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Geological exploration of Cockburn Island, Antarctic Peninsula

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ABSTRACT: Cockburn Island is one of the most historically significant places on the Antarctic continent. The isle was first surveyed in early 1843 during Captain James Ross' famous expedition, but the early explorers failed to recognise its geological and palaeontological significance. Cockburn Island is exceptional for it has the only succession of Upper Cretaceous, Eocene and Miocene–Pliocene rocks on the continent, which is now known to contain an admirable and diverse fossil record of fauna and flora. These fossil assemblages are providing exciting new information on the evolutionary history of Antarctica. At least 22 species of Late Cretaceous macroinvertebrates and vertebrates have been recognised, whereas the Eocene record is slightly more diverse at 28 macroinvertebrate taxa recorded. The Pliocene macrofossil record is depauperate at some 11 species, but microfossils (diatoms, ostracods, foraminifera) are represented by at least 94 taxa. The palaeoecologic and palaeobiogeographic significance of fossil assemblages is explored in this paper. Further, a checklist of fossils is presented herein, for the first time, as is a bibliography of the geology and palaeontology of the island.

Key words: Antarctica, Cockburn Island, geology, palaeontology, history, bibliography.

Introduction

Cockburn Island (Figs 1, 2, 12), a small but prominent isle some 5 km north of Cape Bodman on Seymour Island at the boundary of Admiralty Sound and Erebus and Terror Gulf at latitude 64°13'S and longitude 56°50'E, has the honourable distinction of being one the first places to be visited by early Antarctic explorers during the first half of the nineteenth century. This small island has a surface area of approximately 4 km and measures 2.8 × 1.8 km (Jonkers 1998a). The early exploration of Cockburn Island failed to recognise, as will be discussed in detail below, a treasure trove of geologic and palaeontologic information on the now frozen continent. Not only is this island significant historically, but it is the only place in Antarctica with a stratigraphic succession, albeit unconformable, of Upper Creta-

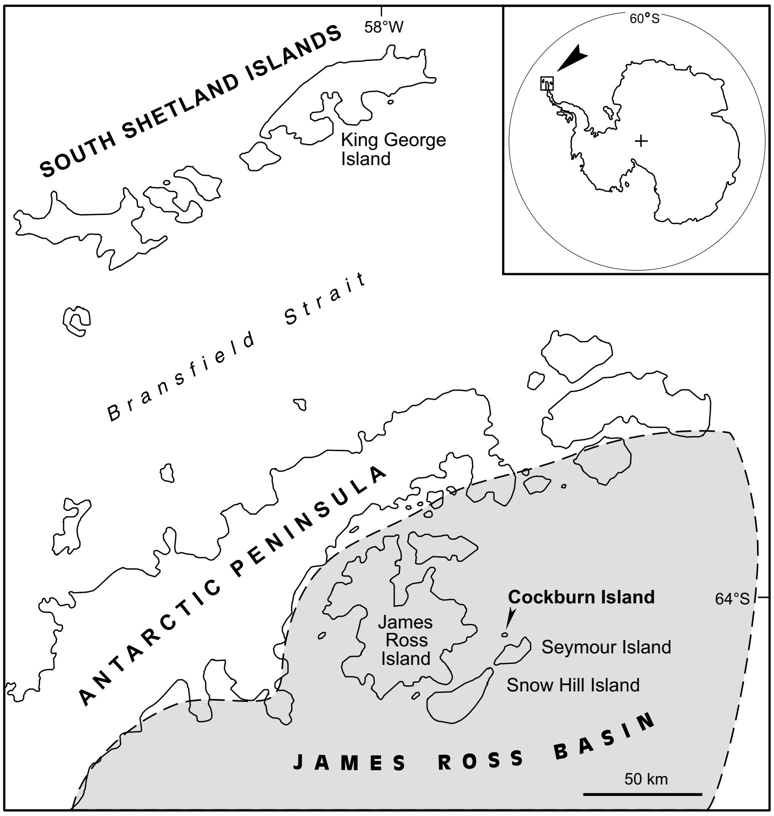

Fig. 1. Location map of Cockburn Island, Antarctic Peninsula, in the James Ross Island Group, approximately 100 km southeast of the tip of the Antarctic Peninsula in Admiralty Sound.

ceous, Eocene and Miocene-Pliocene rocks. These rocks contain an notable fossil record that is providing exciting new information on the evolutionary history of Antarctica. At the time of this writing in 2000, it is appropriate here to honour the publication more than 150 years ago of one of the classics in the exploration of Antarctica that saw the discovery of Cockburn and surrounding islands, Captain James Clark Ross' (1847) *A Voyage of Discovery and Research in the Southern and Antarctic Regions, during the years 1839-43* (two volumes). It is endeavoured herein, for the first time, to present a complete history of geologic and palaeontologic investigations of Cockburn Island from 1843 to the present and to provide both an extensive list of scientific works on the island and also systematic checklists of fossil fauna and flora. A summary of the geology of the island and the palaeobiogeographic and palaeoecologic significance of the fossils recovered are presented. The faunal and floral lists comprise both published and unpublished data that yield important information on the life that existed in this part of Antarctica from the Late Cretaceous to the Pliocene.

Fig. 2. Photograph from helicopter of Cockburn Island, illustrating the stratigraphy of the island: Miocene–Pliocene volcanics of the James Ross Island Group and Pliocene Cockburn Island Formation, underlain unconformably by Cretaceous and Eocene marine sediments of the Snow Hill Island Formation (SHIF) and La Meseta Formation (Seymour Island in background).
Photograph by J.D. Stilwell, January 4, 1987.

Captain Ross and the discovery of Cockburn Island in 1843

Although the New Year opened up to beautiful weather, just two hours after New Year's Eve at 2 am in 1843, Captain Ross (Fig. 3) and crew encountered a strong westerly wind while moving south and dangerous ice conditions near latitude 64˚14'S, longitude 55˚54'W along the northeastern tip of the Antarctic Peninsula: "*...we found the ice so close, that to prevent getting beset, we were compelled to stand back to the northward, to await a more favourable opportunity, and with the hope that the westerly breeze would drive the ice away from the shore, and leave a clear passage between them.*" (Ross 1847, 2, 332–333).

Being New Year's Day, it was customary to present to the crews a complete suit of warm clothing and additional allowance of provisions. Captain Ross, accompanied by Commander Bird, in the afternoon went on board the *Terror* to visit Captain Crozier and to wish him a Happy New Year. The weather was pleasingly calm and the surrounding views along the Antarctic Peninsula were spectacular, according to Ross. The discovery and description of Cockburn Island (Fig. 4) followed an account of majestic Mount Haddington: "*...A small island, of a deep brown colour, of great elevation for its size, with rock resembling a watch tower on*

Fig. 3. Portrait of Arctic and Antarctic English navigator and explorer, Sir James Clark Ross (1800–1862), the first explorer to survey the Cockburn Island region of the Antarctic Peninsula (from Nordenskjöld *et al.* 1904, vol. 1, p. 113).

its north point, and a high volcanic crater-like peak on its south end, being perfectly clear of snow, formed a striking contrast to the main land. It was named Cockburn Island, after Admiral the Right Honourable Sir George Cockburn, G.C.B., Senior Naval Lord of the Admiralty. Its elevation above the sea was two thousand seven hundred and sixty feet, and its diameter was about twice as much." (Ross 1847, 2, p. 333–334).

Unfavourable weather during the next several days and thick ice conditions including an immense iceberg that was an "*inconveniently close companion*" (Ross 1847, 2, p. 334), prevented any landing on Cockburn Island until 9 am on January 6th when the weather cleared and the shores of the island were free of ice. Captain Ross made a signal to Captain Crozier and both parties landed together and took possession of the island for the British Empire, an historic moment indeed as Cockburn Island is the only place in West Antarctica where Ross set foot ashore: "*...As we expected, we found it [Cockburn Island] to be entirely of volcanic formation; but the most interesting feature of our visit to this barren rock is that here the last vestiges of vegetation are to be found...*" (Ross 1847, 2, p. 335).

Thus, Ross, Crozier and parties including the famous botanist, J.D. Hooker, erroneously surmised that the island was entirely volcanic and concentrated largely on the interesting botany of the island (see Hooker *in* Ross 1847, 2, p. 335–343). Ross had two surgeons/naturalists with him during the voyage, namely the designated expedition geologist Robert McCormick and botanist J.D. Hooker. McCormick did not accompany the shore party, as Ross had a policy that during the expedition one of the surgeons had to remain on board the ship anytime the other went ashore. It was Hooker's turn to go ashore (Zinsmeister 1988, p. 9). The rock sam-

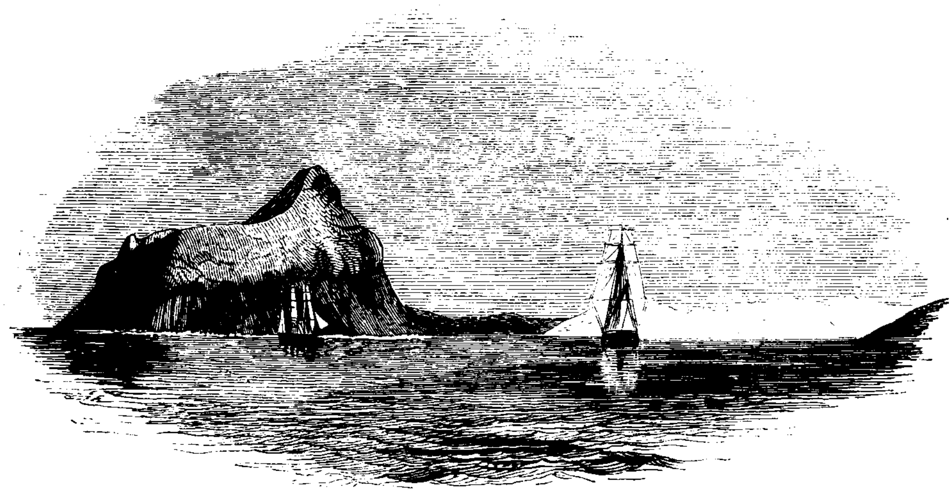

Fig. 4. The first published view of Cockburn Island showing the *Erebus* and *Terror* in Admiralty Inlet, illustrated as a title vignette to Chapter 12 of Ross (1847, 2, p. 320).

ples collected during the three hour visit to Cockburn Island remained unstudied until the end of the century when Prior (1899) wrote a short paper on the few samples collected. The basaltic glass, basalt and calcareous glauconitic sandstone samples could have been taken from *in situ* outcrop or float, but two granite samples must have been glacial erratics (Askin *et al.* 1991, p. 101). The sandstone samples are probably from what is now the La Meseta Formation, or less likely the Snow Hill Island Formation. Zinsmeister (1988, p. 9) wrote that fossil life may have been discovered during the Ross voyage if McCormick had gone ashore with Ross. It is interesting to note that Hooker *in* Ross (1847, 2, p. 341) wrote that Cockburn Island was always covered with snow throughout the whole year, even during the summer weeks. This constant snow cover would have diminished the possibility of finding the fossiliferous strata during their partial day visit. However, Hooker's statement that the island was constantly covered with snow has to be taken with lightly as Ross wrote that the island was "perfectly clear of snow", forming "a striking contrast to the main land" (p. 333), and also speaks of it as "this barren rock" (p. 335). That the island was snow-free is also obvious from the chapter title vignette (reproduced here as Fig. 4), and from Hooker's own account, in which he writes of lichens growing "on the ground", and "among the rocky debris". Further, it should be mentioned herein that the first figure of Cockburn Island is to be found as a chapter title vignette in Ross (1847, 2, unpaginated, but p. 320), reproduced herein for the first time since the publication of this book (Fig. 4). Below this vignette, it states that the discussion of Cockburn Island commences on page 322 in Ross' Chapter 12. This is an error. The account of Cockburn Island begins on page 332 and ends on page 343.

Bodman Skottsberg K.A. Andersson
Ohlin Nordenskjöld Larsen Ekelöf

Fig. 5. Members of the Swedish South Polar Expedition just prior to their departure to the Antarctic from Gothenburg, Sweden, reproduced from Nordenskjöld *et al.* (1904, p. xxxv).

The Swedish South Polar Expedition of 1901–03 and the discovery of fossils on Cockburn Island

Some 59 years would lapse before Cockburn Island was again visited, by members of the Swedish South Polar Expedition of 1901–03 between November 21 and 25, 1902, under the leadership of Otto Nordenskjöld of the ship *Antarctic* (Figs 5–6). On November 21st, Gösta Bodman, Erik Ekelöf and Ole Jonassen made a sledge journey to Cockburn and Seymour islands, and upon reaching Cockburn Island, pitched their tent almost in the same spot where Ross and crew landed in 1843 (see early photographs of Cockburn Island in Nordenskjöld *et al.* (1904), Nordenskjöld *in* Nordenskjöld and Andersson (1905), Nordenskjöld (1911), and Andersson (1944), reproduced herein as Figs 7–8). They collected some “uncommonly well-preserved ammonites” on Seymour Island, but all rock specimens collected from Cockburn Island consisted of “volcanic tuff” (Nordenskjöld *in* Nordenskjöld and Andersson 1905, p. 243). Thus, the members of the Swedish party initially failed again to recognise the presence of sedimentary strata

Fig. 6. Photograph of the expedition ship *Antarctic* during the Swedish South Polar Expedition 1901–1903.

of Cretaceous and Eocene marine rocks capped by a relatively thin veneer of volcanics that form most of the island. As reviewed by Zinsmeister (1988, p. 9), none of the members of the Seymour-Cockburn islands party were trained geologists, and as perceived earlier by the Ross voyage, the cone-shaped nature of the island and volcanic rock samples led them to believe the island was entirely volcanic in origin. But, Nordensköld *in* Nordenskjöld and Andersson (1905, p. 494) did write that "the island cannot be considered as a real volcano". The expedition was struck with disaster with the loss of the *Antarctic* in February 1903 when the ship had been crushed by pack ice and had sunk, which stranded the expedition members in the Antarctic for 2 years (Nordenskjöld and Andersson 1905, see also Gaździcki 2001). During their forced stay in the James Ross Island group, the team made a number of important scientific discoveries, but the astounding fossil record of this part of the Antarctic Peninsula remained virtually unexploited for another 70 years. Nordenskjöld decided after their sledge journey not to return to Cockburn Island and to concentrate his efforts elsewhere: "*...As this last circumstance seemed to agree with the account given by Ross, I became convinced that it was of no very great use to make further geological investigations on this island, and the consequence was that it was reserved for some one else to make the valuable geological discoveries which were made, most fortunately, ere we left these regions.*" (Nordenskjöld and Andersson 1905, p. 243)

Fig. 7. Photograph of sledge journey to Cockburn Island taken during the Swedish South Polar Expedition, reproduced from Nordenskjöld (1911, pl. 12, fig. 1), depicting, as translated from the German, a scene under a hard volcanic tuff deposit with a steep incline below composed of Cretaceous sandstone.

Fortunately, J. Gunnar Andersson joined Nordenskjöld on October 12, 1903, and discovered the fossils on Cockburn Island from October 21–23. He collected specimens from the Cretaceous strata, the glauconitic sandstones at the base of the Tertiary sequence, and the Pliocene "*Pecten*-conglomerate" (now known formally as the Cockburn Island Formation; Jonkers 1998a). Buckman (1910) described the early Tertiary (now known to be of Eocene age) and Pliocene brachiopods from Cockburn Island. In the same paper as an *Addendum*, Andersson *in* Buckman (1910, p. 41–43) provided a lengthy discussion of the age and stratigraphic relationships of the fossiliferous units exposed on the island, expanding on his earlier paper (Andersson 1906) because the study of the brachiopods by Buckman necessitated a revision of the ages of the beds. Buckman suggested an Oligocene–Miocene age for the glauconitic sandstone unit containing the brachiopods, originally perceived by Andersson to be of Cretaceous age (see locality 13 of Andersson's *Addendum*, reproduced herein as Fig. 9). A schematic cross section through the island and fossil localities 12–14 of the expedition are given by Andersson *in* Buckman (1910, p. 42). Wilckens (1924) described a small, poorly preserved molluscan faunule of ten Palaeogene species collected during the Swedish South Polar Expedition, but left all species in open nomenclature. Nearly all of the identifiable mollusc taxa from Cockburn Island are now known to be conspecific with or closely related to coeval Eocene species from the La Meseta Formation of Seymour Island, which were monographed by Stilwell and Zinsmeister (1992). Refer to Tables 1–3 for lists of macro- and microfossils from the Snow Hill Island Formation, La Meseta Formation and the Cockburn Island Formation.

Fig. 8. Cockburn Island from Nordenskjöld's Hut, Snow Hill Island, photograph by Bodman (Andersson 1944, opposite p. 168).

Recent Exploration of Cockburn Island from 1946 to present

Some 43 years would pass before Cockburn Island would be visited again, this time in 1946 by W. N. Croft of the Falkland Islands Dependencies Survey (now the British Antarctic Survey), who provided a geological sketch of the island and divided the rocks into five units; these include Cretaceous beds with ammonites, Tertiary beds with a brachiopod fauna, Ross Island Formation, "*Pecten* conglomerate" of Pliocene–Pleistocene age, and intrusive rocks of uncertain age (Croft 1947). Owen (1980, p. 125) corrected Croft's misinterpretation of the positions of Andersson's (1906) localities as being situated on the western side of the island, indicating that Croft was "somewhat disorientated" and that Andersson was correct in positioning his localities on the east-southeastern part of the island.

With the establishment of an Argentine base on Seymour Island (Isla Vicecomodoro Marambio) in 1969, several visits were made to Cockburn Island by scientific staff of the Instituto Antártico Argentino, but none resulted in published work. The next landings on the island were by U. S. and British Antarctic Survey scientists in 1982 (Zinsmeister and Webb 1982; Webb and Andreasen 1986) to survey the geology of the island, including collecting samples for potassium-argon dating of volcanic material, and then again twice in early 1987 (Elliot and Rieske 1987; Stilwell and Zinsmeister 1987) to measure geologic sections and to make fossil

Fig. 9. Schematic geologic cross-section through Cockburn Island (NW-SE), showing fossil localities from the Swedish South Polar Expedition and stratigraphic units (Andersson *in* Buckman 1910, p. 42).

collections (Fig. 10). During the following austral field season (1987–1988), the Polish visited the island with support from Argentine researchers to conduct studies on the outcrops of the "*Pecten*-conglomerate" and to sample for micropalaeontological and geochemical analyses (Doktor *et al.* 1988; Gaździcki 1993). Many papers on fossils and geology of the island have resulted from the visit by Polish scientists in 1988 and samples provided by U. S. workers (see Gaździcka and Gaździcki 1985, 1994; Gaździcki and Webb 1996; Szczechura and Błaszyk 1996; Gaździcki and Studencka 1997). Another visit by British workers was made in early 1989. During the 1990s, members of the British Antarctic Survey visited Cockburn Island to analyse the unconformable relationship between the Snow Hill Island and La Meseta formations, and during January 1996 to map the Cockburn Island Formation, and further to study the fossils (predominantly Mollusca) of the unit (see Jonkers 1998a, b; Jonkers and Kelley 1998; Jonkers 1999).

Geologic history of Cockburn Island

The Upper Cretaceous to Pliocene stratigraphic units of Cockburn Island form part of the James Ross Basin sedimentary succession (Figs 11–12), which was deposited in a back-arc basin to the east of the Antarctic Peninsula (Elliot 1988; Hathway 2000) to a maximum thickness of some 6000 m (Jonkers 1998a). All of the islands of the James Ross Island group are situated within an immense alkaline volcanic province along the eastern margin of the Antarctic Peninsula; the volcanic activity is believed to be a reflection of major normal faulting due to post-subduction back-arc isostatic plate recovery (Smellie *et al.* 1988; Jonkers and Kelley 1998). See recent work on the stratigraphical and structural evolution of the James Ross Island group by Hathway (2000). It is interesting to note here that although Cockburn and Seymour islands are in close proximity, it has been suggested that both islands were separated by block-faulting from James Ross Is-

Fig. 10. Upper Cretaceous, nearly flat-lying shallow marine sediments of the SHIF, section measured during 1986–87 expedition (see Askin *et al.* 1991). *Photograph by J.D. Stilwell, January 4, 1987.*

land on the other side of Admiralty Sound post-dating the James Ross Island Volcanic Group, and today belong to the same tectonic block with shallow waters of less than 5 m now separating the islands (see Fox *et al.*1995, Dingle *et al.* 1997, Jonkers 1998a). Cockburn Island has a rather deceptive volcano-like appearance, but is composed of Cretaceous and Eocene marine sediments overlain unconformably by Miocene–Pliocene volcanic rocks and Pliocene coarse-clastic, fossil-bearing rocks. The Snow Hill Island Formation (SHIF), of early Maastrichtian age (Crame *et al.* 1999), forms the lowermost unit of the island and is composed of about 150 m of poorly bedded to massive, medium grey (brownish weathering), variably clayey silt to siltstone to very fine sandstone with sparse horizons of calcareous concretions (up to 1.5 m), containing a relatively well-preserved invertebrate fauna (Stilwell and Zinsmeister 1987; Askin *et al.* 1991; Pirrie *et al.* 1997). The SHIF is exposed in gullies on the northern, eastern and southern sides of the island, and the stratigraphic relationship between this lower unit and the overlying La Meseta Formation of Eocene age is a complex one with faulted and unconformable contacts (Elliot and Rieske 1987, Askin *et al.* 1991, Barnes and Riding 1994, JDS, pers. obs.).

The deposition of Eocene sediments in the Cockburn Island succession relates to tectonism and sea-level lowstands during the latest Palaeocene–earliest Eocene, in which marginal marine to shallow shelf sediments infilled a broad valley that was incised in the Cretaceous beds during this early Palaeogene event (Askin *et al.*

Age	Palaeontological and radiometric data	Lithostratigraphy	Comments
Pleistocene		Scattered igneous and metamorphic erratics	Glacial dissection, uplift of Cockburn Island Formation to 220–250 m above sea level from a palaeodepth of <50–100 m
		U_1	**Glacially dissected erosion surface**
Late Pliocene	3.0 to 2.5 Ma (Diatoms)	Cockburn Island Formation (= *Pecten*-Conglomerate)	Shallow marine (?littoral) conglomerate, sandstone and siltstone: richly fossiliferous, including "*Zygochlamys*" *anderssoni* (Hennig), diatoms, foraminifera, radiolarians, silicoflagellates, sponges, echinoids, bryozoans, ostracods, molluscs, brachiopods and possible penguin bones
		U_2	**Ice and/or water dissected erosion surface**
Miocene? –Pliocene	4.9 to 4.7 Ma (Ar/Ar dates on basalts)	James Ross Island Volcanic Group	?Submarine basal flow and intercalated tuffaceous sediments
		U_3	**Ice and/or water dissected erosion surface**
Middle? Eocene	Palaeontology	La Meseta Formation	Few Eocene fossils reworked into Cockburn Island Formation; lower units Telm1 and Telm2 present only, based on molluscs, stratigraphy and sedimentology
		U_4	
Late Cretaceous (early Maastrichtian)	Palaeontology	Snow Hill Island Formation	Cretaceous foraminifera and calcareous nannoplankton reworked into suprajacent Cockburn Island Formation; age based on microfossils and molluscs

Fig. 11. Cretaceous to Plio–Pleistocene stratigraphy of Cockburn Island (revised from Gaździcki and Webb 1996, p. 155, fig. 4).

1991). The dips of the La Meseta Formation strata are anomalously high and the beds are largely primary with an unexposed steep contact on the east side suggesting either a fault or a possible unconformity, such as a buttress unconformity against a palaeocanyon wall (Askin *et al.* 1991). Buttress unconformities have also been recognised on Seymour Island between the López de Bertodano and overlying La Meseta formations, and have been interpreted as infill of an asymmetrical trough with steep sides (see Stilwell and Zinsmeister 1992, figs 8, 9), yielding further support for the idea that the Eocene beds of the lower units of the La Meseta Formation on Cockburn and Seymour islands represent deposits that filled a valley incised in the Cretaceous beds (see also Sadler 1988, Porębski 1995). The tiny strip of SHIF at the northeastern tip of the island may, indeed, indicate that both sides of the channel/canyon are preserved (see Fig. 12). This fascinating prospect requires further exploration as it is a major sequence boundary and has important implications for Antarctic early Cenozoic geology. The La Meseta Formation on Cockburn Island is more poorly exposed and thinner than coeval deposits on Seymour Island. The formation on Cockburn Island crops out on the northern part of the island where it is approximately 100 m thick of weakly stratified glauconitic sands

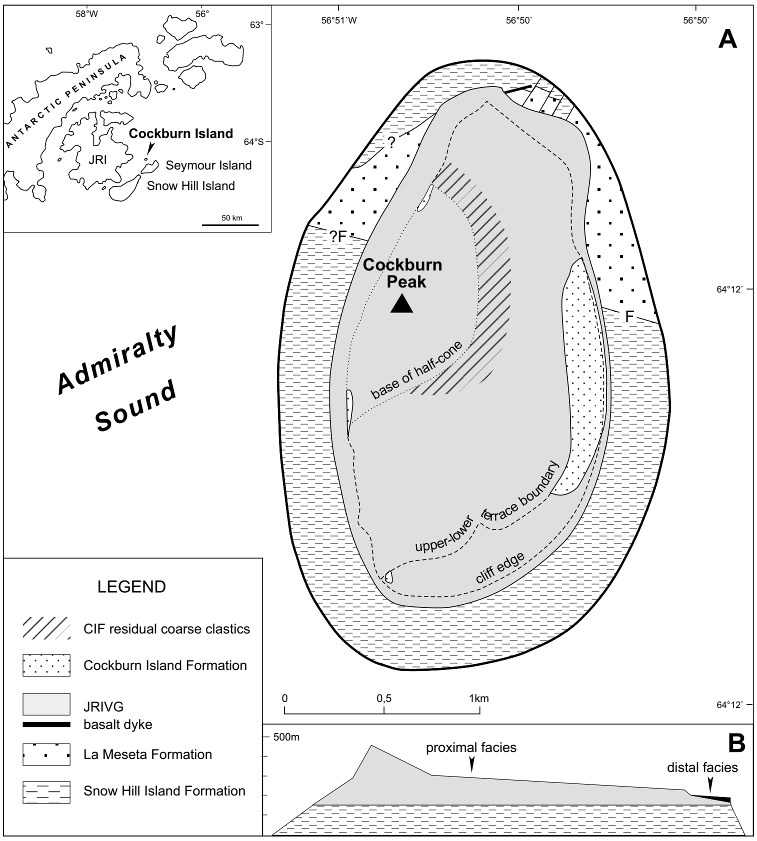

Fig. 12. Geologic sketch map of Cockburn Island, B refers to schematic cross-section of the southern part of Cockburn Island (from Jonkers 1998a, fig. 2).

and sandstone with clay-rich layers (lower 22 m), overlain by medium- to fine-grained sands alternating with muddy beds and sparse concretions. These beds continue to the contact of the overlying basalt (Askin *et al.* 1991). Broad scour and fill structures in the Eocene beds relate to slumping or mass movement of water-saturated sands and muds, some of which produced impressive recumbent folds (*Ibidem,* figs 10–12). The lithology, sedimentology and fossil content of the Eocene beds have been interpreted as a more proximal correlative of the lower Telm 1–2 of the La Meseta Formation on Seymour Island (*Ibidem).*

A large proportion of Cockburn Island is made up of a plateau formed by Miocene–Pliocene volcanic rocks of the James Ross Island Volcanic Group (JRIVG). These volcanic rocks overly the unconformable and faulted Cretaceous and Eocene sedimentary sequences. The average height of the plateau is about 250 m above sea-level, and apart from the western side, stops abruptly in vertical cliffs with steep sides (Jonkers 1998a). Talus from the volcanic rocks covers most of the flanks of the island and this cover is one of the reasons why the early explorers failed to recognise the significant fossil assemblages now known to be present on the island. The highest feature on the island has been recently named "Cockburn Peak", a half-conical hill with a summit height of 450 m on the northwestern part of the island (Fig. 12), which is composed at the base of tuff and volcanic breccia, which are protected from erosion from sub-horizontally bedded olivine lavas near the summit of the hill (Jonkers 1998a). Resting on the JRIVG are coarse-clastic rocks, bearing marine fossils, situated chiefly on the eastern part of the lower terrace and smaller, narrow strips on the northern, western, and southern parts of the island (Fig. 12).

This uppermost, fossil-bearing unit of Pliocene age on Cockburn Island has been recently formally named as the Cockburn Island Formation (Jonkers 1998a), to replace the informal name "*Pecten*-conglomerate" of Andersson (1906), which has been used from 1906 to 1998 by various authors, and is an informal senior synonym. The Cockburn Island Formation, dated as 3.0–2.5 Ma and deposited during the Late Pliocene interglacial interval, is regarded as part of the JRIVG and is partially equivalent in age (Jonkers 1998a, Jonkers and Kelley 1998). The formation is composed of more than 10 m of sandstone and conglomerate with a matrix of rounded to sub-rounded basalt pebbles, which were probably derived from the James Ross Island Volcanic Group. There is little doubt that the macroinvertebrates recovered from the Cockburn Island Formation are of very shallow water origin, which implies a tectonically controlled rise of more than 250 m in some 2.5 m.y. (see Gaździcki and Webb 1996, Jonkers 1998a, b and Jonkers and Kelley 1998) for detailed descriptions of the stratigraphy, sedimentology and palaeontology of the Cockburn Island Formation).

Palaeobiogeographic and palaeoecologic significance of fossil assemblages

The Cockburn Island assemblages are amongst the most significant and important Cretaceous and Tertiary suites of fossils from the Antarctic continent and provide further information in unravelling the palaeobiogeographic history of Antarctica during the final phases of the breakup of the supercontinent Gondwana. As shown in Table 1, molluscs dominate the Cretaceous macrofaunal assemblages of the Maastrichtian SHIF. All of the species-level taxa listed are endemic to Antarctica, and are not recorded elsewhere. Most of the ammonites are all considered to have been nektic carnivores. However, the large heteromorph *Diplomoceras*, which had a cosmopolitan distribution during the Campanian and Maastrichtian (Olivero and Zinsmeister 1989), is considered to have been, in all likelihood, benthic due to a low shell buoyancy (Olivero 1988). The kossmaticeratid ammonites *Gunnarites* and *Maorites* had Austral distributions only with a concentration of species in New Zealand and Antarctica (Henderson 1970, Olivero and Medina 2000). *Pseudophyllites* had a bipolar distribution from the early? Campanian to late Maastrichtian with re-

Table 1

Late Cretaceous (Campanian) Macrofossils from the López de Bertodano Formation of Cockburn Island (data from this table taken from Bibby 1966, Stilwell and Zinsmeister 1987, this work).

CNIDARIA
Genus et species indeterminate (coral)

MOLLUSCA
Gunnarites antarcticus (Weller, 1903) (ammonite)
Maorites sp. (ammonite)
Pseudophyllites peregrinus Spath, 1953 (ammonite)
Diplomoceras lambi Spath, 1953 (ammonite)
Malletia sp. (bivalve)
Nordenskjoeldia sp. (bivalve, reworked into Pliocene beds)
Pinna sp. cf. *P anderssoni* (Wilckens, 1910) (bivalve)
Entolium sp. (bivalve)
Seymourtula antarctica (Wilckens, 1910) (bivalve)
Pycnodonte (*Phygraea*) sp. cf. *P.* (*P.*) *vesiculosa* (Sowerby, 1816) (bivalve)
Lucina sp. (bivalve)
Lahillia sp. (bivalve)
Panopea sp. (bivalve)
"*Cassidaria*" sp. (gastropod)
"*Eunaticina*" sp. (gastropod)
Pyramidellidae? genus and species indeterminate (gastropod)

DECAPODA
Hoploparia stokesi (Weller, 1903) (lobster)

ANNELIDA
Rotularia spp.

ECHINODERMATA
Crinoidea genus and species indeterminate (crinoid stems)
Echinoidea genus and species indeterminate (irregular echinoid and spines)

CHORDATA
fish scales

cords from Greenland to Antarctica (Macellari 1986). Nearly 90% of the recorded bivalves from the SHIF are suspension feeders, with only a single infaunal, burrowing, deposit feeder, *Malletia* sp., collected from the fine-grained shallow marine facies. *Nordenskjoeldia* and *Lahillia* were probably nonsiphonate suspension feeders, whereas both *Pinna* lain and *Seymourtula* were byssate forms. *Entolium* was probably free-swimming, but *Pycnodonte* s.l. was sessile. *Lucina* and *Panopea* burrowed in the soft substrate. None of these bivalves are endemic at genus-level, and most are either palaeoaustral (*Nordenskjoeldia*, *Seymourtula*, *Lahillia*) or cosmopolitan (*Malletia*, *Pinna*, *Entolium*, *Pycnodonte* s.l., *Lucina*, *Panopea*). At species-level all are endemic. Gastropods are poorly known from the SHIF of Cockburn Island, but include endemic species of *Vanikoropsis* (cosmopolitan), "*Cassidaria*" (may represent a new endemic or paleoaustral? genus according to Fricker 1999), and a possible pyramidellid (an ectoparasite). Both *Vanikoropsis* and "*Cassidaria*" were active carnivores. The endemic lobster, *Hoploparia stokesi* (Weller, 1903), ranges from Campanian across the K-T boundary into the Palaeocene, and is recorded from widespread localities in the James Ross Basin (Feldmann *et al.* 1993). *Hoploparia stokesi* is the only member of the benthos known to have survived the K-T boundary extinction event.

Data from the Cockburn Island Maastrichtian assemblage support the contention that Late Cretaceous austral molluscs were derived from evolutionary separation from pre-existing Mesozoic stocks which experienced gradual spatial retractions during the late Mesozoic. The marked endemism of the Cockburn Island fauna at species-level reflects the break-up of Gondwana, in that the final separation would have maximised shelf areas for the dispersal of marine invertebrate taxa, but it would have enhanced provincialism of faunas due to segmentation of oceanic circulation patterns during the latest Cretaceous and early Tertiary. Thus, the occurrence of disjunct species of widespread or cosmopolitan genera in the Antarctic record resulted from retracted and partitioned distributions and evolution in isolation (see Crame 1995; Stilwell 1997 for additional examples from the fossil record).

The Eocene molluscan fauna of Antarctica belonged to a distinct biotic province, as shown by the approximately 11% endemism at genus-level (Stilwell and Zinsmeister 2000); all Eocene species are endemic. Some 28 macroinvertebrate species have now been recorded from the La Meseta Formation of Cockburn Island (Table 2), nearly three times as many taxa as that recognised by Wilckens (1924). Molluscs dominate and comprise c. 65% of the fauna, followed by eight species of brachiopods, and fewer bryozoans and annelids. All of the bivalves and gastropods, apart from the possible exception of *Arca*? sp., are common to Seymour Island and/or McMurdo Sound in East Antarctica. Many records from the Eocene of Cockburn Island are new (see Table 2; taxonomy modernised from Wilckens 1924). These include the recognition of the sole endemic bivalve *Acesta (Antarcticesta) laticosta* Stilwell and Gaździcki, 1998, previously described from the lowermost unit (Telm 1) from basal La Meseta Formation facies of Seymour Island. Brachiopod and mollusc species common to Cockburn Island, Seymour Island and McMurdo Sound include: *Tegulorhynchia imbricata* (Buckman, 1910); *Leionucula nova* (Wilckens, 1911); *Chlamys* s.l. sp.?; *Colposigma euthenia* Stilwell and Zinsmeister, 1992; and ?*Polinices* sp. cf. *P. subtenuis* von Ihering, 1897. *Ringicula* (*Ringicula*) *cockburnensis* Zinsmeister and Stilwell, 1990, previously reported as endemic to Cockburn Island, has now been recognised in Seymour Island deposits (JDS, pers. obs., 2000), and possibly also occurs at McMurdo Sound (Stilwell 2000). The composition of the Eocene Cockburn Island fauna above the level of species has a distinct cosmopolitan flavour with few genera restricted to the Southern Hemisphere. Of the taxa recognised in the Cockburn Island record, only *Acesta*

Table 2

Eocene Macrofossils from the La Meseta Formation of Cockburn Island (data from this table from Buckman 1910, Wilckens 1924, Zinsmeister and Stilwell 1990, Bitner 1996, this work).

BRYOZOA
- Genus and species indeterminate (hemispherical specimens up to 10 cm in diameter)

BRACHIOPODA
- *Hemithiris antarctica* Buckman (1910)
- *Plicirhynchia* sp.
- *Tegulorhynchia imbricata* (Buckman, 1910)
- *Terebratulina buckmani* Owen, 1980
- *Magellania antarctica* (Buckman, 1910)
- *Magella australis* (Buckman, 1910)
- "*Laqueus*" *cockburnensis* Owen, 1980
- *Liothyrella lecta* (Guppy, 1866)

MOLLUSCA
- *Leionucula nova* (Wilckens, 1911) (bivalve)
- *Cucullaea* sp. *cf. C. raea* Zinsmeister, 1984 (bivalve)
- *Arca*? sp. (bivalve)
- *Chlamys* s.l. sp.
- *Acesta (Antarcticesta) laticosta* Stilwell and Gaździcki, 1998 (bivalve)
- *Ostrea* sp. (bivalve)
- *Colposigma euthenia* Stilwell and Zinsmeister, 1992 (gastropod)
- *Sigapatella* sp. cf. *S. disapicula* Stilwell and Zinsmeister, 1992 (gastropod)
- Struthiolariidae gen. and sp. indet.(gastropod, reworked into Pliocene beds)
- *Polinices* sp. (gastropod, reworked into Pliocene beds)
- ?*Polinices* cf. *P. subtenuis* von Ihering, 1897 (gastropod)
- Muricidae genus and species indeterminate (gastropod)
- Buccinidae genus and species indeterminate (gastropod)
- *Eoscaphella*? sp. cf. *E. fordycei* Stilwell and Zinsmeister, 1992 (gastropod)
- *Conomitra* sp. cf. *C. iredale* Stilwell and Zinsmeister, 1992 (gastropod)
- *Ringicula* (*Ringicula*) *cockburnensis* Zinsmeister and Stilwell, 1990 (gastropod)
- *Scaphander* (*Kaitoa*) *antarctidis* (Wilckens, 1911)
- Scaphopoda genus and species indeterminate (scaphopod)

ANNELIDA
- *Serpula* (*Tubulostium*?) *cockburnensis* Wilckens, 1911

(Antarcticesta) is endemic and *Colposigma,* Struthiolariidae, *Eoscaphella,* and *Scaphander* (*Kaitoa*), are austral forms. The balance of the fauna comprised endemic species of widespread or cosmopolitan forms. Of the bivalves, only *L. nova* was a deposit feeder, the remaining bivalves identified as suspension feeders (e.g., *Cucullaea*, *Arca*?, *Chlamys* s.l., *Acesta* (*Antarcticesta*), *Ostrea*). The brachiopods were also suspension feeders. Carnivorous gastropods dominate the snail fauna (e.g., *Polinices,* Muricidae, Buccinidae, *Conomitra, Ringicula* s.s., *Scaphander*

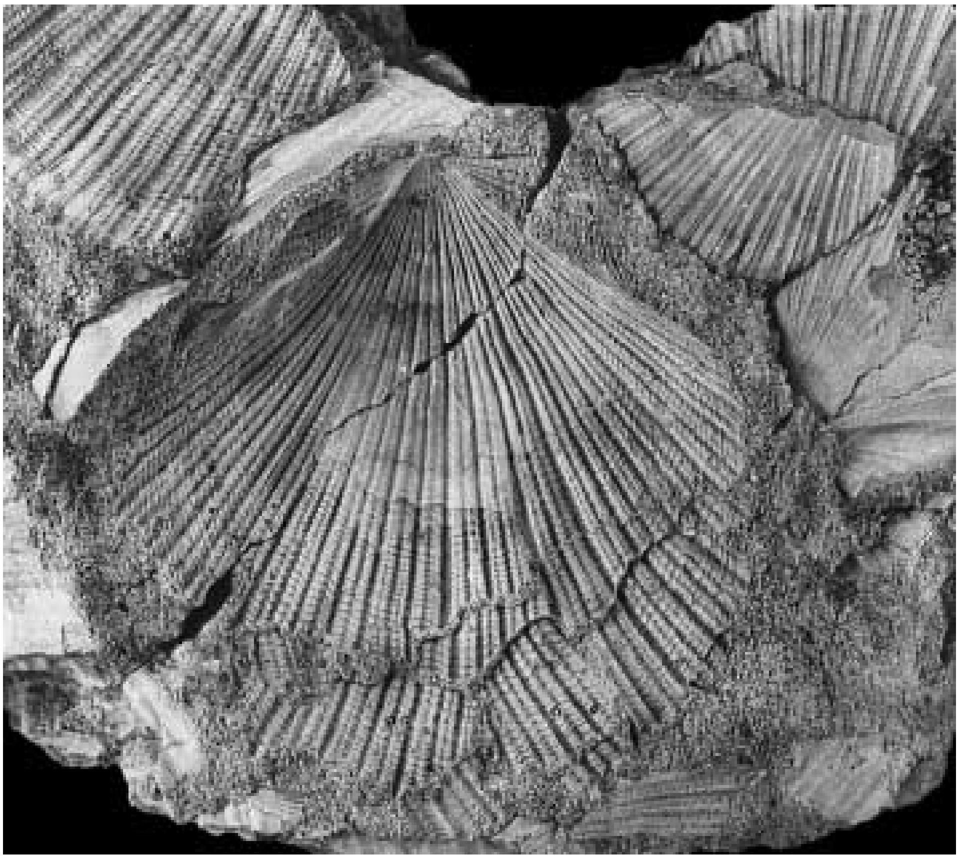

Fig. 13. Bivalve *"Zygochlamys" anderssoni* (Hennig, 1911), × 1. Cockburn Island Formation (Pliocene). *Photograph by G. Dziewińska.*

(*Kaitoa*)). Detritivores and deposit feeders include *Colposigma* and Struthiolariidae. *Sigapatella* was most likely a sedentary filter feeder. The unidentified scaphopods were probably microcarnivores.

The large number of taxa common to both East and West Antarctica suggests unequivocal, circum-Antarctic marine links during the Eocene (Stilwell and Zinsmeister 2000). The low to moderate degree of endemism at genus-level and a high degree of provinciality at species-level in the Antarctic Eocene record attests to the contention that Antarctica was well isolated, both physically and biologically, by the mid Eocene and that the continent belonged to a distinct biotic region.

The Pliocene Cockburn Island Formation has received a great deal of attention in the literature, not only for its palaeontologic significance (see Table 3a, b), but also because this shallow marine deposit records a probable late Pliocene interglacial episode before Antarctica plunged into its present "deep freeze" state (see Gaździcki and Webb 1996, Jonkers 1998a). One of the most conspicuous features of the

Table 3a

Pliocene microfossils from the Cockburn Island Formation (data taken from Harwood 1986, reworked fossils are omitted).

PALYNOMORPHS

Spiniferites sp.

DIATOMS

Achnanthes brevipes Agardh
Achnanthes brevipes var. *angusta* (Greville) Cleve
Actinocyclus actinochilus (Ehrenberg) Simonsen
Actinocyclus curvatulus Janisch
Actinocyclus ingens Rattray
Actinocyclus karstenii van Heurck
Cocconeis costata Gregory
Cocconeis fasciolata (Ehrenberg) Brown
Cocconeis pinnata Gregory ex Greville
Cocconeis schuettii van Heurck
Coscinodiscus janischii Schmidt
Coscinodiscus oculus-iridis Ehrenberg
Coscinodiscus planisulcus Rattray
Coscinodiscus radiatus Ehrenberg
Coscinodiscus stellaris Roper
Coscinodiscus stellaris var. *symbolophorus* (Grunow) Jorgensen
Dactyliosolen antarcticus Castracane
Dicladia cf. *pylea* Hanna and Grant
Eucampia antarctica (Castracane) Mangin
Fragilariopsis barronii
Fragilariopsis ritscheri (Hustedt) Hasle
Grammatophora charcotii Peragallo
Hyalodiscus valens Schmidt *et al.*
Hyalodiscus zonulatus Peragallo
Isthmia spp.
Melosira sulcata (Ehrenberg) Kutzing (*Paralia*?)
Nitzschia aeicularis (Kutzing) Smith
Nitzschia angulata (O'Meara) Hasle
Nitzschia cylindrica (Grunow) Hasle
Nitzschia pseudonana
Nitzschia ?kerguelensis (O'Meara) Hasle
Odontella punctata (Greville)
Odontella weisflogii (Janisch) Grunow
Paralia omma (Cleve)
Paralia sol (Ehrenberg) (incl. *Melosira sol* var. *marginalis* Peragallo)
Porosira sp.
Rhizosolenia hebetata group Bailey
Rouxia antartica Heiden and Kolbe
Rouxia naviculoides Schrader
Stephanopyxis grunowii Grove and Sturt

Table 3a – continued.

Stephanopyxis superba
Stephanopyxis turris (Greville and Arnot) Ralfs
Stictodiscus hardmanianus Greville
Thalassiothrix/Thalassionema spp.
Thalassiosira complicata Gersonde
Thalassiosira fasciculata Harwood and Maruyama
Thalassiosira inura Gersonde
Thalassiosira kolbei (Jouse) Gersonde
Thalassiosira oliveriana (O'Meara) Makarova and Nikolaev
Thalassiosira torokina Brady
Thalassiosira webbii Harwood and Maruyama
Thalassiosira cf. *Oestrupii* (Ostenfeld) Proshkina-Lavrenko
Thalassiosira ?vulnifica (Gombos)
Trachyneis aspera (Ehrenberg)
Trigonium arcticum (Brightwell) Cleve

Table 3b

Pliocene fossils from the Cockburn Island Formation (data taken from Gaździcki and Webb 1996, Buckman 1910, Szczechura and Błaszyk 1996, Jonkers 1998a, b, Gaździcka and Gaździcki 1994, Gaździcki and Studencka 1997, *described as sp. nov. from Cockburn Island; reworked fossils are omitted).

FORAMINIFERA
Ammoelphidiella antarctica Conato and Segre, 1974
Angulogerina angulosa (Williamson, 1858)
Cassidulina crassa d'Orbigny, 1839
Cassidulinoides parkerianus (Brady, 1884)
Cibicides lobatulus (Walker and Jacob, 1798) (incl. *C. refulgens* de Montfort, 1808)
Cribrononion sp.
Discorbinella sp.
Epistominella vitrea Parker, 1953
Fissurina cf. *semimarginata* (Reuss, 1871)
Fissurina cf. *laevigata* Reuss, 1850
Fissurina cf. *quadrata* (Williamson, 1858)
Fursenkoina cf. *earlandi* (Parr, 1950)
Globocassidulina subglobosa (Brady, 1881)
Lenticulina gibba (d'Orbigny, 1839)
Melonis sp.
Nonionella bradii (Chapman, 1916)
Nonionella turgida (Williamson, 1858)
Oolina globosa (Montagu, 1803)
Parellina corrugata Williamson, 1858
Pseudonodosaria sp.
Pyrgo fornasinii Chapman and Parr, 1935
Pyrgo elongata (d'Orbigny, 1826)
Triloculina sp.

Table 3b – continued.

MOLLUSCA
- *Nacella concinna* Strebel, 1908
- *Trophon* sp.
- *Adamussium colbecki* (Smith, 1902)
- *Laternula elliptica* (King and Broderip, 1831)
- "*Zygochlamys*" *anderssoni* (Hennig, 1911)*

BRACHIOPODA
- *Hemithyris antarctica* Buckman, 1910*
- *Magasela australis* Buckman, 1910*
- ?*Magellania fontainei* d'Orbigny, 1847

OSTRACODA
- *Antarctiloxoconcha frigida* (Neale, 1967)
- *Australicythere polylyca* (G.W. Müller, 1908)
- *Copytus caligula* Skogsberg, 1939
- *Hemicytherura* cf. *reticulata* Hartmann, 1962
- *Patagonacythere* cf. *longiducta longiducta* (Skogsberg, 1928)
- *Patagonacythere* cf. *tricostata* Hartmann, 1962
- *Procythereis* cf. *robusta* Skogsberg, 1928
- *Pseudocythereis spinifera* Skogsberg, 1928

CIRRIPEDIA
- *Fosterella hennigi* Newman, 1979*
- ?*Cytheropteron* sp.
- ?*Leptocythere* sp.
- ?*Loxocythere* sp.
- ?*Loxoreticulatum* sp.
- ?*Meridionalicythere* sp.
- ?*Rabilimis* sp.
- ?*Semicytherura* sp.

ECHINOIDEA
- Unidentified cidarid

VERTEBRATA
- Probable penguin bones

Cockburn Island Formation is the abundance of pectinid bivalves (Fig. 13), mainly as thousands of pieces of predominantly umbonal fragments. These pectinids represent "*Zygochlamys" anderssoni* (Hennig, 1911), a large and relatively thick-shelled pectinid, unlike the small, fragile scallops that inhabit the frigid Antarctic waters today. As stated by Jonkers (1998a, p. 68), most of the fragments of "Z." *anderssoni* represent shelly umbonal parts of right valves. Left valves are characterised by moulds, suggesting that this valve was relatively thin. Another poorly represented pectinid, *Adamussium colbecki* (see Table 3), is known only from internal and external moulds. The anomalodesmatan bivalve, *Laternula elliptica* (King and Broderip, 1831) is the only infaunal mollusc in the Cockburn Island Formation that still inhabits circum-Antarctic waters today. This clam is the largest infaunal bivalve of the Southern Ocean and lives in water depths of less than 100 m in a spectrum of substrates, and exhibits pronounced seasonality (see Jonkers 1999). These three species of bivalves belong to suspension-feeding groups, but the pectinids probably did not have a free-swimming lifestyle (B. Jonkers, pers. comm. 2002) and *Laternula* had a deep burrowing habit. Gastropods are rare in the fauna, but include the provisionally identified epifaunal grazing and/or browsing, patellid limpet, *Nacella concinna* (Strebel, 1908), and the carnivorous muricid *Trophon* sp. Both Cretaceous and Eocene taxa have been recorded as reworked elements in the Cockburn Island Formation (Jonkers 1998a). Other faunal groups in the formation include bryozoans (Hennig 1911, see also Hara 2001), cirripeds (Buckeridge 1983), brachiopods (Buckman 1910; Owen 1980), and echinoids; vertebrate remains may represent penguin bones (Jonkers 1998a). Microfossils, including diatoms and silicoflagellates (Harwood 1986), foraminifera (Holland 1910; Gaździcki and Webb 1996), and ostracods (Szczechura and Błaszyk 1996), all provide biostratigraphical control on the formation and indicate a Pliocene age. Geologic and palaeontologic evidence from the Cockburn Island Formation indicates a probable climatic amelioration for the Antarctic Peninsula some 3 Ma with marked marine incursions into East Antarctica during the Late Pliocene (Jonkers and Kelley 1998).

The synthesis above of fossils from Cretaceous to Pliocene age on Cockburn Island reveals the significance of these deposits in deducing geological and biological events during a large time slice of Antarctic history. Further research on poorly known fossil groups and additional collecting from the Cockburn Island record will certainly expand our knowledge of Antarctica's ancient past and provide new insight into the evolutionary history of the high southern latitudes.

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References

(those cited in text and extensive bibliography of major works dealing with Cockburn Island)

ADIE R.J. 1953. The rocks of Graham Land. University of Cambridge. — Unpublished Ph. D. thesis, 259 p.

ADIE R.J. 1958. Geological investigations in the Falklands Dependencies since 1940. — Polar Record, 9 (58): 3–16.

ADIE R.J. 1964. Sea-level changes in the Scotia Arc and Graham Land. *In*: Adie R.J. (ed.), Antarctic Geology, North Holland, Amsterdam; 307–313.

ANDERSSON J.G. 1906. On the geology of Graham Land. — Geological Institute of the University of Upsala Bulletin, 7: 19–71, 6 plates.

ANDERSSON J.G. 1910. The age of the brachiopod yielding beds of Cockburn Island. — *In*: Buckman S.S., Antarctic fossil Brachiopoda collected by the Swedish South Polar Expedition, Wissenschaftliche Ergebnisse der Swedischen Südpolar-Expedition 1901–1903, 3 (7): 41–43.

ANDERSSON J.G. 1954. Antarctic. Stolt har hon levat – Stolt skall hon dö. — Stockholm, Saxon and Lindströms, 305 p.

ASKIN R.A., ELLIOT D.H., STILWELL J.D., and ZINSMEISTER W.J. 1991. Stratigraphy and paleontology of Campanian and Eocene sediments, Cockburn Island, Antarctic Peninsula. — Journal of South American Earth Sciences, 4 (1/2): 99–117.

BARNES R.P. and RIDING J.B. 1994. Angular unconformity between the López de Bertodano and La Meseta formations (Campanian–Maastrichtian and Eocene), Cockburn Island, Antarctic Peninsula. — Journal of South American Earth Sciences, 7: 35–44.

BIBBY J.S. 1966. The stratigraphy of part of north-east Graham Land and the James Ross Island Group. — British Antarctic Survey, Scientific Reports, 53: 1–37.

BIRKENMAJER K. 1980. Discovery of Pliocene glaciation on King George Island, South Shetland Islands (West Antarctica). — Bulletin de L'Académié Polonaise des Sciences, Série des Sciences de la Terre, 27 (1–2): 59–67.

BIRKENMAJER K., GAŹDZICKI A., GRADZIŃSKI R., KREUZER H., PORĘBSKI S.J. and TOKARSKI A.K. 1991. Origin and age of pectinid-bearing conglomerate (Tertiary) on King George Island, West Antarctica. *In*: Thomson M.R.A., Crame J.A. and Thomson J.W. (eds), *Geological Evolution of Antarctica*, Cambridge University Press; 663–665.

BITNER M.A. 1996. Brachiopods from the Eocene La Meseta Formation of Seymour Island, Antarctic Peninsula. *In*: Gaździcki A. (ed.), Palaeontological Results of the Polish Antarctic Expeditions. Part II. Palaeontologia Polonica. Warszawa; 65–100.

BROOD K. Den Svenska Sydpolsexpeditionen 1901–1903. Naturhistoriska Riksmuseet, Stockholm, 32 p.

BUCKERIDGE J.S. 1983. Fossil barnacles (Cirripedia: Thoracica) of New Zealand and Australia. — New Zealand Geological Survey Paleontological Bulletin, 50: 1–151, 13 pls.

BUCKMAN S.S. 1910. Antarctic fossil Brachiopoda collected by the Swedish South Polar Expedition. Wissenschaftliche Ergebnisse der Swedischen Südpolar-Expedition 1901–1903, 3 (7): 1–40, 3 plates.

CRAME J.A. 1989. (ed). Origins and Evolution of the Antarctic Biota. — Geological Society Special Publication No. 47: 183–195.

CRAME J.A. 1994. The Evolutionary History of Antarctica. *In*: Hempel (ed.), Antarctic Science, Berlin–Heidelberg, Springer-Verlag; 188–214.

CRAME J.A. 1995. Evolution of high-latitude molluscan faunas. *In*: Taylor J. (ed.), Origin and Evolutionary Radiation of the Mollusca. — The Malacological Society of London; 119–131.

CRAME J.A. and LUTHER A. 1997. The last inoceramid bivalves in Antarctica. Cretaceous Research, 18: 179–195.

CRAME J.A., MCARTHUR J.M., PIRRIE D. and RIDING J. 1999. Strontium isotope correlation of the basal Maastrichtian Stage in Antarctica to the European and US biostratigraphic schemes. Journal of the Geological Society of London, 156: 957–964.

CRAME J.A., PIRRIE D., RIDING J.B., and THOMSON M.R.A. 1991. Campanian–Maastrichtian (Cretaceous) stratigraphy of the James Ross Island area, Antarctica. — Journal of the Geological Society of London, 148: 1125–1140.

CROFT W.N. 1947. Geological reports for the year ending January 1947, Hope Bay (Falkland Islands Dependency Survey Science Bureau No. E89/47). Parts 1–13, 182 p. [Unpublished report].

DINGLE R.V., MCARTHUR J.M. and VROON P. 1997. Oligocene and Pliocene interglacial events in the Antarctic Peninsula dated using strontium isotope stratigraphy. Journal of the Geological Society, London, 154: 257–264.

DOKTOR M., GAŹDZICKI A., MARENSSI S.A., PORĘBSKI S.J., SANTILLANA S.N. and VRBA A.V. 1988. Argentine-Polish geological investigations on Seymour (Marambio) Island, Antarctica. — Polish Polar Research, 9: 521–541.

ELLIOT D.H. 1988. Tectonic setting and evolution of the James Ross Island basin, northern Antarctic Peninsula. — *In*: Feldmann R.M. and Woodburne M.O. (eds), Geology and Paleontology of Seymour Island. Geological Society of America Memoir 169: 541–555.

ELLIOT D.H. and RIESKE D.E. 1987. Field investigations of the Tertiary strata on Seymour and Cockburn islands. — Antarctic Journal of the United States, 22 (5): 6–8.

FAIRBRIDGE R.H. 1952. The Geology of the Antarctic. *In*: F.A. Simpson (ed.), *The Antarctic Today*. Wellington, A.H. and A.W. Reed; 56–101.

FELDMANN R.M. and TSHUDY D.M. 1989. Evolutionary patterns in macrurous decapod crustaceans from Cretaceous to early Cenozoic rocks of the James Ross Island region, Antarctica. — *In*: Crame J.A. (ed.), *Origins and Evolution of the Antarctic Biota.* Geological Society Special Publication, 47: 183–195.

FELDMANN R.M., TSCHUDY D.M. and THOMSON M.R.A. 1993. Late Cretaceous and Paleocene decapod crustaceans from James Ross Basin, Antarctic Peninsula. — Supplement to Journal of Paleontology, 67 (Supplement to No. 1, Part II of II), The Paleontological Society Memoir 28, 41 p.

FOX A.J., KING S. and THOMSON J.W. 1995. James Ross Island – BAS 100 Series, Sheet 2, 1:100000. British Antarctic Survey, Cambridge.

FRICKER C.A. 1999. Composition and paleobiogeography of a Late Cretaceous (Maastrichtian) gastropod fauna from the López de Bertodano Formation of Seymour Island, Antarctic Peninsula. — Unpublished M.Sc. Thesis, Purdue University, Indiana, 280 p., 7 pls.

GAŹDZICKA E. and GAŹDZICKI A. 1985. Oligocene coccoliths of the *Pecten* Conglomerate, West Antarctica. — Neues Jahrbuch für Geologie und Paläontologie, Monatshefte, 12: 727–737.

GAŹDZICKA E. and GAŹDZICKI A. 1994. Recycled Upper Cretaceous calcareous nannoplankton from the *Pecten* Conglomerate of Cockburn Island, Antarctica. — Polish Polar Research, 15: 3–13.

GAŹDZICKI A. 1993. Geology and paleobiology of Cockburn Island, Antarctic Peninsula. — XX Polar Symposium. Lublin, Poland: 329–332.

GAŹDZICKI, A. Centennial of the Swedish South Polar Expedition (1901–1903). *In*: Gaździcki A. (ed.), Palaeontological Results of the Polish Antarctic Expeditions. Part III. Palaeontologia Polonica 60, 5–6.

GAŹDZICKI A. and STUDENCKA B. 1997. Pectinids (Bivalvia) from the *Pecten* Conglomerate of Cockburn and King George Islands, Antarctica. — *In*: Głowacki P. (ed.), *Polish Polar Studies, 24th Polar Symposium, Warszawa, 1997. Institute of Geophysics of the Polish Academy of Sciences, Warszawa;* 53–56.

GAŹDZICKI A. and WEBB P.-N. 1996. Foraminifera from the *Pecten* Conglomerate (Pliocene) of Cockburn Island, Antarctic Peninsula. *In*: Gaździcki A. (ed.), Palaeontological Results of the Polish Antarctic Expeditions Part II. Palaeontologia Polonica, 55, 147–174.

HARA U. 2001. Bryozoans from the Eocene of Seymour Island, Antarctic Peninsula. *In:* A. Gaździcki (ed.), Palaeontological Results of the Polish Antarctic Expeditions. Part III. Palaeontologia Polonica 60, 33–156.

HARRINGTON H.J. 1965. Geology and morphology of Antarctica. — *In*: van Oye P. and van Mieghem J. (eds), *Biology and Ecology in Antarctica, Monographiae Biologicae*, 15: 1–71.

HARWOOD D.M. 1986. Diatom biostratigraphy and paleoecology and a Cenozoic history of Antarctic ice sheets. — Unpublished Ph.D. dissertation, The Ohio State University, 592 p.

HATHWAY B. 2000. Continental rift to back-arc basin; Jurassic–Cretaceous stratigraphical and structural evolution of the Larsen Basin, Antarctic Peninsula. Journal of the Geological Society of London, 157: 417–432.

HENDERSON R.A. 1970. Ammonoidea from the Mata Series (Santonian–Maastrichtian) of New Zealand. — Special Papers in Palaeontology, London, 6, 82 p.

HENNIG A. 1911. Le Conglomérat pleistocčne ŕ Pecten de l'île Cockburn. — Wissenschaftliche Ergebnisse der Swedischen Südpolar-Expedition 1901–1903, 3 (10): 1–72.

HOLLAND R. 1910. The fossil foraminifera. — Wissenschaftliche Ergebnisse der Swedischen Südpolar-Expedition, 3 (9): 1–11.

HOOKER J.D. Comments on Cockburn Island. — *In*: Turrill W.B. 1953. *Pioneer Plant Geography: The Phytogeographical Researches of Sir Joseph Dalton Hooker.* The Hague, Martinus Nijhof, 325 p.

IHERING H. VON. 1897. Os molluscos dos terrenos tertiarios da Patagonia. — Revista do Museu Paulista, 2: 217–328.

ISHMAN S.E. and WEBB P.-N. 1988. Late Neogene benthic foraminifera from the Victoria Land basin margin, Antarctica: application to glacio-eustatic and tectonic events. — Revue de Paléobiologie, Special Volume, 2(2): 523–551.

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

JONKERS H.A. 1998b. Stratigraphy of Antarctic late Cenozoic pectinid-bearing deposits. — Antarctic Science, 10 (2): 161–170.

JONKERS H.A. and 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: 737–740.

JONKERS H.A. 1999. Aligned growth positions in Pliocene *Laternula elliptica* (King and Broderip) (Bivalvia: Anomalodesmata: Laternulidae). — Antarctic Science, 11 (4): 463–464.

JONKERS H.A. 2000. Gastropod predation patterns in Pliocene and Recent pectinid bivalves from Antarctica and New Zealand. — New Zealand Journal of Geology and Geophysics, 43: 247–254.

KING P.P. and BRODERIP S.P. 1831. Description of the Cirrhipeda, Conchifera and Mollusca, in a collection formed by the officers of H.M.S. *Adventure* and *Beagle* employed between the years 1826 and 1830 in surveying the southern coasts of South America, including the Straits of Magalhaens and the coast of Tierra del Fuego. — Zoological Journal, 5: 332–349.

LAWVER L.A., KELLER R.A., FISK M.R. and STRELIN J.A. 1995. Bransfield Strait, Antarctic Peninsula – active extension behind a dead arc. — *In*: Taylor B. (ed.), *Backarc Basins, Tectonics and Magmatism.* New York, London, Plenum Press; 315–342.

MACELLARI C.E. 1986. Late Campanian–Maastrichtian ammonite fauna from Seymour Island (Antarctic Peninsula). — Supplement to Journal of Paleontology, 60 (Supplement to No. 2, Part II of II), The Paleontological Society Memoir 18: 1–55.

NELSON P.H.H., 1975. The James Ross Island Volcanic Group of north-east Graham Land. — British Antarctic Survey Scientific Reports, 54: 1–62.

NEWMAN W.A. 1979. On the biogeography of balanomorph barnacles of the Southern Ocean including new balanid taxa; a subfamily, two genera and three species. — New Zealand Department of Scientific and Industrial Research, Information Series, 137: 279–306.

NORDENSKJÖLD O., ANDERSSON J.G., LARSEN C.A. and SKOTTSBERG C.J. 1904. *Antarctic två år bland Sydpolens Isar.* — Stockholm, Albert Bonniers, 1, 486 p., 2, 544 p.

NORDENSKJÖLD O. and ANDERSSON J.G. 1905. *Antarctica, or Two Years Amongst the Ice of the South Pole* [English Edition]. — Macmillan, New York, NY, USA, 608 p. [Re-published in 1977 by C. Hurst and Company, London, United Kingdom; and Archon Books, Connecticut, USA].

NORDENSKJÖLD O. 1911. Die Swedische Südpolar-Expedition und Ihre Geographische Tätigkeit. — Wissenschaftliche Ergebnisse der Swedischen Südpolar-Expedition, 1(1): 1–232.

NORDENSKJÖLD O. 1913. Antarktis. — *In*: Steinmann G. and Wilckens O. (eds), *Handbuch der Regionalen Geologie*, Heidelberg, C. Winter, 7 (6): 1–29.

OLIVERO E.B. 1988. Early Campanian heteromorph ammonites from James Ross Island, Antarctica. — National Geographic Research, 4 (2): 259–271.

OLIVERO E.B. and MEDINA F.A. 2000. Patterns of Late Cretaceous ammonite biogeography in southern high latitudes: the family Kossmaticeratidae in Antarctica. — Cretaceous Research, 21: 269–279.

OLIVERO E. and ZINSMEISTER W.J. 1989. Large heteromorph ammonites from the Upper Cretaceous of Seymour Island, Antarctica. — Journal of Paleontology, 63 (5): 626–636.

OLIVERO E., SCASSO R.A. and RINALDI C.A. 1986. Revision del Grupo Marambio en La Isla James Ross – Antartida. — Instituto Antartico Argentino Contribucion, No. 331: 1–30.

OWEN E.F. 1980. Tertiary and Cretaceous brachiopods from Seymour, Cockburn, and James Ross Islands, Antarctica. — Bulletin of the British Museum (Natural History), Geology, 33: 123–145.

PIRRIE D., CRAME J.A., LOMAS S.A., and RIDING J.B. 1997. Late Cretaceous stratigraphy of the Admiralty Sound region, James Ross Basin, Antarctica. — Cretaceous Research, 18: 109–137.

PIRRIE D., DUANE A.M., and RIDING J.B. 1992. Jurassic–Tertiary stratigraphy and palynology of the James Ross Basin: review and introduction. — Antarctic Science, 4: 259–266.

PORĘBSKI S.J. 1995. Facies architecture in a tectonically-controlled incised-valley estuary: La Meseta Formation (Eocene) of Seymour Island, Antarctic Peninsula. *In*: Birkenmajer K. (ed.), Geological Results of the Polish Antarctic Expeditions. Part XI. Studia Geologica Polonica, 107, 7–97.

PRIOR G.T. 1899. Petrographical notes on the rock specimens collected in Antarctic regions during the voyage of H.M.S. *Erebus* and *Terror* under Sir James Clark Ross, in 1839–43. — Mineralogical Magazine, 12: 69–91.

RINALDI C.A., MASSABIE A., MORELLI J., ROSEMAN L.H., DEL VALLE R.A. 1978. Geología de la isla Vicecomodoro Marambio, Antártida. — Contribuciones Instituto Antártico Argentino, 217: 1–37.

ROSS CAPT. J.C. 1847. *A Voyage of Discovery and Research in the Southern and Antarctic Regions, during the years 1839–43*. — 2 volumes. London, J. Murray, 1 (366 p.), 2 (447 p.).

SADLER P.M. 1988. Geometry and stratification of uppermost Cretaceous and Paleogene units on Seymour Island, northern Antarctic Peninsula. — *In*: Feldmann R.M. and Woodburne M.O. (eds), *Geology and Paleontology of Seymour Island, Antarctic Peninsula.* Geological Society of America, Memoir 169; 303–320.

SMELLIE J.L., PANKHURST R.J., HOLE M.J., and THOMSON J.W. 1988. Age, distribution and eruptive conditions of Late Cenozoic alkaline volcanism in the Antarctic Peninsula and eastern Ellsworth Land: a review. —British Antarctic Survey Bulletin, 80: 21–49.

SOOT-RYEN T.1952. *Laternula elliptica* (King and Broderip, 1831) from the Pecten-conglomerate, Cockburn Island. — Arkiv für Zoologie, 4: 163–164.

STEWART D.1937. Petrography of some rocks of the South Orkney Islands and the Antarctic Archipelago. — American Mineralogist, 22: 178–194.

STILWELL J.D. 1997. Tectonic and palaeobiogeographic significance of the Chatham Islands, South Pacific, Late Cretaceous fauna. — Palaeogeography, Palaeoclimatology, Palaeoecology, 136: 97–119.

STILWELL J.D. 2000. Eocene Mollusca (Bivalvia, Gastropoda and Scaphopoda) from McMurdo Sound: systematics and paleoecologic significance. — *In:* Stilwell J.D. and Feldmann R.M. (eds), *Paleobiology and Paleoenvironments of Eocene Rocks, McMurdo Sound, East Antarctica,* American Geophysical Union, Antarctic Research Series, 76; 261–320.

STILWELL J.D. and GAŹDZICKI A. 1998. A new limid bivalve from the La Meseta Formation (Eocene) of Seymour Island, Antarctic Peninsula. — Acta Geologica Polonica, 48 (2): 149–155.

STILWELL J.D. and ZINSMEISTER W.J. 1987. Late Cretaceous fossils from Cockburn Island collected during the 1986–1987 expedition to the Antarctic Peninsula. — Antarctic Journal of the United States, 22 (5): 5–6.

STILWELL J.D. and ZINSMEISTER W.J. 1992. Systematics and biostratigraphy. Lower Tertiary La Meseta Formation, Seymour Island, Antarctic Peninsula. — American Geophysical Union Antarctic Research Series, 55, 192 p.

STILWELL J.D. and ZINSMEISTER W.J. 2000. Paleobiogeographic synthesis of the Eocene macrofauna from McMurdo Sound, Antarctica. — *In* Stilwell J.D. and Feldmann R.M. (eds), *Paleobiology and Paleoenvironments of Eocene Rocks, McMurdo Sound, East Antarctica,* American Geophysical Union Antarctic Research Series vol. 76, 365–372.

STREBEL H. 1908. Die Gastropoden. — Wissenschaftliche Ergebnisse der Schwedischen Südpolar-Expedition 1901–1903, Stockholm, 6(1):1–111, 6 pls.

SZCZECHURA J. and BŁASZYK J. 1996. Ostracods from the *Pecten* Conglomerate (Pliocene) of Cockburn Island, Antarctic Peninsula. *In*: Gaździcki A. (ed.), Palaeontological Results of the Polish Antarctic Expeditions Part II. Palaeontologia Polonica, 55: 175–186.

VALLE R.A. DEL and MEDINA F. 1985. Geologia de Cabo Marsh, Isla Robertson, Antartida. — Contribuciones de Instituto Antártico Argentino, 309: 1–27.

WEBB P.-N. and ANDREASEN J.E. 1986. Potassium/argon dating of the volcanic material associated with the Pliocene Pecten Conglomerate (Cockburn Island) and Scallop Hill Formation (McMurdo Sound). — Antarctic Journal of the United States, 21 (5): 59.

WELLER S. 1903. The Stokes collection of Antarctic fossils. — Contributions from Walker Museum, 1 (5): 65–71 (reference for Weller in Feldmann *et al.* 1993, 40, in error).

WILCKENS O. 1910. Die Anneliden, Bivalven und Gastropoden der Antarktischen Kreideformation. — Wissenschaftliche Ergebnisse der Swedischen Südpolar-Expedition 1901–1903, 3(12), 132 p.

WILCKENS O. 1911. Die Mollusken der Antarktischen Tertiärformation. — Wissenschaftliche Ergebnisse der Swedischen Südpolar-Expedition, 3 (13), 1–62.

WILCKENS O. 1924. Die Tertiäre Fauna der Cockburn-Insel (Westantarktika). — Further Zoological Results of the Swedish Antarctic Expedition 1901–1903, 1 (5): 1–18.

ZINSMEISTER W.J. 1988. Early geological exploration of Seymour Island, Antarctica. — *In*: Feldmann R.M. and Woodburne M.O. (eds), *Geology and Paleontology of Seymour Island, Antarctic Peninsula.* Geological Society of America Memoir 169; 1–19.

ZINSMEISTER W.J. and STILWELL J.D. 1990. First record of the family Ringiculidae (Gastropoda) from the middle Tertiary of Antarctica. — Journal of Paleontology, 64 (3): 373–376.

ZINSMEISTER W.J. and WEBB P.-N. 1982. Cretaceous–Tertiary geology and paleontology of Cockburn Island. — Antarctic Journal of the United States, 17 (5): 41–42.

ZULLO V.A., FELDMANN R.M. and WIEDMAN L.A. 1988. Balanomorph Cirripedia from the Eocene La Meseta Formation, Seymour Island, Antarctic Peninsula. — *In*: Feldmann R.M. and Woodburne M.O. (eds), *Geology and Paleontology of Seymour Island, Antarctic Peninsula*. Geological Society of America Memoir 169; 459–464.

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