

SHELF, COASTAL AND SUBGLACIAL POLAR CARBONATES, EAST ANTARCTICA

C. Prasada Rao¹, I.D. Goodwin² and J.A.E. Gibson³

¹*Department of Geology, University of Tasmania, GPO Box 252-79, Hobart, Tasmania, Australia 7001*

²*Antarctic CRC, University of Tasmania, GPO Box 252-80, Hobart, Tasmania, Australia 7001*

³*Institute of Antarctic and Southern Ocean Studies, University of Tasmania, GPO Box 252-80, Hobart, Tasmania, Australia 7001*

ABSTRACT: Modern and Pleistocene polar carbonates occur in East Antarctica in shelf, coast, lakes and marginal to underneath glaciers, associated mainly with glaciogene muds, boulder tills and diamictites. Shelf carbonates (in Prydz Bay) are calcitic and unlithified, and consist mainly of sponges, bryozoans, echinoderms, bivalves and diatoms. Coastal carbonates (in the Vestfold Hills) are calcitic and contain faunal assemblages similar to those on the shelf, with calcareous algae, microbial mats, minor peloids and cements. Lake carbonates are aragonitic micrites and peloids. Carbonates close to glaciers (the Løken Moraines) are aragonitic and contain abundant ooids with intragranular fibrous cements. Subglacial carbonates are aragonitic micrites and peloids. Carbonate mineralogy changes from mainly low-Mg calcite in marine shelf to aragonite in brackish to freshwater dominated inland regions.

Antarctic carbonate $\delta^{18}\text{O}$ values (4.5 to -47‰ PDB) vary markedly due to frigid temperatures (0 to -2°C) and salinity (0 to 35‰) changes, as a result of meltwater dilution from adjacent glaciers. Their $\delta^{13}\text{C}$ values (-9 to 8‰ PDB) also vary markedly due to exposure to atmospheric CO_2 , the circulation of water masses and reaction of carbonate with CO_2 trapped in glacial ice.

The regional distribution of carbonate sediments and their sedimentology, mineralogy, and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ compositions indicate three types of glacial environments of formation. The first corresponds to a glacial stage and the formation of subglacial and bank carbonates, when the Antarctic ice sheet expanded onto the inner shelves. The second corresponds to interglacial stages and the formation of ice-marginal carbonates, during the retreat of the ice sheet from the inner shelf grounding line and accompanying the discharge of appreciable meltwater. The third corresponds to an interglacial oasis and the formation of coastal carbonates, proximal to distal lacustrine carbonates, and distal subglacial carbonates.

INTRODUCTION

Extensive modern tropical, temperate and polar shallow marine carbonates are forming in many global regions, and these differ in field, sedimentological and geochemical characteristics (Rao 1996). In the present study, we document the occurrence of shelf, coastal and marginal to subglacial polar carbonates from East Antarctica and present preliminary results on their sedimentology, mineralogy and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotope compositions. These results demonstrate: (1) the occurrence of inorganic components such as ooids, peloids and cements along with biota; (2) a shift from calcite to aragonite mineralogy from marine shelf to brackish to freshwater dominated marginal to subglacial regions; and (3) a marked variation in both oxygen and carbon isotopic compositions of marginal and subglacial carbonates.

The occurrence of ooids and peloids in East Antarctic carbonates is significant, because these characteristics are mainly reported from tropical (Lees 1975) and temperate (Rao 1983) settings and have not been previously reported from polar regions. Cementation in polar carbonates provides evidence for the saturation of CaCO_3 in cold seas (Rao 1996), in contrast to the dissolution of CaCO_3 resulting from under saturation in some cold seas (Alexandersson 1978). The dominance of calcite mineralogy in marine polar shelf carbonates may occur due to the temperature dependence of carbonate mineralogy in seawater. The occurrence of aragonitic carbonates in ice-free regions of Antarctica (Hendy et al. 1979; Aharon 1988; Bird et al. 1991; Gore et al. 1996; this study) is unusual, because calcite is the common mineral

precipitate in glaciated areas in North America (Hallet 1976; Hanshaw and Hallet 1978), Scandinavia (Bjaerke and Dypvik 1977), the European Alps (Lemmens et al. 1982) and Irian Jaya (Peterson and Moresby 1979). The heaviest and lightest $\delta^{18}\text{O}$ compositions occur in polar carbonates, due to frigid temperatures and meltwater dilution (Rao and Green 1982; Rao 1996). The occurrence of heavier and lighter $\delta^{13}\text{C}$ values in polar carbonates compared to tropical and temperate carbonates (Rao 1996), as observed in this study, is also significant to understand the origin of polar carbonates, since the $\delta^{13}\text{C}$ values in polar carbonates may be related to temperature, $\delta^{13}\text{C}$ in CO_2 trapped in the Antarctic ice sheet, exposure to atmospheric CO_2 , and the circulation of water masses.

The glacial history of a region is now mainly deduced from the distribution of terrigenous clastic sediments, such as tillites, diamictites, pebbly mudstones and glacio-marine conglomerates, sandstones, mudstones and siltstones (Hambrey 1995; Anderson and Ashley 1991). We propose, in this study, that the regional distribution of carbonate sediments and their sedimentology, mineralogy and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ composition can contribute significantly in understanding the glacial history of Antarctica. Therefore, similar studies of ancient polar carbonates can unravel regional glaciation through time (Rao 1981; Rao and Green 1982; Rao 1988).

REGIONAL SETTING

The East Antarctic carbonate sediments studied are from the Prydz Bay shelf and coastal areas within the Vestfold Hills, the

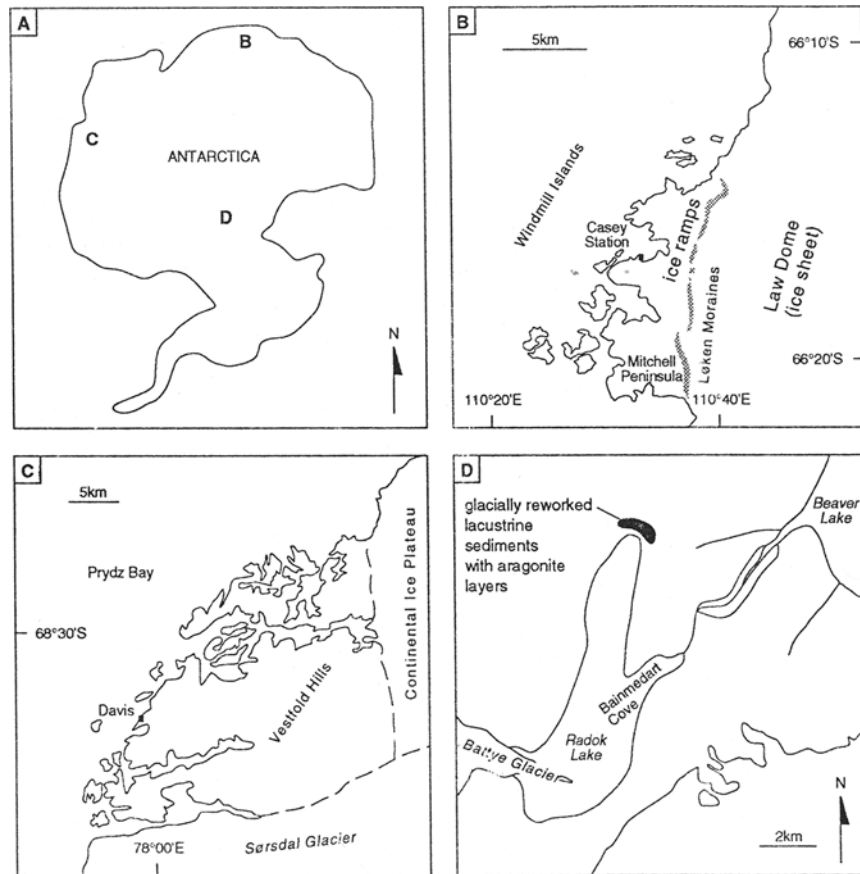


Figure 1. (A) Occurrence of carbonates in Antarctica with three sample localities, namely Løken Moraines (B), Prydz Bay (C), Vestfold Hills (C) and Radok Lake (D). (B) Location of Løken Moraines along the Budd Coast at the margin of the Law Dome ice sheet and inland of the Windmill Islands, East Antarctica. (C) Location of Prydz Bay and Vestfold Hills, East Antarctica. Carbonate samples from Prydz Bay shelf studied range up to a depth of 200 m, whereas those at Vestfold Hills are now exposed. (D) Location of Radok Lake in the Amery Oasis, in the northern Princes Mountains, East Antarctica

Løken Moraines, and the Law Dome ice margin, along the Budd Coast and Radok Lake, the Amery Oasis, Northern Prince Charles Mountains (Fig. 1A).

The Løken Moraines are located along the Budd Coast margin of the Law Dome ice sheet, inland of the Windmill Islands during the Holocene (Fig. 1B). The 20 km long supraglacial moraine complex of ice-cored ridges and flats also outcrops as continuous debris bands in coastal ice cliffs to the north of the Windmill Islands (Goodwin 1993). These comprise proglacial and coastal marine sediments that have been incorporated onto the base of the Law Dome ice margin by an overriding Late Holocene readvance of glaciers onto the Windmill Islands (Goodwin 1996). The readvance occurred subsequent to the bulk of post-glacial isostatic rebound, following an early to mid-Holocene marine transgression of the region. Carbonate cobble and boulder-sized slabs and carbonate-coated boulders were observed in the Løken Moraines (Fig. 2), seaward of an early to mid Holocene embayment. These contain abundant aragonitic non-skeletal grains as documented by entirely aragonite mineralogy from



Figure 2. Carbonate boulder forming a conglomerate with carbonate cement and detrital quartz and feldspar fragments. These conglomerates were observed together with diamict and carbonate cobbles, and laminated slabs in the supraglacial Løken Moraines of Late Holocene age, along the Budd Coast margin of the Law Dome ice sheet.

X-ray analysis of bulk carbonates that contain abundant non-skeletal grains.

Carbonates in Prydz Bay (Fig. 1C) are associated with glaciogene mud in the inner shelf to a depth of 1000 m; they grade to pure carbonates on the offshore banks at present water depths of about 200 m, to turbidites, carbonate-terrigenous sand and mud in the outer shelf, slope and deep basin, and to muds and carbonates in the outer shelf. Carbonate samples studied here are from coastal inner shelf and bank sites within the depth range of <200 m. The ^{14}C dates of fauna, corrected for reservoir effects, range from 140 to 8030 year BP (Harris et al 1996).

The Vestfold Hills region of East Antarctica (Fig. 1C) is a coastal area of ice-free terrain, approximately 400 km² in area. The region was glaciated during the Last Glacial Maximum, and the area has subsequently become exposed as a result of both glacial retreat and isostatic uplift during the Holocene. The Vestfold Hills can be divided into two distinct areas (Fig. 3): land that was below 10 m elevation and was inundated by a marine incursion during the early to mid-Holocene, and higher elevation areas which have not been inundated (Gore et al. 1996). The inundated areas are characterized by the presence of many marine biota, including bivalves, sponge spicules, foraminifera, worm tubes and unconsolidated microbial stromatolites (up to 0.5 m across; Pickard 1984), which have been dated to 6000 - 8000 years BP (uncorrected for reservoir effect). Further evidence for a marine transgression comes from the presence of raised shorelines around many of the numerous saline lakes of marine origin that are scattered throughout the Vestfold Hills (Peterson et al. 1988). These shorelines are characterized by marine terraces, which were formed by the action of tides and sea ice, at about 6 m above present sea level. Isostatic uplift resulted in relative sea-level lowering and the isolation of a number of fjord systems from the sea, forming salt lakes.

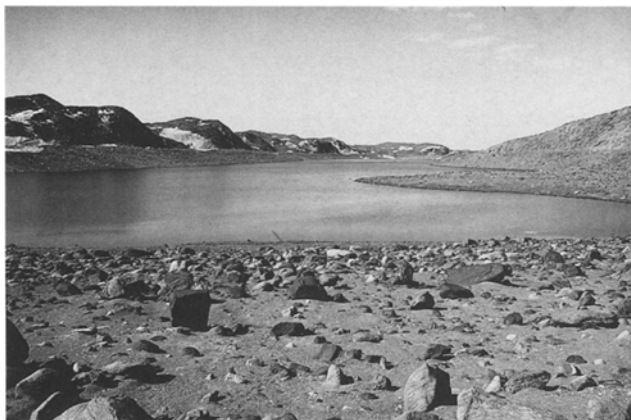


Figure 3. Boulder tills that contains marine carbonate, and fossiliferous marine terraces (high areas in background), Vestfold Hills, East Antarctica. Scale not recorded.



Figure 4. Exposure of lacustrine sediments deposited on the northern shoreline of Radok Lake (Fig. 1). The lacustrine sediments are laminated with silty clay and fine sand with dropstone couplets, grading to massive silty clays with interbedded layers aragonitic sediments, up to 15 mm thick. The lacustrine sediments were eroded from the base of Radok Lake.

Radok Lake is the deepest known proglacial water body in East Antarctica (Fig. 1D) and is located in the Amery Oasis in the northern Prince Charles Mountains (Fig. 4). It has been glacially carved to a depth of more than 350 m (Bardin et al. 1990). The lake is freshwater and isothermal, and is supplied by meltwater from the Battye Alpine Glacier. During some Quaternary glacials, Radok Lake was overridden by an outlet glacier ice stream of the Lambert Glacier system. The dates of these events are unknown. Radok Lake drains via an outlet, at 13 m above present sea level, into the fluvial Pagodroma Gorge and then into the epishelf Beaver Lake. Carbonate layers were observed above siliciclastic laminites in glacio-lacustrine sediments 10 m above the present northern shoreline of the lake.

METHODS OF STUDY

The Prydz Bay samples studied are grab samples at water depths ranging from 0 to about 200 m in the inner shelf and banks. Samples are also obtained from a 0.6 m long core (with samples at about 25 mm intervals) in 134 m water depth. Carbonate gravel, sand and mud and fauna were collected during reconnaissance studies around coastal areas at the Vestfold Hills (Fig. 1), in the Løken Moraines, the Budd Coast and in Radok Lake, Northern Prince Charles Mountains. Petrographic studies were made from thin sections of grab and core material from Prydz Bay, the Vestfold Hills, the Løken Moraines and Radok Lake. X-ray diffraction analyses were made on biota and bulk carbonates for Prydz Bay (Rao et al. 1996) and for the bulk carbonates from the Vestfold Hills, the Løken Moraines and Radok Lake. Skeletal fragments and bulk carbonates were reacted with 100% anhydrous H_3PO_4 at 25°C. The evolved CO_2 gas was analyzed by a VG SIRA series II mass-spectrometer at the University of Tasmania for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, the values being expressed in conventional per mil

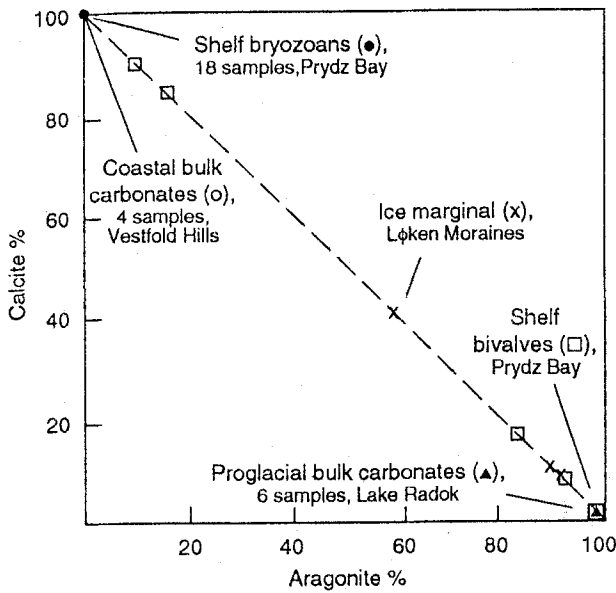


Figure 5. Calcite and aragonite percents of East Antarctic carbonates determined from peak area ratios from X-ray diffractograms. Note shelf carbonates from Prydz Bay and coastal carbonates from Vestfold Hills are mainly calcitic, whereas ice marginal carbonates from Løken Moraines and proglacial carbonates from Lake Radok are aragonitic.

notation relative to the PDB standard. The precision of data, established from duplicate analysis, is $\pm 0.1\%$ for both O and C.

CARBONATE MINERALOGY AND SEDIMENTOLOGY

X-ray diffractometric analyses of Prydz Bay bryozoans indicate that these are calcites with a predominance of low-Mg calcite, whereas bivalve molluscs are aragonite with variable amounts of calcite up to 90% (Fig. 5). Coastal skeletal carbonates from the Vestfold Hills are entirely low-Mg calcite

Table 1. Major characteristics of polar carbonates from Prydz Bay, Vestfold Hills, Løken Moraines and Radok Lake, East Antarctica.

Parameter	Prydz Bay	Vestfold Hills	Løken Moraines, Budd Coast	Radok Lake, Prince Charles Mountains
Depositional environments	Shelf (0 to 800m) to bank (~200m)	Coastal marine	Ice marginal marine	Deep lake, non-marine
Associated sediments	Mainly muds and minor sands	Boulder till, skeletons and calcareous soils	Diamictite	Muds and fine sands
Salinity ‰ (*from $\delta^{18}O$ ‰ composition of carbonate)	33.9 to 35.4	29 to 33.5* up to 250	9 to 25*	0
Water temperatures °C	-1.9	0	0	0
Carbonate mineralogy	Mainly low-Mg calcite	Mainly low-Mg calcite	Mainly aragonite	Aragonite
Non-skeletal grains	Rare	Intraclasts & oncolites	Ooids, grapestones, intraclasts	Intraclasts
Cements	None	Common	Abundant	Abundant
Flora	Diatoms and minor algae	Calcareous algae and microbial mats and stromatolites and oncolites	Rare	Microbial mats
Fauna	Siliceous sponges, bryozoans, barnacles, bivalves and echinoderms	Bivalves, siliceous sponges, and foraminifera	Rare	None
Dolomites	None	None	None	None
Evaporites	None	Common: halite, sylvite, thenardite and gypsum	None	Rare
$\delta^{18}O$ ‰ PDB of carbonates	2 to 5	1.5 to 3	-9 to -14	-33 to -34
$\delta^{13}C$ ‰ PDB of carbonates	-2 to 2	0.5 to 2	-8 to -9	1 to 2

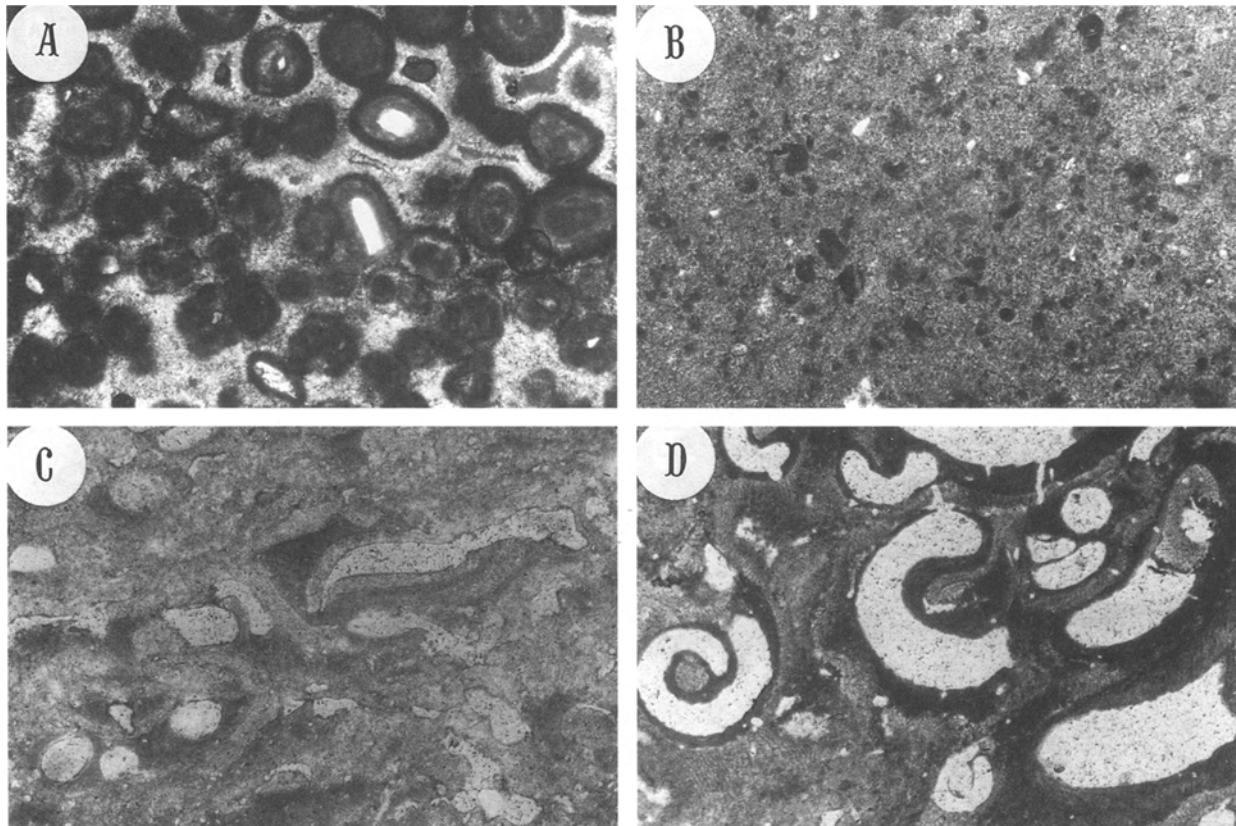
(Fig. 5). Non-skeletal carbonates in the Løken Moraines are mainly aragonites with minor calcite (Fig. 5), whereas those from Radok Lake are entirely aragonite. Since bulk carbonates from Løken Moraines and Radok Lake are mainly aragonitic, the abundant non-skeletal grains in them are inferred to be mainly made of aragonite.

Major characteristics of polar carbonates from Prydz Bay, the Vestfold Hills, the Løken Moraines and Radok Lake are summarized in Table 1. These polar carbonates formed in shelf, bank, coastal and ice marginal and deep lake depositional environments. They are associated with glaciogene muds, fine sands, boulder tills and diamictites. The measured seawater temperatures are -1.9°C , whereas coastal to lake-water temperatures are around 0°C in summer and much cooler than shelf water temperatures in winter. There is a distinct change in carbonate mineralogy from calcite to aragonite from marine to brackish and freshwater carbonates (Table 1). Shelf sediments are uncemented, whereas sparry

calcite intragranular cementation is common in coastal sediments, and isopachous aragonite cementation is abundant in inland brackish to freshwater carbonates. Dolomites are not detected in X-ray diffractograms of the polar carbonates studied. Evaporites are absent in shelf to bank environments, but in the form of halite (NaCl), sylvite (KCl), thenardite (Na_2SO_4) and gypsum (CaSO_4), they are widespread in coastal sediments from the Vestfold Hills (Gore et al. 1996).

Petrographic counts of relative percentages of biota from the Prydz Bay shelf carbonates indicate that the biota is mainly in gravel (mean 51%) but some is in coarse sand (mean 25%) and sand fractions (Rao et al. 1995). The type of biota generally depends on the grain size of the sediment (Rao 1996). The gravel fraction mainly contains sponges and bivalves with minor echinoderms and worm tubes. The coarse sand comprises sponges, diatoms, foraminifera, bryozoans and minor bivalves. The sand fraction comprises a variety of biota, dominated by sponges, foraminifera, diatoms and bryozoans,

Figure 6. Photomicrographs of lithified carbonates from East Antarctica in plain polarised light. Scale in microns. (A) Ooids and fibrous aragonite cements in carbonates from Løken Moraines, East Antarctica. Ooid nuclei compose angular quartz and micritic intraclasts. (B) Micrite with peloids (dark circular areas) from proglacial Radok Lake, East Antarctica. (C) Coralline algae with interparticle calcite cement, Vestfold Hills, East Antarctica. Note the sample is heavily bored, and some bores are empty while others are filled by calcite cement. (D) Serpulid worm tubes in micrite. Note most worm tubes occur as molds due to dissolution of formerly aragonitic shells.



250 μm

with minor amounts of echinoderms, bivalves and ostracodes. The variation of these biota, in different grain-size fractions, is unrelated to water depth, because these fauna are aphotic organisms and are living or lived in depths of a few meters to about 1000 m. The ^{14}C dates of bivalves and foraminifera, corrected for reservoir effects, range from 140 to 2470 year BP for grab carbonate samples and between 4314 and 8030 year BP for two core bulk carbonate samples (Harris et al. 1996). These dates confirm that the fauna lived during the Late Holocene.

Non-skeletal grains and cements are abundant in ice marginal polar East Antarctic carbonates from the Løken Moraines (Fig. 6A). Non-skeletal grains are mainly aragonitic ooids (Fig. 6A) along with peloids; aragonite (Figs. 6) isopachous cements (Fig. 6A). Abundant aragonite micrite with some peloids (Fig. 6B) occurs in proglacial carbonates from Radok Lake. The chemistry of the Radok Lake water is alkaline with a pH of ~8 and $(\text{Ca}+\text{Mg})(\text{HCO}_3)_2$ of about 64 mg/l.

Extensive deposits of marine carbonates occur in the Vestfold Hills. This material, which was not reported by Pickard et al. (1986) in previous studies of the fossils of the region, is found associated with many of the marine terraces (Fig. 2). The carbonate material is generally present as relatively thin (up to *circa* 10 mm) shards lying on the surface of the terraces and on the downslope from the terraces to the relict marine lakes. Coralline algae occur in coastal carbonates from the Vestfold Hills (Fig. 6C). These rocks are extensively bored and these borings are either empty or filled by sparry calcite. Formerly aragonitic serpulid tubes are present in coastal carbonates (Fig. 6D), which are partially or completely dissolved. The moulds of these are empty (Fig. 6D). These carbonates from Vestfold Hill formed between 6,000 to 8000 BP, based on ^{14}C values.

OXYGEN AND CARBON ISOTOPES

The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data on skeletons from Prydz Bay (Rao et al. 1996), from the Vestfold Hills, the Løken Moraines, Radok Lake and other shelf localities (donated by Domack) in Antarctica are listed in Table 2. The East Antarctic polar carbonates show a wide range of $\delta^{18}\text{O}$ (-47 to 4.5‰ PDB) and $\delta^{13}\text{C}$ (-9 to 8‰ PDB) values (Fig. 7). The most positive $\delta^{18}\text{O}$ values (2.4 to 4.5‰ PDB) are from shelf calcitic fauna (Figs. 7 and 8). The $\delta^{18}\text{O}$ values progressively decrease from shelf carbonates to the coastal bulk calcitic carbonates of the Vestfold Hills (1.6 to 3‰ PDB), deep inner shelf calcitic benthic foraminifera (4 to -16‰), ice marginal bulk aragonitic carbonates in Løken Moraines (-11.3 to -10‰ PDB) and Radok Lake (-33.5 to -33‰ PDB) and interior Pleistocene subglacial aragonitic bulk carbonates from the Vestfold Hills (-47 to -43‰ PDB; Aharon 1988). The $\delta^{18}\text{O}$ values (-39 to -23‰ PDB) of aragonitic Pleistocene proglacial bulk carbonates from Taylor Valley, East Antarctica (Hendy et al. 1979) overlap those of proglacial aragonite bulk carbonates from Radok Lake (Fig. 7; Hendy et al. 1979). The

most positive $\delta^{13}\text{C}$ values (up to 8‰ PDB) are from Pleistocene proglacial aragonitic bulk carbonates from the Taylor Valley (Fig. 7) and the most negative $\delta^{13}\text{C}$ values (-8.7 to -8‰ PDB) are from ice marginal aragonitic bulk carbonates in the Løken Moraines (Fig. 7). The $\delta^{13}\text{C}$ values of deep inner shelf benthic foraminifera (0.2 to -6.1‰ PDB) and shelf carbonates (-2 to 2‰ PDB) are more variable than those in coastal calcitic bulk carbonates (0.4 to 1.8‰ PDB) from the Vestfold Hills (Figs. 7 and 8). The $\delta^{13}\text{C}$ values in Pleistocene subglacial aragonitic bulk carbonates are low (-3 to -4.2‰ PDB; Aharon 1988).

DISCUSSION

The characteristics of polar carbonates (Table 2) are related to: (1) water temperatures, (2) carbonate mineralogy, (3) biochemical fractionation, (4) salinity, (5) meltwater dilution, (6) ^{18}O in water, (7) $\delta^{13}\text{C}$ in water, in atmospheric CO_2 and in CO_2 trapped in Antarctic glaciers and (8) environments of carbonate formation.

Water Temperatures

Seawater temperatures on the Prydz Bay shelf are uniform and close to -1.9°C. Seawater freezes at temperatures below -2°C at normal salinities of about 34‰ and forms sea ice. The freezing of seawater is prevented at temperatures below -2°C by increasing salinity. Hypersaline lake waters in Antarctica have temperatures down to -20°C because their salinities are high and commonly range up to about 250‰ (Ferris and Burton 1988). Temperatures of freshwater, released from the melting of glaciers and snow, are around 0°C. Therefore, polar carbonates form from meltwaters at water temperatures of around 0°C.

The fauna in Antarctic shelf environments differs from tropical equivalents by the absence of corals, which are abundant in seawater temperatures ~25°C. The polar occurrence of bryozoans and foraminifera is similar to that in temperate carbonates of southern Australia, which are forming at surface seawater temperatures from 12 to 24°C. The Prydz Bay shelf fauna is dominated by siliceous sponges, which occur in minor amounts in temperate and tropical carbonates (Rao 1996). The alga *Halimeda*, abundant in tropical Great Barrier Reef and elsewhere, is absent in East Antarctic carbonates. However, calcareous algae, abundant in the tropical carbonates, do occur in East Antarctic coastal carbonates. In northern polar regions with appreciable meltwater dilution, calcareous algae are abundant in shallow depths of about 7 m (Freiwald 1993; Freiwald and Henrich 1994).

Non-skeletal grains, such as ooids and peloids, found in Antarctic polar carbonates are unusual, because these grains are mainly observed in the tropical marine environments, where the seawater temperatures are greater than 25°C and the water is more saline (salinity >38‰). Freshwater ooids

Table 2. Oxygen and carbon isotopes of East Antarctic carbonates and carbon isotopes of water at Vestfold Hills.

LOCALITY			OXYGEN AND CARBON ISOTOPES						MINERALOGY								
Sample No	Depth, m		Bulk sediment	Brachiopods	Bivalves	Bryozoans	Forams	Bulk sediments	Bryozoans	Bivalves							
			$\delta^{18}\text{O}$	$\delta^{18}\text{O}$	$\delta^{16}\text{O}$	$\delta^{18}\text{O}$	$\delta^{18}\text{O}$	Aragonite%	$\delta^{18}\text{O}$	$\delta^{16}\text{O}$	$\delta^{13}\text{C}$	Aragonite%	Calcite%	Aragonite%	Calcite%	Calcite%	
Prydz Bay shelf carbonates																	
93099	Grab 98																
93031C	Grab 101										3.897						
93035	Grab 98										3.933						
93036 A	Grab 69										4.122						
93037	Grab 95										4.132						
93038C	Grab 110										3.958					100	
93040	Grab 95										3.865						
93058	Grab 38										3.945						
93099	Grab 26										3.72						
93102	Grab 21										3.56						
93103	Grab 21										-0.169						
93104	Grab 33										2.858						
93108	Grab 90										3.985					93	
93132	Grab 76										3.529						
JMW3	Grab 5										3.34						
JMW6	Grab 5										4.022						
Bivalve 1	Grab 0										3.991						
Bivalve 2	Grab 0										-0.03						
Bivalve 3	Grab 0																
Bivalve 4	Grab 0																
Bivalve 5	Grab 0																
Bivalve 6	Grab 0																
Bivalve Lat 1	Grab 0																
Bivalve Lat 2	Grab 0																
Bivalve Lat 3	Grab 0																
Bivalve Lat 4	Grab 0																
Gco3-12.5cm	Core 134										3.462						
Gco3-15cm	Core 134										1.072						
Gco3-17.5cm	Core 134										3.682						
Gco3-20cm	Core 134										3.676						
Gco3-22.5cm	Core 134										3.644						
Gco3-25cm	Core 134										0.353						
Gco3-27.5cm	Core 134										3.613						
Gco3-30cm	Core 134										3.572						
Gco3-32.5cm	Core 134										3.582						
Gco3-35cm	Core 134										3.614						
Gco3-37.5cm	Core 134										0.82						
Gco3-40cm	Core 134										3.717						
Gco3-42.5cm	Core 134										0.604						
Gco3-45cm	Core 134										3.636						
Gco3-47.5cm	Core 134										0.933						
Gco3-50cm	Core 134										3.651						
Gco3-52.5cm	Core 134										0.435						
Gco3-55cm	Core 134										3.696						
Gco3-57.5cm	Core 134										-0.039						
Other shelf skeletal carbonates (given by Domack, 1992)																	
	1. gravel size		3.5														
	2. sand size		-0.06														
	3. gravel size		3.8														
	4. sand size		0														
	5. Fauna		4														
	6. Fauna		3.7														
	7. Fauna		0.1														
	8. Micrite		4.5														
			1.2														
			2.5														
			2.7														
			-1.4														
			-1.7														
			-0.1														

Table 2. Oxygen and carbon isotopes of East Antarctic carbonates and carbon isotopes of water at Vestfold Hills (continued).

5. Worm tubes	2.9	-0.1								
Vestfold Hills coastal biotic carbonates										
1. Litled carbonate	1.6	0.6					0		100	
2. Litled carbonate	2.8	1.9					0		100	
3. Litled carbonate	2.2	0.4					0		100	
4. Litled carbonate	3.1	1					0		100	
Loken Moraine carbonates with aragonite oolites and isopachous aragonite cements										
1. sand size	-11.2	-8.2					100		0	
2. sand size	-11	-8.2					100		0	
3. sand size	-11.3	-8.5					60		40	
4. sand size	-10.5	-8.1					92		8	
5. sand size	-11	-8					93		7	
6. sand size	-11.1	-8.6					98		2	
7. sand size	-9.5	-8.5								
8. sand size	-10.7	-8.7								
Radok Lake carbonates with aragonite micrite and intraclasts										
1. micritic	-33.3	2.1					100		0	
2. micritic	-33.3	1.3					100		0	
3. micritic	-33.4	1.5					100		0	
4. micritic	-33.4	1.5					100		0	
5. micritic	-33.2	1.5					100		0	
6. micritic	-33.4	1.7					100		0	

occur in the temperate settings of Tasmania (Rao 1983), and these are composed of low-Mg calcite. As discussed below, these polar non-skeletal grains occur in brackish to fresh waters and are absent in marine shelf waters.

The occurrence of carbonate cementation in Antarctic polar carbonates confirms that it occurs in tropical, temperate and polar environments (Rao 1996). The dominance of low-Mg calcite in Prydz Bay shelf carbonates is in conformity with experimental data (Kinsman and Holland 1969; Mucci 1987; Burton and Walter 1991) and mineralogy of biota (Lowenstam 1954; Chave 1954; Morse and MacKenzie 1990) that show the decrease of aragonite content and increase of low-Mg calcite with decreasing seawater temperatures. However, aragonite dominates in carbonates from Radok Lake, the Løken Moraines and Pleistocene subglacial carbonates (Aharon 1988; Gore et al. 1996) and in proglacial lacustrine carbonates (Hendy et al. 1979). As explained below, these aragonitic carbonates have formed and are forming in brackish to fresh waters.

Carbonate mineralogy

$\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in carbonate vary depending on the carbonate minerals present. The Antarctic carbonates studied are mainly low-Mg calcite and aragonite. The enrichment of $\delta^{18}\text{O}$ in aragonite relative to low-Mg calcite is 0.6‰ (Tarutani et al. 1969); whereas $\delta^{13}\text{C}$ enrichment in aragonite relative to low-Mg calcite is 1.7‰ (Rubinston and Clayton 1969). Since the East Antarctic polar carbonates show a wide range of $\delta^{18}\text{O}$ (-47 to 4.5‰ PDB) and $\delta^{13}\text{C}$ (-9 to 8‰ PDB) values (Fig. 8), the effect of carbonate mineralogy on $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of these carbonates is small.

Biochemical fractionation

The biochemical fraction of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ depends on metabolic effects (photosynthesis and respiration) and kinetic fractionation, which is common in tropical biota and minor in temperate and polar biota (Rao 1996). The biochemical fractionation is characterized by strong depletion in $\delta^{13}\text{C}$ than $\delta^{18}\text{O}$ values relative to equilibrium values (McConaughy 1989), unlike strong depletion in $\delta^{18}\text{O}$ values than $\delta^{13}\text{C}$ values. Instead $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of Antarctic carbonates studied, as explained below, are in equilibrium with $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in seawater and their exposure to atmospheric CO_2 .

Salinity

Unlike the small temperature range of 2°C in Antarctic water, the salinity in Antarctic waters varies markedly between 250‰ and 0‰ (Ferris and Burton 1988). The salinities higher than seawater occur in lakes because Antarctica is the driest continent, where evaporation far exceeds precipitation. Antarctic shelf waters have a salinity of about 34‰, which is about 1‰ lower than temperate and tropical shelf waters. The lowest salinities are due to the influx of meltwater from

SHELF, COASTAL AND SUBGLACIAL POLAR CARBONATES, EAST ANTARCTICA

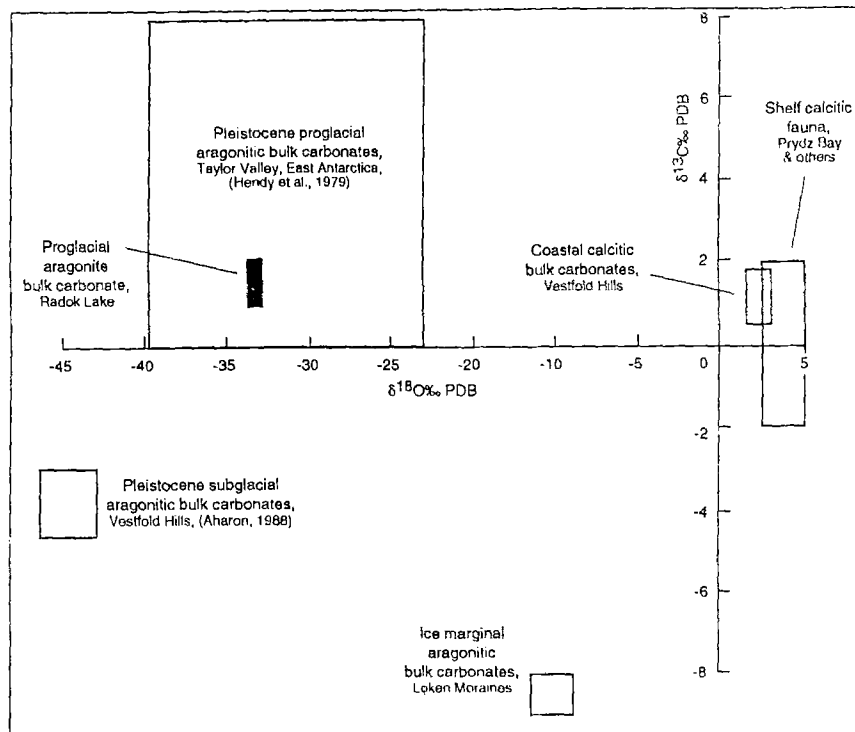


Figure 7. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ compositions of East Antarctic carbonates.

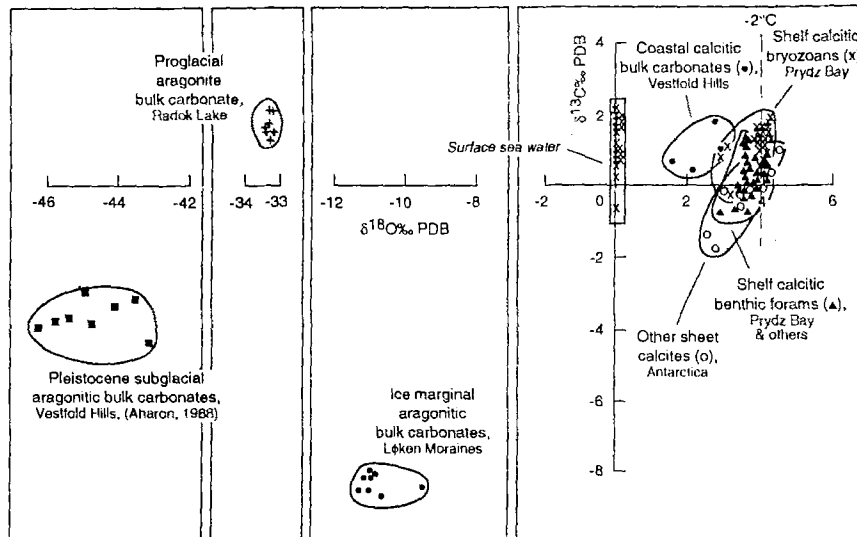


Figure 8. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of calcitic bryozoans and foraminifera from shallow Prydz Bay and other shelf areas (<200m), coastal calcitic bulk carbonates, Vestfold Hills, ice marginal aragonitic bulk carbonates, Løken Moraines, proglacial aragonite bulk carbonates from Radok Lake and Pleistocene subglacial aragonitic bulk carbonates, Vestfold Hills and $\delta^{13}\text{C}$ values in surface seawater near Vestfold Hills.

glaciers and some snow during summer, and the melting of Pleistocene coastal to submarine grounded glaciers during their retreat to the interior land. The Radok Lake water salinity is 0‰ as its source meltwater is supplied by the Battye Glacier.

Meltwater Dilution

The amount of meltwater dilution can be determined by the

salinities of mixing waters. The salinity difference of 1.5‰ in surface seawater at Prydz Bay (Table 1) is due to the addition of about 4% meltwater into the shallow sea. Water with 0‰ salinity, such as in the Radok Lake, is due to the sole meltwater insource. The amount of meltwater dilution can also be estimated from ^{18}O values in waters and carbonates, as explained below.

$\delta^{18}\text{O}$ in Waters

The Antarctic seawater ^{18}O values range from 0 to -1‰ SMOW (Jacobs et al. 1985), whereas East Antarctic meltwaters range from -10 to -55‰ SMOW (Fig. 9; Hendy et al. 1979; Morgan 1982). A similar range of ^{18}O values in meltwaters is observed from other parts of Antarctica (Matsubaya et al. 1979). The amount of meltwater dilution can be determined by the variation of ^{18}O values of waters from the mixing lines drawn from ^{18}O values of mean ocean water (0‰ SMOW) and meltwaters from different glaciers and ice masses, such as those from the Law Dome ice cap (-22 to -27‰ SMOW; Morgan 1982), the Amery Ice Shelf ($\sim -40\text{‰}$ SMOW; Morgan 1982) and the ice sheet interior ($\sim -50\text{‰}$ SMOW; Morgan 1982; Fig. 9). In order to calculate the amount of meltwater during the formation of carbonates, East Antarctic carbonate $\delta^{18}\text{O}$ values were converted to δw SMOW values, using the equation of Craig (1965) and the carbonate-water ^{18}O fractionation factor of 34.8 at 0°C (Rao and Green 1982). These calculations indicate: the Prydz Bay shelf waters were diluted by 0 to 7% meltwater, which is similar to the estimate of 4% average meltwater dilution from measured salinity difference in these waters; Vestfold Hills coastal waters were diluted by 2 to 14% meltwater; the Løken Moraine waters were diluted by 26 to 72% meltwater; and Radok lake waters were produced from 100% meltwater (Fig. 9). Therefore, calcitic carbonates from Prydz Bay shelf and Vestfold coastal areas have formed in near normal seawaters, whereas aragonitic carbonates from the Løken Moraines and Radok Lake have formed in brackish and freshwater, respectively.

Water temperatures can be calculated from the calcite-water

temperature relationship of Anderson and Arthur (1983):

$$T^\circ\text{C} = 16.0 - 4.14 (\delta_c - \delta_w) + 0.13 (\delta_c - \delta_w)^2$$

where δ_c is the isotopic composition of the calcite sample (relative to PDB) and δ_w is the oxygen isotopic composition of the water (relative to SMOW) in which the carbonate formed. The $\delta^{18}\text{O}$ values (4.5 to -47‰ PDB) of East Antarctic carbonates substituted in the above ^{18}O thermometry equation, using the seawater ^{18}O value of 0‰ SMOW, give abnormal temperatures ranging from -2°C to 498°C due to mixing of water masses. Only some carbonate $\delta^{18}\text{O}$ values, particularly those of bryozoans from Prydz Bay and other shelf areas, are close to -2°C shelf water temperatures (Fig. 8). The majority of carbonate $\delta^{18}\text{O}$ values give warmer temperatures, up to 498°C , because most East Antarctic carbonates are affected by meltwater dilution (Fig. 9). Ancient polar carbonates also gave warmer temperatures, up to 131°C , because they were affected by meltwaters (Rao and Green 1982; Rao 1988). These anomalous temperatures are due to meltwater dilution that reduces the ^{18}O values in the water.

The ^{18}O values in Antarctic waters vary with the salinity of water (Fig. 8). The ^{18}O values at similar salinities differ because of variation in the ^{18}O values of meltwaters. Therefore, the $\delta^{18}\text{O}$ values of carbonates from Antarctica vary with salinity, ^{18}O of meltwaters and water temperatures (Fig. 10). Since temperature variation is small in Antarctic waters, the $\delta^{18}\text{O}$ values of carbonates mainly depend on salinity of waters. The same $\delta^{18}\text{O}$ values of carbonates indicate higher salinities with increasing ^{18}O values of meltwaters (Fig. 8). The $\delta^{18}\text{O}$ values of carbonates also depend on carbonate mineralogy, with aragonite $\delta^{18}\text{O}$ values being 0.6‰ higher

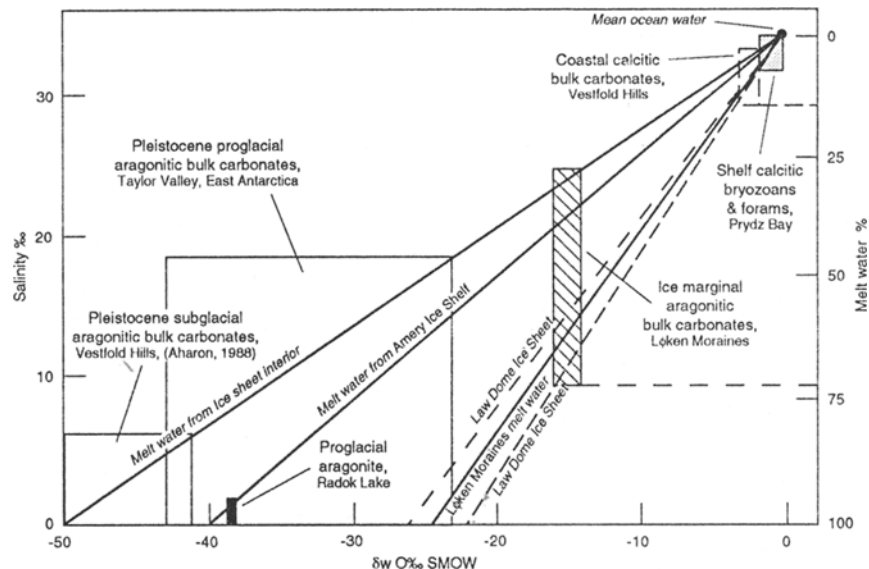


Figure 9. Meltwater dilution in polar environments, deduced from ^{18}O values of mean ocean water (0‰ SMOW) and ^{18}O values of meltwaters from coast to interior areas (-22 to -50‰ SMOW). The ^{18}O values of water in equilibrium with carbonates, calculated from carbonate-water ^{18}O fractionation at 0°C , indicate meltwater dilution ranging from 0 to 100% during the formation of East Antarctic carbonates. Note that most East Antarctic carbonates were affected by meltwater dilution.

SHELF, COASTAL AND SUBGLACIAL POLAR CARBONATES, EAST ANTARCTICA

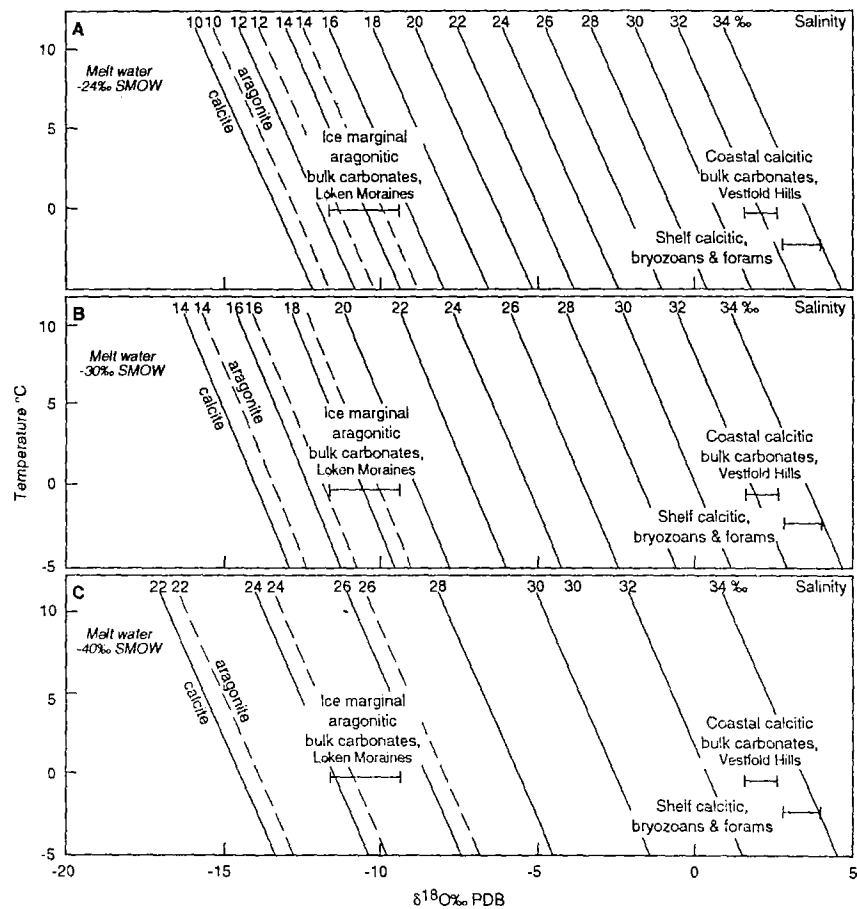


Figure 10. Variation of $\delta^{18}\text{O}$ values in carbonates related to water temperature, salinity and carbonate mineralogy corresponding to ^{18}O values of meltwater of -24‰ SMOW (A), -30‰ SMOW (B) and -40‰ SMOW (C). This diagram is drawn considering $\delta^{18}\text{O}$ values of carbonates, ^{18}O thermometry, ^{18}O values of seawater diluted by meltwaters ranging in ^{18}O from -24‰ , -30‰ and -40‰ , and enrichment factor of 0.6 in $\delta^{18}\text{O}$ between calcite and aragonite. Note variations in water temperatures are small, whereas variations in salinities are large in polar carbonates.

than calcite values (Tarutani et al. 1969). These relationships can be extended to ancient polar carbonates by determining the ^{18}O of meltwater from freshwater cements, deducing carbonate mineralogy from carbonate crystal morphology (Rao 1981) and determining the $\delta^{18}\text{O}$ of marine components, such as fossils and marine cements (Rao and Green 1982; Rao 1988).

$\delta^{13}\text{C}$ in Waters

The $\delta^{13}\text{C}$ values in Antarctic waters vary considerably (Fig. 11). The $\delta^{13}\text{C}$ values measured in 19 shelf seawaters (1.1, 0.9, 1.0, -0.3, 0.6, 0.9, 0.9, 0.8, 1.2, 1, 0.6, 1.1, 1.7, 2.1, 2.0, 2.2, 1.8, 2.2, 1.9; all in ‰ PDB) near the Vestfold Hills range from -0.3 to 2.3‰ PDB, with an average value of 1.3‰ PDB (Fig. 8). The deep Antarctic seawater $\delta^{13}\text{C}$ values are around 0 to 0.5‰ PDB (Kroopnick 1985). The wide range of $\delta^{13}\text{C}$ values in the shelf waters around Antarctica are due to advection and mixing of deep water with shelf waters and photosynthetic activity. The $\delta^{13}\text{C}$ values of meltwaters depend on the $\delta^{13}\text{C}$ in CO_2 trapped in glaciers (Leuenberger et al. 1992; Marino et al. 1992), that range from -6.5‰ PDB (present) to -7.5‰ PDB

(Pleistocene), and the $\delta^{13}\text{C}$ values in the atmosphere, which are similar to those stored in present and Pleistocene glaciers.

The $\delta^{13}\text{C}$ values in biotic and abiotic carbonates depend on $\delta^{13}\text{C}$ in seawater, meltwater, atmosphere, temperature, biochemical fractionation, and carbonate mineralogy (Rao 1996). The marine biotic calcite in equilibrium with atmospheric CO_2 in surface shelf waters at 0°C will be around 5.1‰ PDB (Rao 1993). The maximum $\delta^{13}\text{C}$ value in Antarctic shelf carbonates is 2.1‰ PDB, which is lower than equilibrium value of 5.1‰ PDB, due to the strong mixing of surface waters with deep water. In Prydz Bay, physical oceanographic evidence suggests the operation of a large cyclonic effect, called the Prydz Bay Gyre (Smith et al. 1984), which affects the distribution of fauna and sediment types (Franklin 1993). Marine calcitic carbonates around Antarctica are observed to be preserved in areas of strong upwelling (Domack 1988; Taviani et al. 1993). In contrast to marine carbonates, the $\delta^{13}\text{C}$ values in brackish to freshwater aragonitic carbonates are highly variable, ranging from -9 to 8‰ PDB (Fig. 11). The maximum $\delta^{13}\text{C}$ value of 8‰ , observed in proglacial aragonite from the Taylor Valley,

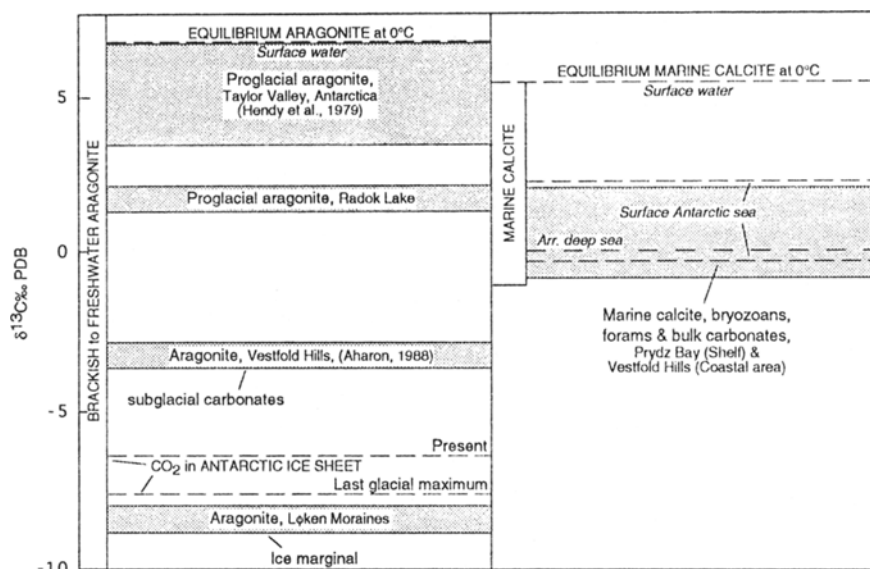


Figure 11. The variation of $\delta^{13}\text{C}$ values in marine calcite and brackish to freshwater aragonite in East Antarctic carbonates. Note $\delta^{13}\text{C}$ values range from those expected at 0°C equilibrium with -7.2‰ $\delta^{13}\text{C}$ in atmospheric CO_2 to lower values due to circulation of water masses and reaction with $\delta^{13}\text{C}$ in CO_2 trapped in glaciers. See text for details.

Antarctica (Hendy et al. 1979), is similar to that expected in aragonite in equilibrium with the $\delta^{13}\text{C}$ in atmosphere, where CO_2 value is -7.2‰ PDB at 0°C (Rao 1993). The $\delta^{13}\text{C}$ values in aragonite from proglacial lacustrine deposits in Radok Lake, subglacial deposits exposed in the Vestfold Hills and ice marginal deposits in the Løken Moraines are due to the formation of aragonite primarily in local meltwaters that have $\delta^{13}\text{C}$ values down to -7.5‰ PDB. The minimum $\delta^{13}\text{C}$ values observed in the Løken Moraines are due to the strong reaction with meltwaters that were locally cut off from atmosphere, such as those occurring close to the grounding zone in ice marginal environments.

Environments of Carbonate Formation

During glacial stages, such as the Last Glacial Maximum, the Antarctic ice sheet margins expanded onto the inner shelves, together with expanded ice shelves (Fig. 12A). The extent of ice expansion is inferred from relict diamictites in the inner shelf and meltwater dilution of bank carbonates (Rao 1996; this study). At this time carbonate banks occurred in Prydz Bay and other parts of Antarctica (Domack 1988; Taviani et al. 1993). Some of these carbonates were transported on to the outer shelf slopes by turbidity currents (Domack 1988; Rao 1996). During interglacial stages, the ice-sheet margins retreated and released large volumes of meltwater at water depths $>200\text{m}$ (Rao 1996). This shifted the $\delta^{18}\text{O}$ values from 4.5‰ PDB to -14‰ PDB and the $\delta^{13}\text{C}$ values to -6‰ PDB in the deep inner shelf (200 to 1000 m water depth; Fig. 7) benthic foraminifera, relative to shallow marine benthic foraminifera, due to strong meltwater dilution. These values may also be due to differences in the palaeoecology and environmental conditions under which the fauna were living

in the deep inner shelf troughs .

During the retreat, ice-sheet margins exposed some large coastal ice-free areas known as 'oases' (Fig. 12C), such as at the Vestfold Hills. These arid sites experienced high evaporation relative to precipitation, which led to the formation of evaporites and carbonates in lakes in the Vestfold Hills (Gore et al. 1996). At this time, carbonates also formed in coastal and proglacial lakes (Radok Lake), proximal to distal proglacial lakes in the Taylor Valley and McMudo 'Dry Valley' region subglacial environments. At the Vestfold Hills, coastal algal and skeletal carbonates formed when a marine transgression occurred during the mid-Holocene. These calcitic carbonates are now exposed, as a result of isostatic uplift and relative sea-level lowering. Radok Lake aragonitic carbonates formed from alkaline meltwaters, fed by an alpine glacier. The Taylor Valley algal carbonates formed from meltwaters derived from the East Antarctic ice sheet, about 30 km beyond the present terminus of the Taylor Glacier (Hendy et al. 1979). Cemented carbonates from the Vestfold Hills formed subglacially in distal inland areas (Aharon 1988).

Along the Budd Coast, the expanded Law Dome ice sheet, retreated from the inner shelf grounding line (Fig. 12B) during the early to mid Holocene. At this time, aragonite ooids, non-skeletal grains and cements formed in brackish waters, as a result of the mixing of up to 72% meltwaters with seawater. These calcareous sediments were later reworked by an ice sheet expansion with the deposition in the Løken Moraines.

SHELF, COASTAL AND SUBGLACIAL POLAR CARBONATES, EAST ANTARCTICA

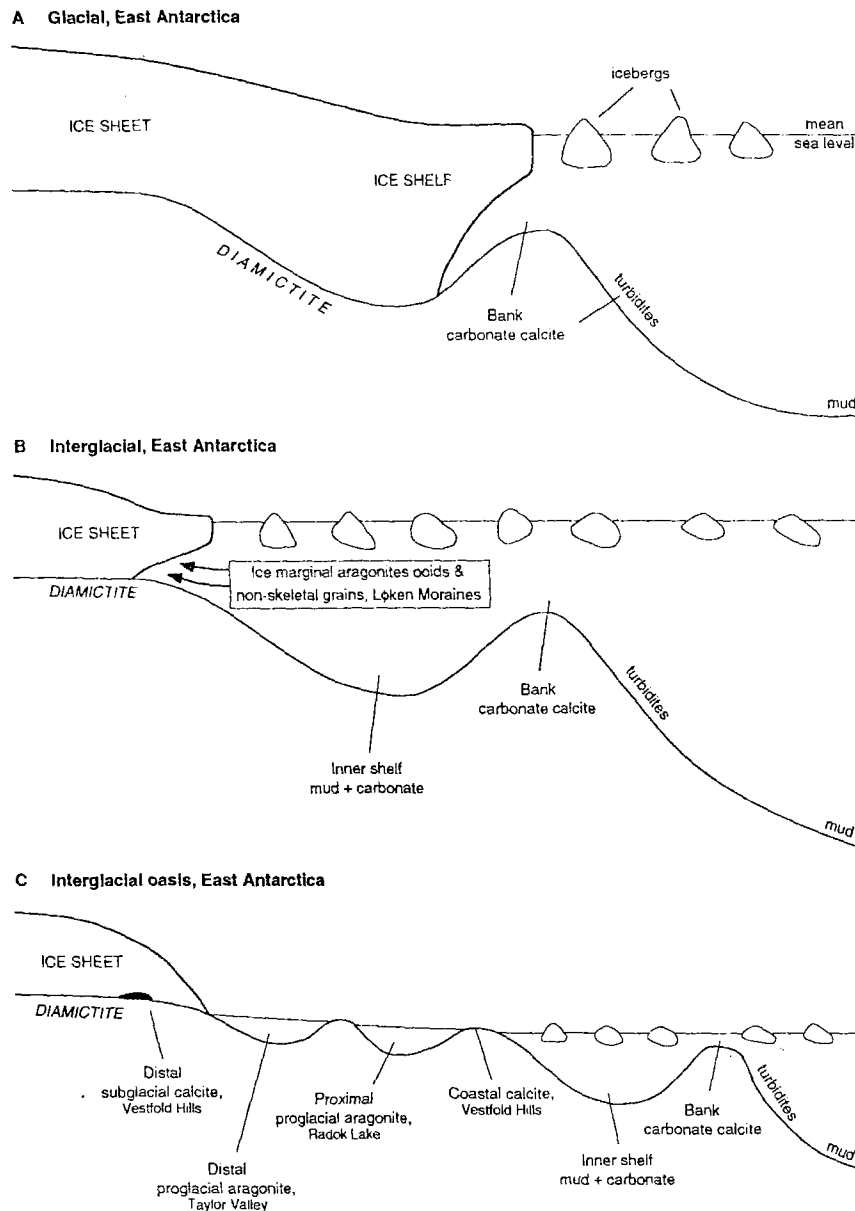


Figure 12. Three scenarios during the formation of East Antarctic carbonates. (A) Glacial stages, corresponding to extension of ice sheet with ice shelves into inner shelves and formation of bank and turbidite carbonates. (B) Interglacial stages with ice marginal, bank carbonates and carbonates associated with inner shelf muds. (C) Interglacial oasis with distal subglacial carbonates, proximal and distal proglacial carbonates, coastal and bank carbonates and carbonates associated with inner shelf muds.

CONCLUSIONS

Modern and Pleistocene shelf, coastal, lacustrine and inland polar modern and Pleistocene carbonates occur in East Antarctica and are associated mainly with glaciogene muds, boulder tills and diamictites. These carbonates differ in the type of biota, non-skeletal grains, cements, carbonate mineralogy, and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values.

Shelf carbonates are mainly unlithified bioclastic accumulations comprising sponges, bryozoans, foraminifera, bivalves and echinoderms. Coastal carbonate skeletons are similar to those in shelf carbonates, but contain calcareous algae,

microbial mats and minor stromatolites. Subglacial and ice marginal carbonates contain mainly inorganic components, such as ooids, peloids and cements. Shelf and coastal carbonates are mainly calcitic, whereas subglacial lacustrine and ice marginal carbonates are aragonitic. This carbonate mineralogy coincides with the change from marine through brackish to freshwater.

$\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values vary markedly. The most positive $\delta^{18}\text{O}$ values are due to the frigid temperatures (-1.9°C), whereas all other lower values are due to the decrease in salinity as a result of meltwater dilution. The $\delta^{13}\text{C}$ values are related to carbonate mineralogy, exposure to atmospheric CO_2 , the circulation of

water masses and the reaction with $\delta^{13}\text{C}$ in CO_2 trapped in glaciers.

During glacial stages, the Antarctic ice sheet and ice shelves expanded onto the inner shelves. At this time, carbonate banks formed. During interglacial stages, such as the Holocene, two scenarios occurred. One with coastal ice sheet with appreciable meltwater, due to the retreat of ice sheet from the inner shelf grounding line. At this time, aragonite ooids and non-skeletal grains formed in ice marginal environments. The second scenario is an oasis, formed by the retreat of the inland ice sheet for a considerable distance, where carbonates formed in coastal areas, proximal and distal lake, and distal subglacial areas.

ACKNOWLEDGMENTS

We are grateful to the Australian Research Committee for providing financial assistance. ANARE provided field and financial support. We very much appreciate the valuable comments by reviewer S.T. Mazzullo that improved the manuscript. We are thankful to Z.Z. Amini for petrographic counts of biota from Prydz Bay, M. Power and C. Cooke for isotope analysis, the Resources of Tasmania for X-ray diffraction of samples, and Debbie Harding for drafting illustrations.

REFERENCES

AHARON, P., 1988, Oxygen, carbon and U-series isotopes of aragonites from Vestfold Hills, Antarctica: Clues to geochemical processes in subglacial environments: *Geochimica et Cosmochimica Acta*, v. 52, p. 2321-2331.

ALEXANDERSSON, E.T., 1978, Destructive diagenesis of carbonate sediments in the eastern Skagverrak, North Sea: *Geology*, v. 6, p. 324-327.

ANDERSON, T.F. and ARTHUR, M.A., 1983, Stable isotopes of oxygen and carbon and their application to sedimentologic and environmental problems, in *Stable Isotopes in Sedimentary Geology*, edited by M.A. Arthur and T.F. Anderson, Society of Economic Paleontologists and Mineralogist, Tulsa, Oklahoma, p. 1-151.

ANDERSON, J.B. and ASHLEY, G.M., 1991, Glacial Marine Sedimentation; Paleoclimatic significance. Geological Society of America, Inc., 232 p.

BARDIN, V.I., PISKUN, A.A., and SHMIDBERG, N.A., 1990, Hydrological and hydrochemical characteristics of deep water basins in Prince Charles Mountains: Antarktika, doklady komissii, No. 29, p. 97-112

BIRD, M.I., CHIVAS, A.R., RADNELL, C.J., and BURTON, H.R., 1991, Sedimentological and stable-isotope evolution of lakes in the Vestfold Hills, Antarctica: *Paleogeography, Paleoclimatology, Palaeoecology*, v. 84, p. 109-130.

BJAERKE, T. and DYPVIK, H., 1977, Quaternary "stromatolitic" limestone of subglacial origin from Scandinavia: *Journal of Sedimentary Petrology*, v. 47, p. 1321-1327.

BURTON, E.A. and WALTER, L.K., 1991, The effects of P_{CO_2} and temperature on magnesium incorporation in calcite in seawater and MgCl_2 - CaCl_2 solutions: *Geochimica et Cosmochimica Acta*, v. 55, p. 777-785.

CHAVE, K.E., 1954, Aspects of the biogeochemistry of magnesium 2. Calcareous sediments and rocks: *Journal of Geology*, v. 62, p. 587-599.

CRAIG, H., 1965, The measurement of oxygen isotope paleotemperatures, in *Stable isotopes in Oceanographic Studies and Paleotemperatures*: Spoleto, July 26-27, 1965, Consiglio Nazionale delle Ricerche, Laboratorio di Geologia Nucleare, Pisa, p. 1-124.

DOMACK, E.W., 1988, Biogenic facies in the Antarctic glacial marine environment: Basis for a polar glacial marine summary: *Paleogeography Palaeoclimatology Palaeoecology*, v. 63, p. 353-372.

FERRIS, J.M. and BURTON, H.R., 1988, Annual cycle of heat content and mechanical stability of hypersaline deep lake, Vestfold Hills, Antarctica: *Hydrobiologia*, v. 165, p. 115-128.

FRANKLIN, D.C., 1993, Recent diatom and foraminiferal assemblages in surficial sediments of Prydz Bay, Antarctica: Australian National Antarctic Research Expedition Research Notes, v. 90, 27 p.

FREIWALD, A., 1993, Coralline algal maerl frameworks - islands within the phaeophytic kelp belt: *Facies*, v. 29, p. 133-148.

FRIEWALD, A. and HENRICH, R., 1994, Reefal coralline algal build-ups within the Arctic Circle: morphology and sedimentary dynamics under extreme environmental seasonality: *Sedimentology*, v. 41, p. 963-984.

GOODWIN, I.D., 1993, Holocene deglaciation, sea-level change and the emergence of the Windmill Islands, Budd Coast, Antarctica: *Quaternary Research*, v. 40, p. 70-80.

GOODWIN, I.D., 1996, A mid to late Holocene readvance of the Law Dome ice margin, Budd Coast, East Antarctica: *Antarctic Science*, v. 8, p. 395-406.

GORE, D.B., CREAGH, D.C., BURGESS, J.S., COLHOUN, E.A., SPATE, A.P., and BAIRD, A.S., 1996, Composition, distribution and origin of surficial salts in the Vestfold Hills, east Antarctica: *Antarctic Science*, v. 8, p. 73-84.

HALLET, B., 1976, Deposits formed by subglacial precipitation of CaCO_3 : *Geological Society of America Bulletin*, v. 87, p. 1003-1015.

HANSHAW, B.B. and HALLET, B., 1978, Oxygen isotope composition of subglacially precipitate calcite: possible paleoclimate implications: *Science*, v. 200, p. 1267-1270.

HAMBREY, M., 1995, *Glacial Environments*, UCL press, London, 296 p.

HARRIS, P.T., O'BRIEN, P.E., SEDWICK, P. and TRUSWELL, E.M., 1996, Late Quaternary history of sedimentation on the Mac. Robertson Shelf, East Antarctica: problems with ^{14}C -dating of marine sediment core: *Papers and Proceedings Royal Society of Tasmania*, v. 130, p. 47-53.

HENDY, C.H., HEALY, T.R., RYNER, E.M., SHAW, J., and WILSON, A.T., 1979, Late Pleistocene glacial chronology of the Taylor Valley, Antarctica, and the global climate: *Quaternary Research*, v. 11, p. 172-184.

JACOBS, S.S., FAIRBANKS, R.G., and HUBBERTEN, H.W., 1995, Origin and evolution of water masses near the Antarctic continental margin: Evidence from $\text{H}_2^{18}\text{O}/\text{H}_2^{16}\text{O}$ ratios in seawater: *Antarctic Research Series*, v. 43, p. 59-86.

KINSMAN, D.J.J. and HOLLAND, H.D., 1969, The co-precipitation of the cations with CaCO_3 - IV. The co-precipitation of Sr^{2+} with aragonite between 16° and 96°C : *Geochimica et Cosmochimica Acta*, v. 33, p. 1-17.

KROOPNICK, P.M., 1985, The distribution of ^{13}C of CO_2 in the world oceans: *Deep Sea Research*, v. 32, p. 57-84.

LÉMMENS, M., LORRAIN, R., and HAREN, J., 1982, Isotopic

SHELF, COASTAL AND SUBGLACIAL POLAR CARBONATES, EAST ANTARCTICA

- composition of ice and subglacially precipitated calcite in an alpine area: *Zeitschrift für Gletscherkunde und Glazialgeologie*, v. 18, p. 151-159.
- LEES, A., 1975, Possible influence of salinity and temperature on modern shelf carbonate sedimentation: *Marine Geology*, v. 19, p. 159-198.
- LEUENBERGER, M., SIEGENTHALER, U., and LANGWAY, C.C., 1992, Carbon isotope composition of atmospheric CO₂ during the last ice age from an Antarctic ice core: *Nature*, v. 357, p. 488-490.
- LOWENSTAM, H.A., 1954, Factors affecting the aragonite calcite ratios in carbonate secreting marine organisms: *Journal of Geology*, v. 62, p. 284-322.
- MARINO, B.D., McELROY, M.B., SALAWITCH, R.J., and SPAULDING, W.G., 1992, Glacial-to-interglacial variations in the carbon isotopic composition of atmospheric CO₂: *Nature*, v. 357, p. 461-466.
- MATSUBAYA, O., SAKAI, H., TORIL, T., BURTON, H., and KERRY, K., 1979, Antarctic saline lakes - stable isotopic ratios, chemical composition and evolution: *Geochimica et Cosmochimica Acta*, v. 43, p. 7-25.
- MORGAN, V.I., 1982, Antarctic ice sheet surface oxygen isotope values: *Journal of Glaciology*, v. 28, p. 315-323.
- MORSE, J.W. and MacKENZIE, F.T., 1990, *Geochemistry of Sedimentary Carbonates*. Developments in Sedimentology 48, Elsevier, 707 p.
- MUCCI, A., 1987, Influence of temperature on the composition of magnesian calcite overgrowths precipitated from seawater: *Geochimica et Cosmochimica Acta*, v. 51, p. 1977-1984.
- PETERSON, J.A. and MORESBY, J.F., 1979, Subglacial travertine and associated deposits in the Carstensz area, Irian Jaya, Republic of Indonesia: *Zeitschrift für Gletscherkunde und Glazialgeologie*, v. 15, p. 23-29.
- PETERSON, J.A., FINLAYSON, B.L., and ZHANG, Q., 1988, Changing distribution of late Quaternary terrestrial lacustrine and littoral environments in the Vestfold Hills, Antarctica: *Hydrobiologia*, v. 165, p. 221-226.
- McCONNAUGHEY, T., 1989, ¹³C and ¹⁸O isotopic disequilibrium in biological carbonates. I. Patterns: *Geochimica et Cosmochimica Acta*, v. 53, p. 151-162.
- PICKARD, J., 1984, The Holocene fossil marine macrofauna of the Vestfold Hills, East Antarctica: *Boreas*, v. 14, p. 189-202.
- PICKARD, J., ADAMSON, D., HARWOOD, D.M., MILLER, G.H., QUILTY, P.G., and DELL, R.K., 1984, Early Pliocene marine sediments in the Vestfold Hills, East Antarctica: Implication for coastline, ice sheet, and climate: *South African Journal of Science*, v. 82, p. 520-521.
- RAO, C.P., 1981, Criteria for recognition of cold-water carbonate sedimentation: Berriedale Limestone (Lower Permian), Tasmania, Australia: *Journal of Sedimentary Petrology*, v. 51, p. 491-506.
- RAO, C.P., 1983, Cold-water spherical grains from a fresh-water drainage pipe, Gordon Dam, Tasmania, Australia: *Journal of Sedimentary Petrology*, v. 53, p. 1169-1173.
- RAO, C.P., 1988, Oxygen and carbon isotope composition of cold-water Berriedale Limestone (Lower Permian), Tasmania, Australia: *Sedimentary Geology*, v. 60, p. 221-231.
- RAO, C.P., 1993, Carbonate minerals, oxygen and carbon isotopes in modern temperate bryozoa, eastern Tasmania, Australia: *Sedimentary Geology*, v. 88, p. 123-135.
- RAO, C.P., 1996, *Modern Carbonates: tropical, temperate and polar - introduction to sedimentology and geochemistry*, Carbonates, Hobart, 206 p.
- RAO, C.P. and GREEN, D.C., 1982, Oxygen and carbon isotopes of Early Permian cold-water carbonates, Tasmania, Australia: *Journal of Sedimentary Petrology*, v. 52, p. 1111-1125.
- RAO, C.P., AMINI, Z.Z., and FRANKLIN, D., 1995, Grain-size, biota, sedimentology and oxygen and carbon isotopes of sediments, Davies Station and Prydz Bay, Antarctica: evidence for occurrence and recession of shelf ice: *ANARE Res. News*, v. 94, p. 33-34.
- RAO, C.P., AMINI, Z.Z., and FRANKLIN, D., 1996, Comparison between modern polar and temperate skeletal carbonate mineralogy and oxygen and carbon isotopes, Antarctica and Tasmania shelves. In Banks, M.R. and Brown, M.J., eds., *Climatic succession and glacial history of the southern hemisphere over the last five million years: Papers and Proceedings of Royal Society of Tasmania*, v. 130, p. 87-93.
- RUBINSON, H. and CLAYTON, R.N., 1969, Carbon-13 fractionation between aragonite and calcite: *Geochimica et Cosmochimica Acta*, v. 33, p. 997-1004.
- SMITH, N.R., DONG, Z., KERRY, K.R., and WRIGHT, S., 1984, Water masses and circulation in the region of Prydz Bay, Antarctica: *Deep Sea Research*, v. 31, p. 1121-1147.
- TARUTANI, T., CLAYTON, R.N., and MAYEDA, T.K., 1969, The effect of polymorphism and magnesium substitution on oxygen isotope fractionation between calcium carbonate and water: *Geochimica et Cosmochimica Acta*, v. 46, p. 987-996.
- TAVIANI, M., REID, D.E., and ANDERSON, J.B., 1993, Skeletal and isotopic composition and paleoclimatic significance of late Pleistocene carbonates, Ross Sea, Antarctica: *Journal of Sedimentary Petrology*, v. 63, p. 84-90.

Received: December 10, 1997

Accepted: May 13, 1998