff. Their associated biofacies is dominated by the extinct balanid *Fosterella hennigi* (Newman) and patellid limpets.

The presence of large and thick-shelled *Zygochlamys*, the sessile barnacles in the littoral facies, and the absence of ice-rafted debris, favour deposition in a largely ice-free setting.

A Pliocene age is now generally accepted for the Cockburn Island Formation (e.g. Gaździcki & Webb 1996). The two thus far reported K–Ar isotope ages from Cockburn Island suggest a late Pliocene maximum age for the pectinid-bearing strata; an age of 3.65±0.3 Ma (early Pliocene) was obtained from basalt underlying the Cockburn Island Formation (Webb & Andreasen 1986), but topographically higher volcanic rocks gave an age of 2.781±0.032 Ma (late Pliocene; Lawver *et al.* 1995). However, new evidence from $^{40}Ar/^{39}Ar$ determinations casts doubt on the validity of these ages; lavas from the summit peak, which are the youngest on the island, yielded concordant ages of 4.9±0.4 Ma and 4.7±0.2 (earliest Pliocene; S.P. Kelley, personal communication 1997). Since these lava flows pre-date the pectinid-bearing strata on Cockburn Island (Jonkers in press), the new data may point to a considerably older maximum age of the Cockburn Island Formation than suggested by the K–Ar results.

Sr-isotope analysis of *Zygochlamys anderssoni* shells has not resolved the formation's age, as ages vary widely between 5.3 and 3.5 Ma (mean 4.7 Ma, early Pliocene) (Dingle *et al.* 1997). Lack of variation of $^{87}Sr/^{86}Sr$ ratios during the Pliocene (e.g. Howarth & McArthur 1997, fig. 2a), severely limits the application of Sr-stratigraphy in rocks of that age. Harwood (1986) gave a late Pliocene age of 2.8–2.0 Ma on the basis of diatom stratigraphy. However, the combined presence of *Actinocyclus actinochilus* (Ehrenberg) Simonsen and of *Thalassiosira complicata* Gersonde, may point to an age of about 3–2.5 Ma (Gersonde & Burckle 1990, Harwood & Maruyama 1992). Palaeontological evidence from the Scallop Hill Formation (see below) suggests an age close to 3 Ma for the Cockburn Island Formation (Fig. 7).

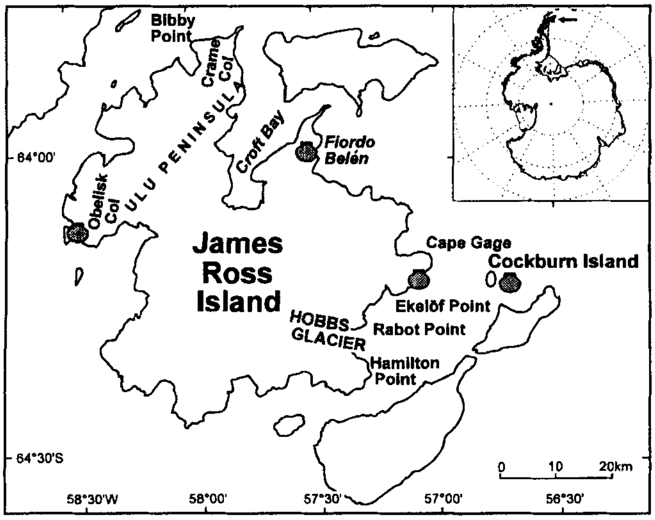

Fig. 2. Location map of late Cenozoic pectinid localities in the James Ross Island group.

James Ross Island

Glaciomarine fossiliferous tillite, conglomerate and tuff overlying Cretaceous strata and underlying the volcanic rocks of the James Ross Island Volcanic Group have been reported from various localities on Ulu Peninsula, James Ross Island (e.g. Bibby Point (Bibby 1966) and Crame Col (Sykes 1988)), and from Croft Bay, Hobbs Glacier ("tuffaceous conglomerates" of Nelson 1975) and Hamilton Point (Andersson 1906) (Fig. 2). More recently, Pirrie *et al.* (1997) gave an account of the lithostratigraphy, sedimentology and palaeontology of these rock units on southern James Ross Island and incorporated them into the new Hobbs Glacier Formation. Usually of no more than 5 m thickness, this unit has yielded sparse macrofossil assemblages. In the type section at Rabot Point (Fig. 2) the fauna includes poorly preserved nuculanid and limopsid bivalves, and a thin-shelled *Laternula* ("*Panope* sp." of B.J. Taylor in Nelson 1975) was recovered from the formation at Croft Bay. Pectinid-bearing pebbly clays near Obelisk Col, Ulu Peninsula (Fig. 2), were found to contain "*Chlamys anderssoni*" (Anonymous 1983).

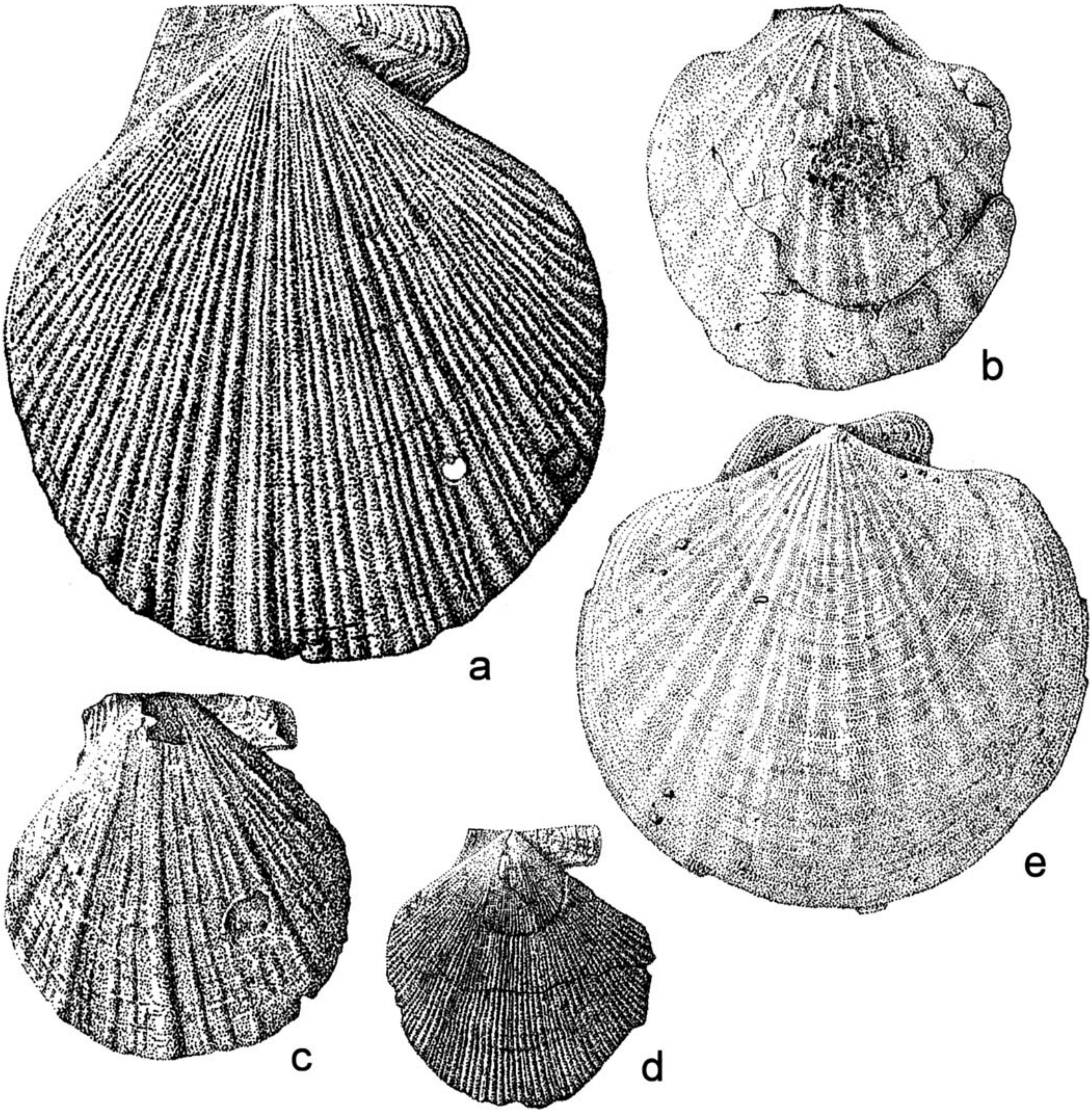

Fig. 3. Characteristic scallops in late Cenozoic Antarctic pectinid-bearing strata: **a.** *Zygochlamys anderssoni* (Hennig), right valve from the late Pliocene Cockburn Island Formation, Cockburn Island, James Ross Island group (DJ.851.5; kept at the British Antarctic Survey (BAS)), **b.** *Adamussium* sp., left valve, locality as for a (DJ.853.60, internal mould; BAS), **c.** *"Chlamys" tuftsensis* Turner, right valve from the ?early Pliocene Prospect Mesa Gravels, Wright Valley, Victoria Land (MCZ256085, holotype, drawn from fig. 3(1) of Turner 1967; Museum of Comparative Zoology, Cambridge , Massachusetts, USA), **d.** *"Chlamys"* sp., right valve of an immature specimen from the Oligocene/?Early Miocene Polonez Cove Formation, Lions Rump area, King George Island, South Shetland Islands (P.2856.38; BAS), **e.** *Adamussium colbecki* (Smith), right valve from the Recent, Explorers Cove, New Harbour, McMurdo Sound (BAS). All specimens at natural size.

The fragmented specimens, lodged in the collections of the British Antarctic Survey, are small and finely ribbed, and cannot be identified with certainty.

A pectinid-rich facies of the Hobbs Glacier Formation, between Cape Gage and Ekelöf Point (Fig. 2), was recently discovered by R.A. del Valle (personal communication 1997).

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There, the formation is at least 10 m thick and consists in its lower part of an alternation of thin-bedded mudstone and sandstone. The upper two thirds of exposed section consist of thick-bedded diamictite in which numerous large, but comparatively thin-shelled specimens of *Zygochlamys* occur. These constitute the oldest record (see below) for the genus in Antarctica. Microfauna from this sequence includes *Ammoelphidiella antarctica* Conato & Segre (syn. *Trochoelphidiella onyxi* Webb 1974), an extinct benthic foraminiferal species hitherto found exclusively in Pliocene strata (e.g. Gaździcki & Webb 1996).

K–Ar ages suggest that the Hobbs Glacier Formation scallops may be significantly older than those in the Cockburn Island Formation; a basaltic clast from a tillite underlying the James Ross Island Volcanic Group at Crame Col yielded an age of 7.13±0.49 Ma, and the oldest reported age of the group proper is 6.45±0.60 Ma (Sykes 1988). Based on a combination of biostratigraphical and regional geological evidence, Pirrie *et al.* (1997) suggested a late Miocene age for the Hobbs Glacier Formation. Barnacle plates from the type section gave a Sr-isotope age of 9.9±0.97 Ma (late Miocene; Fig. 7) (Dingle & Lavelle in press).

Del Valle *et al.* (1987) described marine, tuffaceous conglomerate from Fiordo Belén (Fig. 2), in a lenticular body of limited lateral extent and a maximum thickness of 3 m. Clasts present include olivine basalt, metamorphic rocks, and intraformational sandstone with abundant "*Pecten anderssoni*". The stratigraphical context of this conglomerate, which occurs at *c.* 100 m altitude, is uncertain. It could be either a correlative of the Hobbs Glacier Formation or represent a slightly younger deposit interbedded with volcanic rocks of the James Ross Island Volcanic Group. Shell material from this locality produced a Sr-isotope age of 6.8 + 1.3/–0.5 Ma (late Miocene) (M. Lavelle, personal communication 1997).

Because of their different stratigraphical position, lithology and age, the Hobbs Glacier Formation and the Fiordo Belén deposit cannot be correlated with the Cockburn Island Formation (Fig. 7).

King George Island

Pectinid-bearing monomict basaltic conglomerate of the Low Head Member, Polonez Cove Formation, is exposed near Lions Rump and Low Head on King George Island, South Shetland Islands (Birkenmajer 1982, 1994) (Fig. 4). The conglomerate forms part of a thick (>200 m) sequence of sedimentary and volcanic rocks and has been interpreted as high-energy bars or shoals formed in an upper shoreface environment close to a rocky coast (Porbski & Gradziński 1987). *Chlamys*-like pectinids were initially reported only from the Low Head Member, but subsequently they have also been found in arkosic sandstone of the stratigraphically younger Oberek Cliff Member (Birkenmajer 1994).

The fossiliferous conglomerate has until recently been correlated with the "*Pecten*-conglomerate" of Cockburn

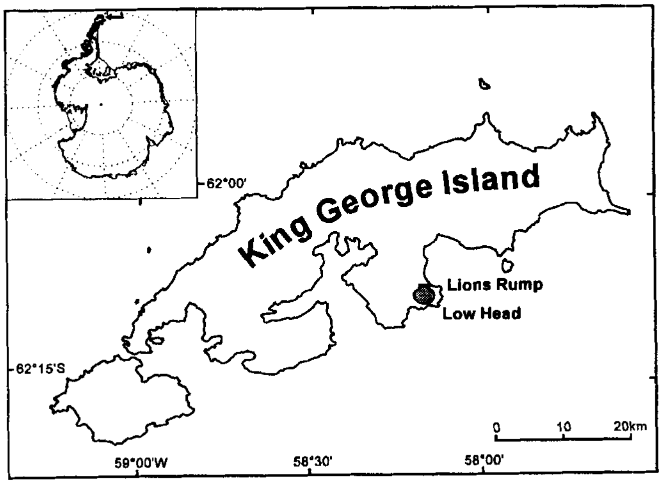

Fig. 4. Location map of the Oligocene-?Early Miocene Polonez Cove Formation, King George Island, South Shetland Islands.

Island, on account of assumed faunal similarities (Barton 1965, Birkenmajer 1982). It was thus originally thought to be of Pliocene age. The component pectinid was considered to be conspecific with the Cockburn Island chlamydinid and assigned to *Chlamys (Chlamys) anderssoni* by Pugaczewska (in Gaździcki & Pugaczewska 1984). K–Ar dating of acidic porphyritic lava unconformably overlying the pectinid-bearing strata, and of a cross-cutting basaltic dyke, suggests that the sequence is in fact older than 23.6±0.3 Ma (Birkenmajer & Gaździcki 1986; i.e. basal Miocene or older). However, evidence from calcareous nannofossils and from a sparse planktonic foraminiferal fauna in support of an Oligocene age (Birkenmajer & Gaździcki 1986, Gaździcki 1989) is less convincing. The representatives of both these groups are now known to include only long-ranging species.

A sparse palynoflora from the Low Head Member is dominated by the dinoflagellate cyst *Selenopemphix nephroides* Benedek, a living species known from the Middle Eocene onwards. Of particular interest are rare specimens of *Bitectatodinium tepikiense* Wilson, which has not been reported from deposits pre-dating the Early Miocene (J.B. Riding, personal communication 1997).

Comparison of the fossil pectinids of King George and Cockburn islands reveals that those of the former differ from *Zygochlamys anderssoni* in a number of important respects: their smaller size (valve height in the Low Head Member usually less than 50–60 mm, maximum height of valves in the Oberek Cliff Member *c.* 70 mm, but 110–120 mm in *Z. anderssoni*), thinner shell, simpler ribbing pattern and prominent antimarginal microsculpture. They clearly represent a new and as yet undescribed taxon (Fig. 3d). Rare specimens of a non-costate pectinid in the Polonez Cove Formation, similar to *Adamussium?* n. sp. from the Oligocene section in the CIROS-1 drill hole, McMurdo Sound (Beu & Dell 1989) (Fig. 7), suggest that the pectinid-bearing strata on King George Island are indeed much older than the Cockburn

Island Formation. This view is supported by Sr-isotope dating of the Polonez Cove Formation *"Chlamys"* at 29.8 +0.5/–0.6 Ma and 29.0 + 0.6/–0.7 Ma (latest Early Oligocene; Dingle *et al.* 1997). A somewhat younger age, between 23.7±2.1 Ma and 22.6±1.7 Ma (Late Oligocene–Early Miocene), was inferred from stratigraphical relationships and $^{40}Ar/^{39}Ar$ dating of volcanic rocks associated with the Polonez Cove Formation at Low Head by Smellie *et al.* (1998) (Fig. 7).

East Antarctica

McMurdo Sound region

Two lithostratigraphical units, both initially considered to be of Quaternary age, were introduced by Speden (1962) for pectinid-bearing deposits in the McMurdo Sound region of the Ross Sea. The younger unit, the Taylor Formation, crops out at New Harbour, Ross Island and Minna Bluff (Fig. 5) and consists of unconsolidated sand, silt and mud, up to 15 m above sea level. It contains *Adamussium colbecki* (Fig. 3e) and various other macrofossils (Chapman-Smith 1981). Stuiver *et al.* (1976) obtained uncorrected Holocene ^{14}C-ages between 6670±200 and 4620±60 years BP from *A. colbecki* shells.

Sedimentary rocks of the older unit, the Scallop Hill Formation, consist of cemented, tuffaceous sandstone and conglomerate, and are characterized by a large pectinid, referred by Speden (1962) to *Chlamys* (*Zygochlamys*) *anderssoni*. Another fossil, common to both the Scallop Hill and Taylor formations, is the extant balanomorph barnacle *Bathylasma corolliforme* (Hoek) (=*Hexelasma antarcticum* Borradaile in Speden 1962).

The Scallop Hill Formation is exposed on Ross, White and Black islands and on Brown Peninsula (Fig. 5), but at most localities the formation is not *in situ*. According to Speden (1962) it is *in situ* only at the type locality on Scallop Hill, a trachytic dome on eastern Black Island (his locality 18), where it was thought to have been deposited on an irregular surface, now at *c.* 200 m altitude. In a re-examination, Leckie & Webb (1979) concluded that at its type locality the Scallop Hill Formation is also *ex situ*. The trachyte at this locality has yielded a K–Ar age of 4.4±0.6 Ma (Leckie & Webb 1979) and 3.8±0.2 Ma (*fide* Eggers 1979).

A 2–3 m thick, barnacle-rich *in situ* occurrence of the Scallop Hill Formation was reported from Brown Peninsula at an approximate elevation of 150–200 m (Eggers 1979), where it is also underlain by a trachyte, radiometrically dated at 2.25 Ma, and capped by a basalt 2.2 Ma old. Webb & Andreasen (1986) were unable to confirm the stratigraphical relationships claimed by Eggers, but reported K–Ar ages from volcanic boulders in the formation of 2.62±0.04 Ma and 2.58±0.09 Ma, suggesting a late Pliocene maximum age.

Speden (1962) postulated a possible correlation of the Scallop Hill Formation and the Cockburn Island strata. However, there are a number of palaeontological considerations which could suggest that the former is somewhat younger than the Cockburn Island Formation. First, their barnacle content is different; the extinct *Fosterella hennigi* from Cockburn Island has not been reported from the McMurdo Sound area, where instead the extant, circum-Antarctic *Bathylasma corolliforme* is common (Fig. 7). A second line of evidence for a younger age may come from close inspection of *Zygochlamys* fragments from the Scallop Hill Formation; whereas the average number of byssal teeth in *Zygochlamys anderssoni* from Cockburn Island is 4.6 (n = 190), this figure is only 2.1 (n = 12) in the specimens from East Antarctica. The latter figure is comparable to that in Recent populations of mature, free-living individuals of the New Zealand *Z. delicatula*, and thus it is conceivable that the lifestyle of Antarctic *Zygochlamys* may have changed in the course of the Late Pliocene from byssal attachment to one of higher motility.

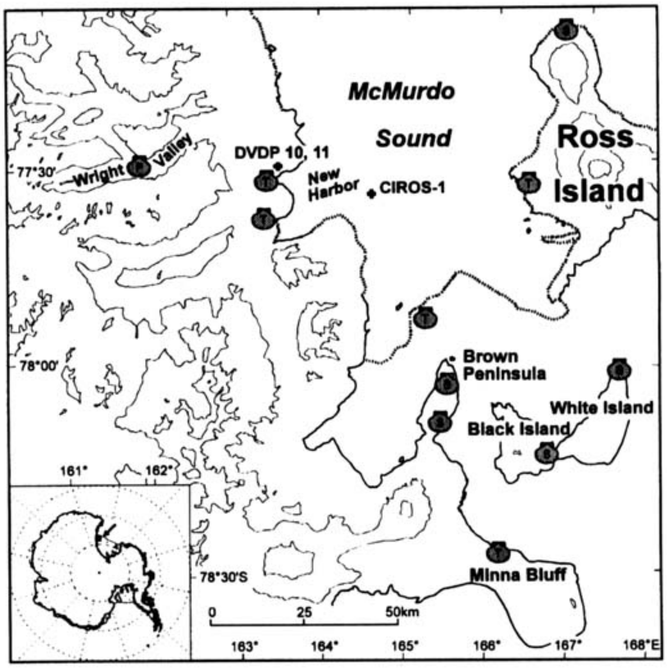

Fig. 5. Location map of Pliocene and Holocene scallop-containing strata, with localities of selected drill holes, in the McMurdo Sound region and Victoria Land. P: Prospect Mesa Gravels; S: Scallop Hill Formation; T: Taylor Formation. Contours at 1000 m intervals. The ice front is indicated by dashed lines.

Wright Valley

The Prospect Mesa Gravels, an up to 6 m thick interval of fossiliferous gravels, occur at an altitude between 155 and 170 m in Wright Valley, Victoria Land (Prentice *et al.* 1993) (Fig. 5). The unit, of limited lateral extent, has been interpreted as a fjord deposit (Webb 1972). Its macrofauna consists exclusively of an extinct, thick-shelled pectinid, described as *Chlamys* (*Zygochlamys*) *tuftsensis* (Turner 1967) (Fig. 3c).

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The age and correlation of the Prospect Mesa Gravels is still problematic, due to varying ages assigned to benthic foraminiferal and diatom 'index' taxa in the literature. Prentice *et al.* (1993) suggested, on the presence of the diatom species *Fragilariopsis kerguelensis* (O'Meara) and *Thalassiosira insignis* (Jousé) Harwood & Maruyama, that the Prospect Mesa Gravels could be between 3 and 2.5 Ma old (2.7–2.4 Ma using figures given by Baldauf & Barron 1991). They also reported a Sr-isotope age of 5.5±0.4 Ma (latest Miocene-earliest Pliocene) for *"Chlamys" tuftsensis* shells, which they considered to be the best age estimate for the unit. However, it must be stressed here again that the application of Sr-isotope dating in the Pliocene is of limited usefulness.

Webb (1972) assumed a direct correlation between the Prospect Mesa Gravels and the Scallop Hill Formation, based on the presence of the extinct benthic foraminifera *Ammoelphidiella antarctica* in both units. This correlation was recently extended to include the Cockburn Island Formation and sedimentary strata in the Larsemann Hills, East Antarctica (Gaździcki & Webb 1996). However, the value of *A. antarctica* in long-distance correlation may be fairly limited, as it appears to have a long stratigraphical range and an intermittent record in Late Neogene Antarctic sequences (Gaździcki & Webb 1996). Although Ishman & Rieck (1992) estimated its age-range as only 3.8–3.4 Ma in DVDP Site 10, Taylor Valley (Fig. 5), where the *A. antarctica* (Total Range) Zone is bounded by unconformities, the species' presence in late Miocene deposits on James Ross Island, as well as in the late Pliocene Scallop Hill Formation, indicates that its total range extends much further back in time. In defence of his correlation, Webb (1972, and in Bull & Webb 1973) suggested that *"Chlamys" tuftsensis* and *Zygochlamys anderssoni* might have been ecological variants of a single species, with the former being primarily a fjord-dweller, and the latter confined to more 'open' marine environments. However, Beu (1985) pointed out that both taxa are phylogenetically unrelated and therefore they can not be utilized to support any correlation.

Significantly different ages for the McMurdo Sound and Victoria Land area chlamydinids are suggested by the elevation of the palaeo-shorelines of the Prospect Mesa Gravels and the Scallop Hill Formation. Whereas the present Wright Valley palaeo-shoreline lies at 300 m altitude (Prentice *et al.* 1993), the nearshore barnacle-rich facies of the Scallop Hill Formation on Brown Peninsula indicates a shoreline at only 150–200 m above present sea level. These altitude differences could imply that the Prospect Mesa Gravels have had a longer history of uplift, suggesting that the unit antedates the Scallop Hill Formation, its deposition possibly coinciding with one of the two major periods of sea level highstand between 2.9 and 5 Ma (Haq *et al.* 1987). Rare occurrences of the diatom species *Fragilariopsis praeinterfrigidaria* (McCollum) in the Peleus Till, which overlies the Prospect Mesa Gravels (Prentice *et al.* 1993), are consistent with an older Pliocene age.

Vestfold Hills

A *c.*7 m thickness of sandstone and lithified diatomaceous sand and silt overlying Precambrian metamorphic rocks at less than 20 m above sea level on Marine Plain, Vestfold Hills, Ingrid Christensen Coast (Fig. 6), contains a rich molluscan fauna. This consists chiefly of exant species, but also includes the extinct *"Chlamys" tuftsensis* (Pickard *et al.* 1986, 1988) (Fig. 3c) and representatives of *Zygochlamys* (Feldmann & Quilty 1997, fig. 2). The latter authors reported on a palinurid lobster, the only post-Miocene fossil decapod crustacean known from the Antarctic. Vertebrate fossils include various cetaceans (Quilty 1993).

The Marine Plain deposit is free from glacial debris and was interpreted as having accumulated during an interglacial period. An increase of the cold-water diatom *Eucampia antarctica* (Castracane) Mangin observed in the upper 3 m, and above the shelly sandstone, was thought to reflect cooling conditions.

Pickard *et al.* (1986) assumed an early Pliocene age of about 4.5–4.0 Ma for the Marine Plain strata, based on the occurrence of *Fragilariopsis praeinterfrigidaria*; this was later amended to *c.* 4.5–3.5 Ma (Pickard *et al.* 1988), and 4.2–3.5 Ma (Quilty 1993).

Discussion and conclusions

Palaeontology, radiometric age determinations and Sr-isotope stratigraphy allow recognition of six distinct intervals of

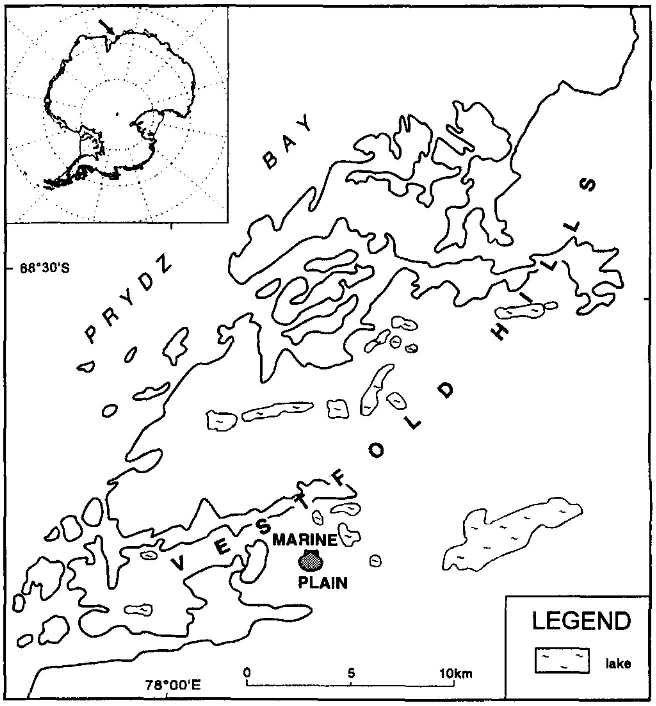

Fig. 6. Location map of Pliocene pectinid-bearing sedimentary strata in the Vestfold Hills, Ingrid Christensen Coast.

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deposition of pectinid-bearing rocks in the Antarctic, the chronological order of which is shown in Fig. 7. The oldest strata, belonging to the Polonez Cove Formation (latest Early Oligocene or earliest Miocene), differ from all younger fossiliferous deposits in their scallop content; no pectinids related to the undescribed "*Chlamys*" sp. from King George Island (Fig. 3d) have been reported from onshore Neogene deposits elsewhere in the Antarctic. Representatives of *Zygochlamys* characterize most of the younger formations, their chronological order being as follows:

a) Scallop Hill Formation (Late Pliocene, 2.6–2.4 Ma),

b) Cockburn Island Formation (Late Pliocene, *c.* 3 Ma),

c) Marine Plain strata (with the Prospect Mesa Gravels as a possible correlative; Early Pliocene, 4.2–3.5 Ma),

d) Hobbs Glacier Formation and Fiordo Belén deposits (Late Miocene, 9.9–6.8 Ma).

The fauna of the Holocene Taylor Formation is set apart from the fauna in the older units by the absence of *Chlamys*-like taxa.

The record shows that the stratigraphical distribution of the fossil-bearing rocks is biased towards the younger occurrences (Fig. 7), and our knowledge of the Late Oligocene–Mid Miocene interval in particular is extremely limited. With the exception of the earliest Miocene glaciomarine Cape Melville Formation on King George Island (a predominantly fine-grained clastic unit of which the molluscan association consists chiefly of infaunal elements, but which has yielded rare *Adamussium?* n. sp. of Beu & Dell (1989)), no further scallop-containing sequences from within that interval are

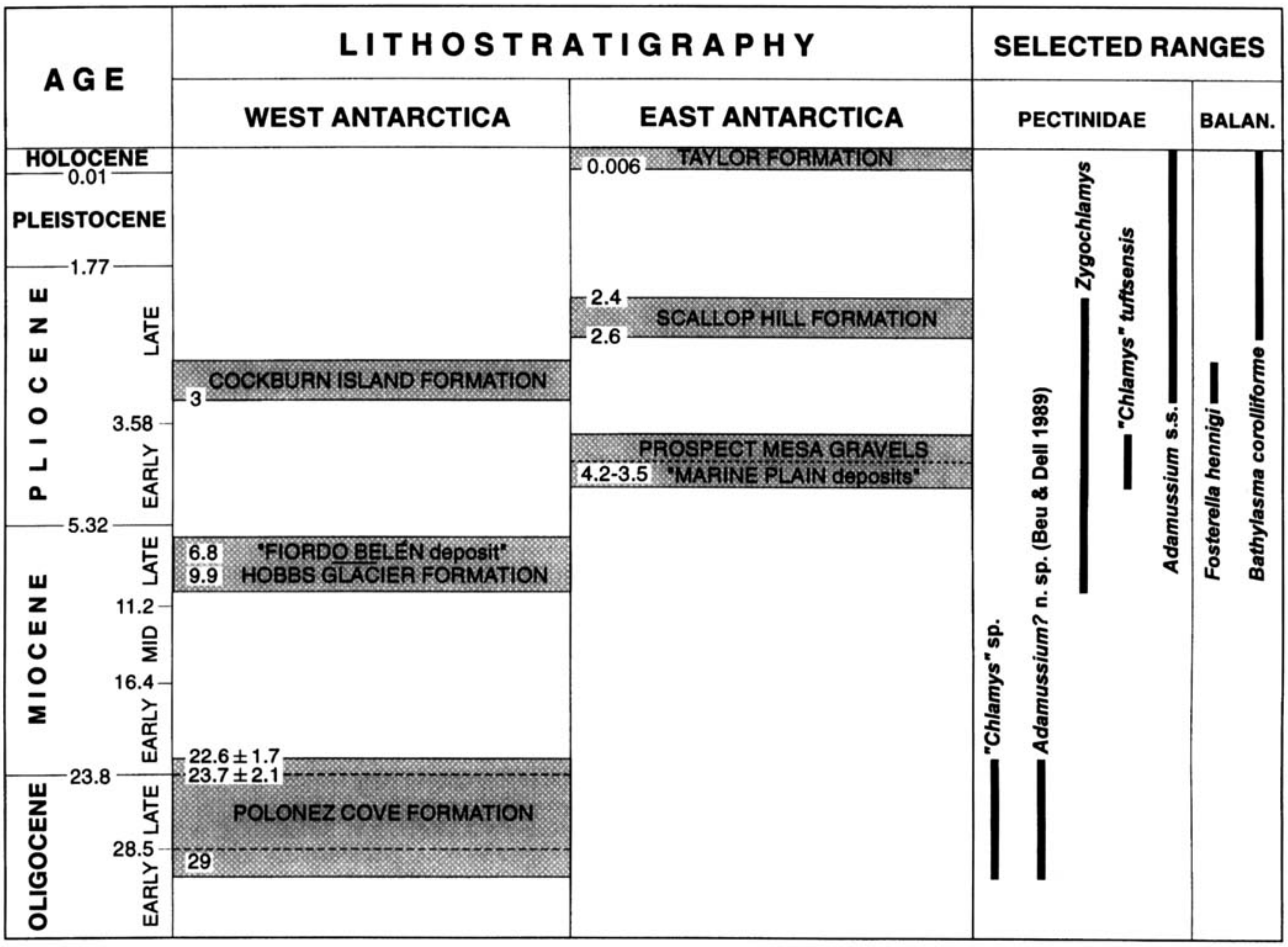

Fig. 7. Relative position of late Cenozoic Antarctic pectinid-bearing deposits and ranges of selected pectinids and cirripedes. Chronostratigraphy and geochronology after Berggren *et al.* (1995). A Sr-isotope age determination by Dingle *et al.* (1997) suggests a latest Early Oligocene age of about 29 Ma for the Polonez Cove Formation; $^{40}Ar/^{39}Ar$ dating by Smellie *et al.* (1998) and palynological evidence point to a latest Oligocene-earliest Miocene age. Age of the Hobbs Glacier Formation from Dingle & Lavelle (in press); Sr-isotope age of Fiordo Belén deposit supplied by M. Lavelle (personal communication 1997); maximum age of the Cockburn Island Formation based on re-calibrated diatom data of Harwood (1986); age of Marine Plain deposits from Quilty (1993); maximum age of the Scallop Hill Formation from K–Ar age determinations in Webb & Andreasen (1986); maximum age of the Taylor Formation from ^{14}C-age determinations by Stuiver *et al.* (1976). Ages in Ma; not to scale. Balan. – Balanomorpha.

known in outcrop.

Chlamys-like taxa demonstrably thrived in the Southern Ocean until the Late Pliocene, with *Zygochlamys* as the most persistent and widespread genus, being present in both West and East Antarctica. Whether its distribution was circum-Antarctic at any given time during the late Neogene can not as yet be conclusively tested, as the deposits in which the fossils occur around the continent are all of different ages. Also, at this moment it is unclear how many species are involved.

Although sedimentological and palaeontological evidence favour prevailing interglacial conditions for the deposition of the younger (Pliocene) fossiliferous rocks, the late Miocene Hobbs Glacier Formation, and perhaps also the Oligocene Polonez Cove Formation, evidently formed under a glacial regime. Thus, *Chlamys*-like scallops could survive both interglacial *and* glacial episodes during the late Palaeogene and most of the Neogene, and their fossils alone cannot be used to just indicate interglacial conditions, as has hitherto been widely accepted. It must be said here that glacial and interglacial conditions within the studied interval possibly were not the same at all times; Neogene interglacials may have been colder than older glacials.

The ultimate disappearance of chlamydinids from Antarctic waters may have been linked to severe Late Pliocene climate change; a major cooling phase, dated at *c.* 2.4 Ma and marking the onset of bipolar glaciation, has been interpreted from a large shift towards more positive $\delta^{18}O$ values (e.g. Kennett 1986, Hodell & Ciesielski 1990), and from the arrival of *Zygochlamys delicatula* in northern New Zealand during the latest Pliocene (early Nukumaruan; Beu 1995). It is likely that this cooling had a further profound impact on the distribution and composition of Antarctic marine faunas. Changes in the chemical environment, through enhanced carbonate solubility in waters of decreasing temperature, might have affected biota that secrete calcitic or aragonitic shells. Particularly for *Zygochlamys*, it may have become increasingly difficult to precipitate their large, thick shells in the Antarctic realm (Berkman & Prentice 1996). However, physical changes in the environment as a result of major build-up of shelf ice must also have played a significant, and possibly more important, rôle. Intensified ice abrasion in the littoral zone drastically reduced the availability of suitable shallow-water habitat. In addition, the expansion of ice shelves further limited primary production, leaving the remaining shallow-water environments largely oligotrophic. This would have severely affected growth in *Zygochlamys*, of which modern South American representatives occupy a zone of high bioproductivity (Walossek 1991).

The thin-shelled, non-chlamydinid genus *Adamussium* was not affected by late Pliocene environmental change and escaped extinction in Antarctica. Both its occurrence in the interglacial Cockburn Island Formation and in modern Antarctic waters, where it apparently can survive in oligotrophic habitats underneath floating shelf ice (Hain & Melles 1994), indicate that the distribution of the genus is not so strongly dependent on seasonal food availability, thus enabling it to become the sole surviving scallop in the Southern Ocean.

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