LATE NEOGENE SEDIMENTS OF COASTAL EAST ANTARCTICA—AN OVERVIEW

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Abstract: Coastal East Antarctica has thin sediment sequences of Pliocene and younger ages. Most are marine and show evidence of deposition in a glacial environment. Marine Plain in the Vestfold Hills contains a 9 m thick section of 3.5–4.2 Ma diatomite and sandstone which is important because of cetacean remains including a dolphin, three species of whale, fish and possibly penguins. The sediments contain no evidence of glacial debris, and oxygen isotope analysis of bivalves suggests water considerably warmer than today. The icecap margin was considerably inland, and the icecap smaller. Stornes Peninsula in the Larsenmann Hills contains a 40 cm thick unit, covering a few hectares, that has provided well preserved benthic foraminifers of Pliocene age. Diatoms indicate that this is in the 2–3 Ma range. More work is needed to obtain its full palaeoenvironmental significance. In the Windmill Islands, sediment entrained in ice contains diatom floras, mostly marine, but one lacustrine, indicating an age of 1–2 Ma but lacking expected cold water indices. Work on these floras is in its infancy. Near Davis in the Vestfold Hills are marine sediments with a diverse biota, including both planktonic and benthic foraminifers. Various dating techniques lead to an age estimate of 300 Ka–1 Ma. Oxygen isotope analysis suggests a water temperature a little above that of today. Thin Quaternary sequences are widespread and represent several episodes of deposition, some marine, some subglacial, some fluvial. These sequences represent intervals of warm water and high sea level. They provide data supporting hypotheses apparently in conflict with some ideas generated from deep sea sections. Much work, including deep sea drilling, is needed to make all stories compatible.

Key words: global change, Neogene, Pliocene, Quaternary, palaeoanalogue

Introduction
The path of evolution of the modern Antarctic glaciation through the late Neogene has become of general interest for the following reasons:

- Over this interval, Antarctica has evolved from a continent with a small ice cover to the present ice cap,
- It is now believed that amplitude of change under the “Greenhouse” scenario will be greatest in the polar regions and will be detectable early there,
- The path of evolution of the climate has had great, but as yet insufficiently studied, impact on the evolution of the Antarctic fauna and flora,
- It is necessary to document the natural rate and amplitude of change so that human-induced change can be differentiated from the natural,
- It is desirable to place human-induced change in the context of the natural,
- Recently there has been interest in identifying possible palaeoanalogues of the conditions that may prevail should the “Greenhouse” scenario come into play,
- In a broader geological context, the region is a large one about which little is known, and it is necessary to add Antarctic data to the global evolution story for other geological reasons.

Sources of information to aid the study are deep sea drilling (by either the Deep Sea Drilling Project - DSDP, or the Ocean Drilling Program - ODP), onshore sections (such as those of the Sirius Formation of the Transantarctic Mountains, and the Pagodroma Tillite sections of the Prince Charles Mountains), and for the younger part of the section, the record in the thick ice. The latter has provided very fine scale data for the last 160,000 years (Jouzel et al., 1987) and has the potential to yield data of comparable definition over the last 400,000–500,000 years.

There seems to be developing a dichotomy in scientific hypotheses arising from studies based on onshore data and those based on offshore data. This dichotomy relates particularly to the interpretation of the Antarctic environment during the Early Pliocene when one school identifies a warm interval and the other does not. This dichotomy needs to be addressed and resolved. The East Antarctic coastal sections are important sources of data relevant to this debate.

This paper provides a summary of what is known from sediments occurring in a series of small localities on the East Antarctic margin between longitudes 75–115°E. The number of outcrops and the range of ages represented suggest that the area will continue to increase in importance as the years pass. In addition to the coastal sections recorded here, there are further outcrops, including in the Framnes Mountains, south of Mawson, and farther inland, particularly in the Prince Charles Mountains (Bardin, 1982; McKelvey and Stephenson, 1990; McKelvey et al., 1991). Localities mentioned in the text are shown in Fig. 1.

The region is tectonically very stable lacking any evidence of significant post-depositional tectonically controlled elevation change, or of volcanic activity. Post-glacial eustatic readjustment is active at about 1–1.5 mm/yr and has been analysed by Adamson and Pickard (1986).

Some of the known outcrops have been studied enough that an indication of the significance can be given here, but for most, research has not advanced beyond the recognition of the potential significance. Steps are being taken now to focus research efforts on these occurrences. The area with the
best studied and most diverse sections known is the Vestfold Hills, an oasis of some 400 km$^2$ on the northeastern corner of Prydz Bay. Over the last ten years many important discoveries have been made and led to a focus on the East Antarctic coastal region.

The outcrops are thin (maximum known about 9 m), scattered, small in area (maximum about 10 km$^2$) and sometimes consist of reworked debris, commonly of unknown but probably local source. The age range extends from approximately 4.2 Ma to the present day and much of the interval probably is not represented. Dating is based primarily on biostratigraphic methods, using molluscs, foraminifera, protein racemisation and particularly marine diatoms. In addition, there has been some radiocarbon dating in the younger parts of the section, uranium series dating on carbonates, and a little oxygen isotope analysis has been carried out on some mollusc material.

What is known suggests that the sediments known to date represent deposition during intervals of high sea level, relatively warm water conditions and thus they constitute a very biased record, but one that cannot be ignored. The sediments are sources of a great amount of data concerning a small part of the time since 4.2 Ma, in contrast to the deep sea marine sections which potentially provide a complete time record, but with small samples of the time interval recorded on land.

Pliocene

**Marine Plain, Vestfold Hills**

The area includes both Marine Plain (*sensu stricto*) and the Poseidon Basin, which are separated by a ridge of Precambrian rocks. The sediments unite south of this ridge. The Marine Plain section is the better studied to date.

The section at Marine Plain lies about 10 km southeast of Davis Station and consists of *in situ* 8–9 metres of Early Pliocene sediment overlain by 0.5–1 metre of Holocene (6.49 Ka; Quilty, 1991) glacial debris. It covers an area of some 10 km$^2$, is an essentially horizontal, undisturbed diatomite and sandstone with subsidiary limestone lenses, and is within 15 metres of modern sea level. Adamson and Pickard (1986) and Pickard et al. (1986, 1988) documented many aspects of the Early Pliocene of the Marine Plain/ Poseidon Basin area including its age and the basis for its determination and Quilty (1991) discussed the geology of the region.

The sediment in outcrop appears to be white diatomite, but is more sandy when excavated. There has been little opportunity to examine unweathered material because there is a deep weathering profile on the sequence. Drilling should, in the near future, allow access to fresh sediment at depths greater than 2 or 3 metres. There are several horizons in the upper half of the section in which carbonate is concentrated, with abundant molluscs (including *Chlamys tufensis* Turner). The carbonate is in the form of lenses and there are some areas where these are continuous enough to be regarded as a limestone bed. Poorly preserved fish remains have been recovered from one such bed. The upper part of the section has suffered significant diagenesis and in places is leached of all carbonate to a depth of over two metres. Limestone is replaced by gypsum over this interval and walking commonly releases obvious SO$_2$ suggesting, with the gypsum, that the upper part of the section, when fresh, has a significant pyrite component, consistent with deposition in a reducing environment. There are no glacial features in the sediment.

**Age**

Pickard et al. (1986, 1988) explored the basis for the age determination of the sequence (radiocarbon dating, bivalve molluscs, amino acid racemisation, diatoms). Diatoms have been used to date the section of diatomite as 3.5–4.2 Ma. This date is a minor revision (Harwood, personal communication) of that included in earlier papers (Pickard et al., 1986, 1988).

Pickard’s initial attempt at dating the Pliocene section was based on radiocarbon techniques and suggested an age of >24 and 28 Ka, indicating that the age is beyond the limits of the radiocarbon technique. Zhang and Peterson (1984) also recorded Quaternary radiocarbon dates (31 Ka) but Zhang (1985, 1989), in contrast to Pickard et al. (1986, 1988) and other authors, continues to accept these dates, even though they are in conflict with other widely accepted Pliocene dates.

**Environment of deposition**

The presence of abundant benthic marine diatoms indicates that water depth at the time of deposition of the Marine Plain section was less than 75 m, and other features indicate that for the upper part of the section it was much less. Pickard et al. (1988) referred to a coarsening upward of the sediment, consistent with shallowing with time.

The cetacean fauna occurs only in the upper two metres of the section. The specimens occur as large assemblages of vertebral columns, skulls and even complete specimens, normally about two metres or more in length. They are not broken, disarticulated fragments typical of beach specimens. They do not represent strandings as several species occur together and are from sediments deposited over an interval estimated at several thousand years although the interval of deposition is indeterminate at this stage.

Fordyce (personal communication) states that the cetaceans are non-cryophilic in affiliation and essentially temperate water vertebrates. This is further consistent with the diversity of the bivalve mollusc fauna which is much greater than that in the modern marine environment, and with the apparent absence of seals and penguins (but note that the question of the presence or absence of penguins is debated).

Sediment characters and those of the fauna suggest that the water depth for the upper two metres of the section was quite shallow, perhaps of the order of two metres but not shallower. The features of the dolphin, supported by oxygen isotope data (Quilty, 1991), are consistent with a water temperature of some +5°C.

Thus, at 3.5–4.2 Ma, Marine Plain seems to have been an embayment filled with water much warmer than at present, suggesting a much smaller ice cap than exists at present and thus consistent with the higher sea level documented for the time by Haq et al. (1987). The environment was fully marine and shallow as suggested by the diverse mollusc fauna, and the characteristics of the preservation of the cetacean fauna.
Fauna and flora

The sediments contain a diverse array of marine vertebrates and invertebrates. The best known cetacean of the fauna is a new genus and species of dolphin at present included in the Delphinidae (Fordyce, personal communication). It is represented by three skulls (including earbones; Fordyce, 1989) and a few vertebrae. Other species include a right whale, and others not yet studied (usually of forms up to 7–8 metres long, but one form has a jawbone alone some 1.5 metres long), possibly penguins, fish, and bivalves, gastropods, serpulid worms, bryozoans, asteroids, ophiuroids, echinoids and so on. While the few palynological preparations performed to date have not yielded evidence of land vegetation other than mosses, they have produced arthropod remains that have not been analysed in detail to date. They also contain abundant leiospheres (Truswell, personal communication), probably planktonic in origin.

Larsemann Hills

Quilty et al. (1990) recorded a foraminiferid fauna from a small area (not precisely measured but less than two hectares) in the Larsemann Hills, at 55 metres above sea level, in the Jennings Bluff area of Stornes (Peninsula). The section thickness is only 40 cm and consists of poorly bedded, grey, clayey sand. No complete bivalve molluscs have been recovered, but fragments are very abundant. At least two species are present but are unidentifiable.

Age

Benthic foraminifers are not precise determinants of age but the presence of Ammoeolphiidiella antarctica Conato and Segre (=Troxoeolphiidiella onyxi Webb) (Quilty et al., 1990) suggested an Early Pliocene age following Webb and Wrenn (1982), Ishman and Webb (1988), Leckie and Webb (1986) who identified this species in a sequence isotopically dated as 2.5–3.8 Ma. Harwood (personal communication) has identified highly fragmented planktonic diatoms and silicoflagellates from two samples (of many) from this section and determined a Late Pliocene age of 2–3 Ma (perhaps more restricted to 2.2–2.8 Ma).

Environment of deposition

Assuming that the sediment is in situ, the environment at the time of deposition was high energy, shallow water and the resulting foraminiferid fauna, while very well preserved, lacks planktonic and agglutinated species. The diatom flora (Harwood, personal communication) indicates a water depth less than 50 metres. Much remains to be gained from this section, including documentation of other elements of the biota, oxygen isotope analysis of well preserved but fragmented bivalves (underway) and uranium series dating (underway at present).

Pliocene

Windmill Islands

There has been virtually no study of sediments in this area since their original documentation by Cameron et al. (1959) who noted that they are widespread and thin over the region, and Loken (in Cameron et al., 1959, p. 12) noted that they occurred generally below 30 metres above sea level. Goodwin (in press) discusses them in some detail in relation to the dynamics of Holocene glacial history.

Recent evidence of young marine sediments in the Windmill Islands region came from a report of “fine hollow cylindrical spicules of glass incorporated into the moss and soil to a depth of 15 or more centimetres” (Lewis-Smith, unpublished data). This material, thought initially to be fibreglass, is sponge spicules from sediment underlying moss beds adjacent to Casey Station at elevations to about 40 metres above sea level. Further search has uncovered a diversity of sediments that need study.

Sediments have been recovered from horizons in ice cliffs north of Casey Station. Details of field occurrence are not fully documented but it is clear that the sediments have been transported glacially to their present mobile position. Some samples contain diatoms and sponge spicules in dark grey shale and fine sand. No calcareous fossils have been recovered from these samples but during 1991, samples with a significant carbonate content (including mollusc fragments) have been identified but have not yet been brought back from Antarctica to allow study.

Age

Harwood (personal communication) has examined the siliceous flora (diatoms) from the few samples recovered to date and has identified a probably Late Pliocene-Early Pleistocene (1–2 Ma) age. Although the material is clearly being transported at present, there is no evidence that transport has caused any mixing with younger sediment.

Environment of deposition

The florals lack cold water species and Harwood suggested deposition in waters less than 50 metres deep in water temperatures of 2–6°C. Most of the samples are marine, with one lacustrine exception.

Pleistocene

Airport Road, Vestfold Hills

Drilling was carried out in recent years along Airport Road, between Davis and Lake Dingle for a variety of reasons, including the possibility of constructing a runway for fixed wing aircraft. This drilling intersected sediments representing a previously unsuspected age and environment of deposition. Excavations in this sequence were conducted in early 1989 following the techniques and principles outlined in Hirvas and Nenonen (1990). Information gleaned from the sediments is summarised by Hirvas et al. (in press).

The surface of the area consists of glacial sediments of the widespread 4–8 Ka marine sequence (see below) so common in the Vestfold Hills, overlying older marine sands, clays and glacial debris. It is essentially flat, a straight ENE-WSW trending glacial valley between hills of Precambrian rocks (Collerson and Sheraton, 1986). Elevation of the valley floor is generally 7 to 8 metres above sea level.

The total section known to date from the valley is up to 4.5 metres thick (but possibly thicker in the valley centre) and consists of a younger section (4–8 Ka, perhaps one meter thick) which overlies equally thick units of dark green sandstone (upper) and tillite.

Age

The younger section is part of the widespread 4–8 Ka sequence common in the Vestfold Hills although this has not
been tested specifically yet.

The age of the older material is still not fully identified. Both poorly lithified older tillite and younger sandstone (both predating the younger glacial sediments) contain plentiful marine indices including diverse benthic foraminifers (Hirvas et al., in press), monospecific planktonic foraminifer fauna (Neogloboquadrina pachyderma (Ehrenberg)), radiolarians, diatoms, sponge spicules and bivalves (Laternula elliptica King and Broderip, Hiatella sp.), some in living position. Dating has been based on radiocarbon (beyond limits), amino acid racemisation, and thermoluminescence techniques, but none has defined a reliable age other than 300 Ka-1 Ma (Hirvas and Neenonen, 1989; Hirvas et al., in press).

Adamson and Pickard (1986) recorded a radiocarbon age of 33 Ka from the Heidemann Bay Moraine, which is on the margin of the western end of the valley containing the Airport Road section. This age is beyond the limit of the technique and may represent material reworked into the moraine from the sediment underlying Airport Road.

Environment of deposition

The material is marine. Oxygen isotope data from very well preserved molluscs suggest a water temperature of +2°C, consistent with a warm, high sea level, interglacial phase.

Thin aragonite deposits

Widespread in the Vestfold Hills is a thin (few millimetres) coating of aragonite firmly attached to basement rocks. The relation of these deposits to the history of the region is unknown other than that they were identified by Aharon (1988) as subglacial precipitates. While Aharon examined many such deposits, there are several that he did not, for example those at the southeastern corner of the Vestfold Hills where they are presently being exposed by ice retreat.

Age

Aharon (1988) dated this material at 35 Ka, the only record of rocks of this age in the region. The relation of these deposits to other elements of the history of the region is unknown. It may relate in some way to the buildup to the last glacial maximum.

Environment of deposition

Aharon (1988) regarded the aragonite as a subglacial precipitate, deposited in a closed system during an interval when the Vestfold Hills was covered with an ice sheet that was advancing at the time.

Holocene

4–8 Ka marine sequences

Widespread throughout the Vestfold Hills are scattered patches of in situ sediments, first noted by Voronov (1958), which have been the subject of an extensive radiocarbon dating program (Adamson and Pickard, 1986) on the common shelly faunas. Always thin, the lithology and fossil content vary widely and include bivalves, dominantly Laternula elliptica and Adamussium colbecki (Smith), serpulid worm tubes, sponges and algae. Foraminiferids from this sequence have been the subject of studies by Crespin (1960), Setty et al. (1980) and Quilty (1988). Much remains to be done. A common form of occurrence is of beds of innumerable Laternula elliptica in living position. Possibly similar sediments have been recovered from the Rauer Islands south of the Vestfold Hills and in the Buenger Hills (Colhoun and Adamson, 1992).

There are also undated greenish/grey sands marginal to the Pliocene of the Marine Plain/Poseidon Basin regions and around bays in the coast. These have not been correlated with known dated sediments and probably represent a variety of ages.

Age

Adamson and Pickard (1986) summarised the extensive radiocarbon dating results on these sediments and documented the uncorrected age range of approximately 4–8 Ka, and showed that a reasonable reservoir effect correction to apply is some –1000 to –1300 years for marine carbonate.

Environment of deposition

Most of these Holocene sediments were deposited in diverse, shallow marine environments, but a few are characterised by cyanobacterial mats and are nonmarine (Adamson and Pickard, 1986). Much needs to be done to document the range of environments and the contained fauna and flora.

Lake sediments

The Vestfold Hills is characterised by numerous lakes and fjords. Many are meromictic and thus any sediment that accumulates is not subject to bioturbation. Bird et al. (1991) have shown that the undisturbed sequences are up to 7 Ka old and are continuous over this interval. They are thus of great interest to the objectives of the Past Global Changes (PAGES) program of the International Geosphere Biosphere Program (IGBP) because they may yield virtually annual information on the environment and its change over the last 7 Ka.

Scattered, undated sediments

In addition to the above sediments that are in situ and at low elevation, Gore (personal communication) has reported widespread redistributed sediments from all elevations over the Vestfold Hills which have a maximum elevation of only 160 metres. This material clearly is not in situ and is the residue left from the retreat of the ice cap, although it is unclear which retreat phase was responsible. The material was deposited originally in a marine environment and is characterised by foraminiferids, molluscs and diatoms. No age diagnostic species have yet been identified. Foraminiferids seen to date are extant species. Some dates up to 11 Ka have been obtained by radiocarbon techniques but the range is probably very diverse. Its source is unknown, as is the age of its initial formation and of its emplacement.

Young fluvial activity

The Marine Plain area has been subject to significant fluvial activity over the interval since the deposition of the mid Holocene sequence. There are small patches of lake sediment on the eastern side of Marine Plain formed as a result of deposition at the distal end of small streams emanating from the high land (40–45 metres elevation) between Marine Plain and Poseidon Basin. Stream valleys
and source lakes (now virtually empty) have been identified. There is evidence of water activity also in the Windmill Islands (Goodwin, personal communication). Drilling through ice of Law Dome in the Casey region in the near future will examine questions of variation in precipitation over the last few thousand years.

Other Sequences

Undated sediments occur in abandoned cirques south of Mawson. They have not been studied but they may provide a basis for identifying the past height of the ice sheet and of the age at which it stood high.

In the Buringer Hills there are Holocene sediments (Colhoun and Adamson, 1992) as old as 7.7 Ka. They have been examined so far mainly in relation to the raised beaches in the region, not for their own sake. Like sediments of comparable age in the Vestfold Hills, the fauna is dominated by shells of *Laternula elliptica*. Foraminifers are present in some samples but have not been documented in detail.

Lakes in the Windmill Islands have recently been investigated by Goodwin (in press) and sediments in these lakes have been dated by radioisotope techniques as approximately 8 Ka to 2 Ka and indicate a progressive deglaciation of the Windmill Islands from the south by 8 Ka and the north by 5.5 Ka.

Discussion

Coastal sections around the East Antarctic craton, in a tectonically very stable environment, will contribute significantly to the debate on the evolution of the Antarctic ice cap, and other factors such as sea level stability, and sea ice extent, that depend on that evolution. The study of this material is in its infancy.

The 3.5–4.2 Ma section at Marine Plain in the Vestfold Hills contains clear evidence of a much warmer Early Pliocene with the implication of a much reduced ice cap and ice margin farther inland than is now the case. Evidence from elsewhere in the world indicates that sea level was significantly higher at the time, consistent with the Antarctic data. Other Antarctic evidence (for example the presence of *Nothofagus* in the Sirius Formation in the Transantarctic Mountains) is further consistent with this.

The temperature indications from the Late Pliocene from the Larsemann Hills material have not yet been ascertained although excellent mollusc and benthic foraminferid material exists for that study.

In the Casey region, 1–2 Ma sediments that have not been adequately studied contain evidence of a considerably warmer interval near the Pliocene/Pleistocene transition.

The Marine Plain and Windmill Islands material also indicates that the path of evolution through the Pliocene includes intervals of warm conditions and the temperatures interpreted are as high or even higher than those expected today at or north of the Antarctic Convergence. Did the Convergence disappear for short intervals during this time?

The indications of warm conditions have serious consequences for any understanding of the path and rate of evolution of the modern Antarctic ecosystems and of the resilience of the organisms now living there. When did krill evolve and by what path? What was the impact on the evolution of the penguins, nototheniid fish, and the distinct phytoplankton marked by its own diatom flora and such almost uniquely Antarctic groups as the Parmales?

The Airport Road material from the Vestfold Hills needs to be dated more precisely before its contribution can be incorporated into any evolutionary history.

The evidence for warmer conditions and minor fluvial activity in the Holocene is strong but the interval in which it may have taken place remains undated in this region. It may be related to the hypsithermal discussed by Domack et al. (1991).

A great deal will be contributed to the IGBP discussions on the evolution since the last glacial maximum by the latest Pleistocene and Holocene sequences but it is too early to give any indication of what the contribution is or will be.

Acknowledgements

I thank all those who have followed my admonition to "keep your eyes open for sediments and bring samples home to me", in particular Dr. J. Burgess and Messrs F. Baciu, I. Goodwin, and Dr. R. Seppelt. I am very grateful to the reviewers who have helped significantly in making this a better paper.

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