

# Late Holocene advance of the Müller Ice Shelf, Antarctic Peninsula: sedimentological, geochemical and palaeontological evidence

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**Abstract:** Marine sediment cores were obtained from in front of the Müller Ice Shelf in Lallemand Fjord, Antarctic Peninsula in the austral summer of 1990–91. Sedimentological and geochemical data from these cores document a warm period that preceded the advance of the Müller Ice Shelf into Lallemand Fjord. The advance of the ice shelf is inferred from a reduction in the total organic carbon content and an increase in well-sorted, aeolian, sand in cores proximal to the present calving line. This sedimentological change is paralleled by a change in the foraminiferal assemblages within the cores. Advance of the ice shelf is indicated by a shift from assemblages dominated by calcareous benthic and planktonic forms to those dominated by agglutinated forms. A <sup>14</sup>C chronology for the cores indicates that the advance of the Müller Ice Shelf took place *c.* 400 years ago, coincident with glacier advances in other high southern latitude sites during the onset of the Little Ice Age. Ice core evidence, however, documents this period as one of warmer temperatures for the Antarctic Peninsula. We suggest that the ice shelf advance was linked to the exclusion of circumpolar deep water from the fjord. This contributed to increased mass balance of the ice shelf system by preventing the rapid undermelt that is today associated with warm circumpolar deep water within the fjord. We also document the recent retreat of the calving line of the Müller Ice Shelf that is apparently in response to a recent (four decade long) warming trend along the western side of the Antarctic Peninsula.

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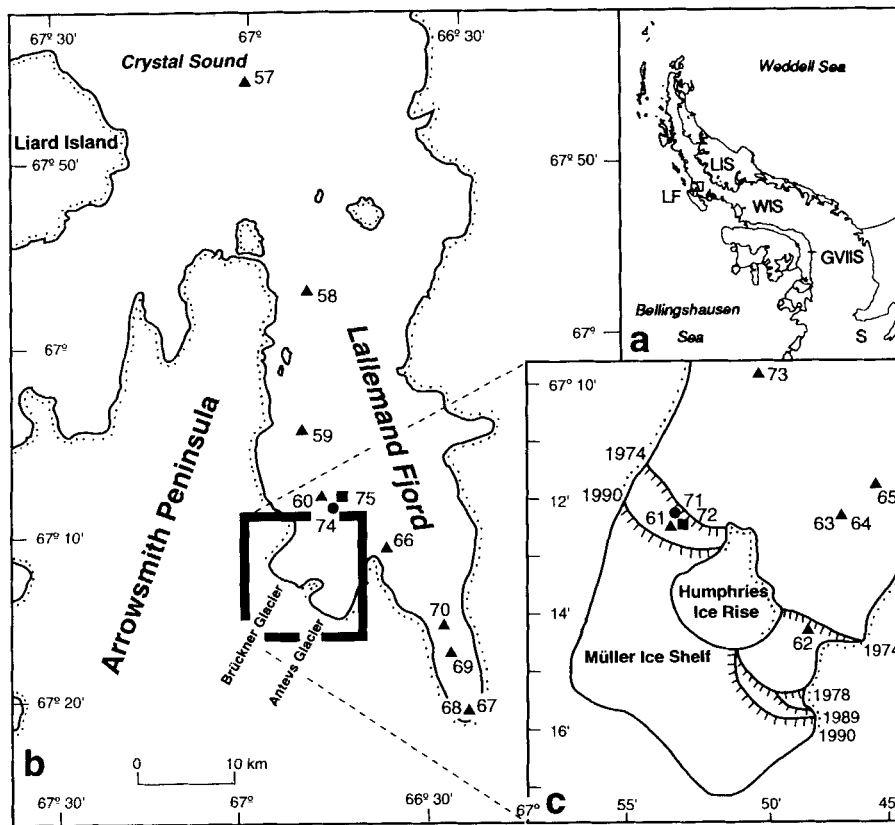
**Key words:** glacial marine sediments, foraminifera, Holocene palaeoenvironment, Little Ice Age

## Introduction

Ice shelves are important glaciological features around the periphery of the Antarctic continent. Their presence is often associated with the cold polar climate of the Antarctic and, in general, they are found where the mean summer temperatures do not exceed 0°C and where mean annual temperatures do not exceed -5°C. The disintegration of the Wordie Ice Shelf, on the western side of the Antarctic Peninsula, and the recession of the Larsen Ice Shelf, on the eastern side of the Antarctic Peninsula, have been attributed to a recent warming trend (Doake & Vaughan 1991, Skvarca 1993). The George VI Ice Shelf is thought to have been non-existent during a middle Holocene warm period but has subsequently reformed sometime since 6000 years B.P. (Clapperton 1990). Hence, ice shelves found along the Antarctic Peninsula may represent sensitive climatic indicators and the past fluctuations of such features may provide us with important paleoenvironmental information. The sediments accumulating under and seaward of ice shelves clearly indicate the location and extent of these contrasting depositional environments (Anderson *et al.* 1991).

The northern-most ice shelf along the western side of the Antarctic Peninsula is the Müller Ice Shelf which is found within the protected embayment of Lallemand Fjord at 67°S

(Fig. 1). In fact, without the protection afforded by the fjord embayment the Müller Ice Shelf probably would not exist under the present climatic conditions of the area (Swithinbank 1988). During the austral summer of 1990–91 the RV *Polar Duke* entered Lallemand Fjord to collect seafloor samples adjacent to the Müller Ice Shelf (United States Antarctic Program cruise PD90-7). In mid-December 1990 we found the fjord free of sea ice, an unusual situation associated with a widespread sea ice minimum for the years 1988–91 (Jacobs & Comiso 1993). The purpose of the seafloor sampling was to determine the history of ice shelf fluctuations in this climatically sensitive region and compare with fjords further north studied by Domack & Ishman (1993). Historical documents, including air photos, demonstrate that the leading edge of the Müller Ice Shelf has been stable from about 1947 (the earliest observation of the ice shelf) to 1974 (Stein 1992) but has been receding since about 1974 (Fig. 1). Some of the core sites are in positions which were formerly located beneath the leading edge of the Müller Ice Shelf (Fig. 1). Hence we have recovered sediments which were deposited both in an open marine environment and under an ice shelf. The results of our sedimentological, geochemical, and palaeontological investigations demonstrate the utility of these parameters to reconstruct ice shelf fluctuations in Lallemand Fjord.



**Fig. 1.** a. Overview of the region of the Antarctic Peninsula showing the location of Lallemand Fjord = LF, Wordie Ice Shelf = WIS, Larsen Ice Shelf = LIS, George VI Ice Shelf = GVIIS, and Siple station = S. b. Detailed view of Lallemand Fjord, Loubet Coast, showing the location of bottom sediment sampling stations, ▲ = surface grabs, ● = piston cores, and ■ = Kasten cores. c. Vicinity of Müller Ice Shelf to show sample stations and the various calving line positions documented since 1974.

## Methods

### Sediment sampling

The bottom sediments of Lallemand Fjord were sampled using Smith-McIntyre grabs, piston and Kasten corers (Domack & Ishman 1991, Fig. 1). The Kasten cores provide an excellent means by which to study recent changes in sedimentation because they collect an intact sediment-water interface and can penetrate down to 3.0 m (Kuehl *et al.* 1985). Piston cores are less likely to obtain the modern sediment water interface and, more often than not, obliterate the uppermost 0.5–2.0 m of sediment. Results in this paper concentrate on the Kasten cores.

### Laboratory analyses

Sediment samples were taken every 10 cm down the length of the Kasten cores and were analysed for their mud and sand content utilizing standard wet sieving techniques. Proportions of sand, coarse silt, medium to fine silt and clay were determined using a Malvern particle size analyser that uses laser diffraction to determine the volume percentage of various grain sizes. Size distributions within the sand fraction were determined by use of a settling tube similar to the one described by Anderson & Kurtz (1979). Total organic carbon percentages were determined to an accuracy of  $\pm .01\%$  with a Leco induction furnace after first removing the acid soluble components. Radiocarbon analyses were conducted on acid insoluble organic matter and foraminifera

calcite at the University of Arizona tandem accelerator mass spectrometer facility. Resulting ages were corrected using a  $\delta^{13}\text{C}$  value of  $25\text{‰}$ .  $^{210}\text{Pb}$  analyses were conducted at the Marine Sciences Research Center at the SUNY Stony Brook. X-ray radiographs of piston cores and grab samples were obtained using an industrial model Hewlett-Packard x-ray machine located at the Department of Geology of Syracuse University. Foraminifera were separated from the greater than 63 micron size fraction.

### Bathymetry

A bathymetric chart (Fig. 2) of Lallemand Fjord was constructed utilizing precision depth records (PDR) of both 12 kHz and 3.5 kHz frequency. PDR data were collected both in 1990 and in 1992 and the track lines are illustrated in two unpublished cruise reports available from the authors. The chart shows a complex series of basins, generally elongated north to south, which range in depth between 600 and 1000 m. Water depths immediately adjacent to the Müller Ice Shelf reach over 600 m (Fig. 2). The fjord has a 550 m deep sill found between Andresen Island and Roux Island.

### Sedimentology and geochemistry

The bottom sediments of Lallemand Fjord consist of grey clayey silts to sandy muds (Frederick 1991). Kasten cores 72 (proximal

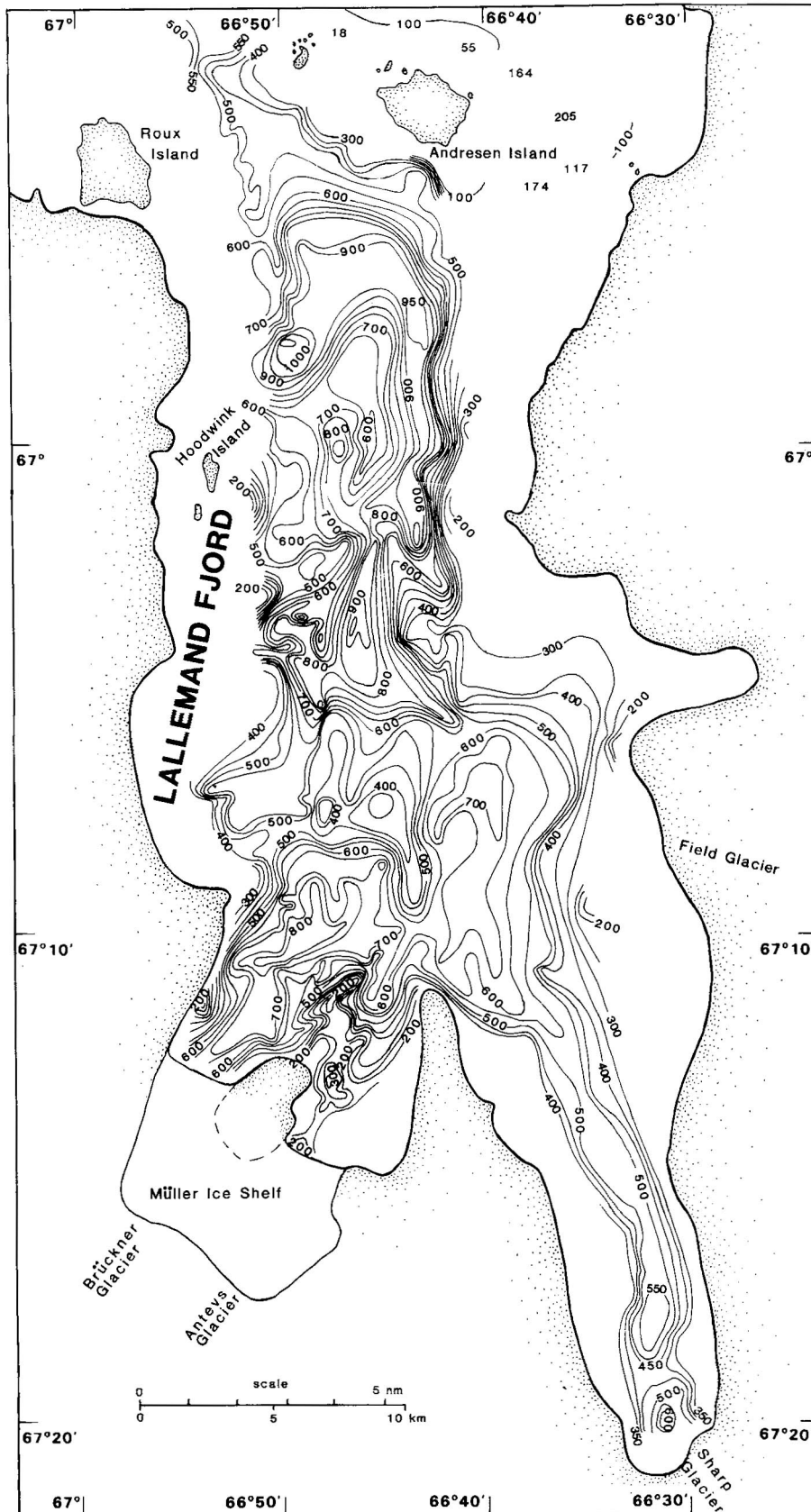
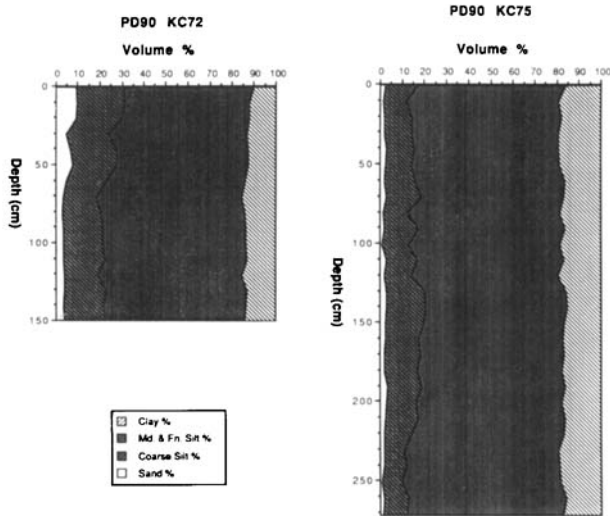
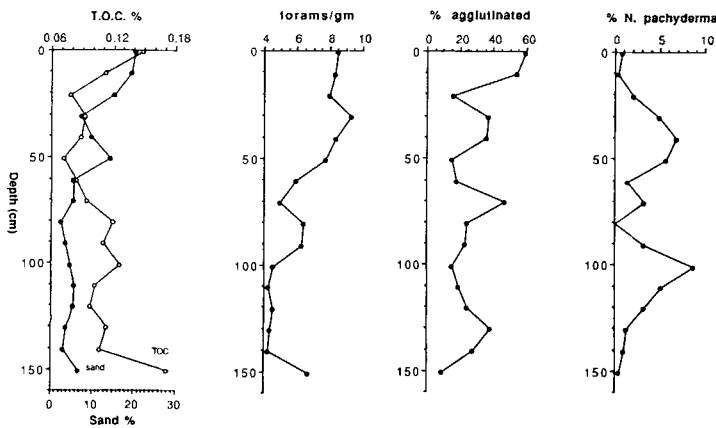


Fig. 2. Bathymetric map of Lallemand Fjord. Contour interval is 50 m.

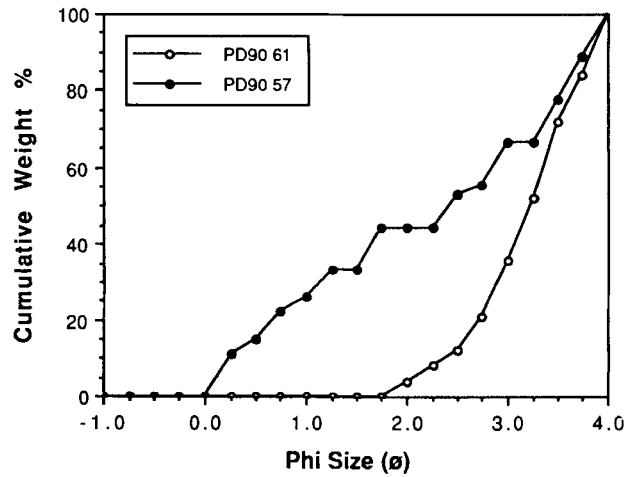


**Fig. 3.** Downcore volume percentages for sand, coarse silt, medium to fine silt, and clay for Kasten cores 72 and 75.

in a water depth of 655 m) and 75 (more distal in a water depth of 644 m) were described in detail by Stein (1992). Core 75 is a uniform grey to grey-green clayey silt with 1–3% poorly sorted sand (Fig. 3), scattered gravel sized clasts, and 20% clay. Of note were 1–5 cm thick intervals that contained concentrations of mud pellets of 1–2 mm in size. These intervals were found in core 75 at 18–20 cm, 55–60 cm, 66–69 cm, 114–118 cm, 183–185 cm, and 269–271 cm. The pellets are similar to those found on Arctic sea ice and described by Reimnitz *et al.* (1993). Core 72 varies from a grey clayey silt with less than 5% poorly sorted sand to a grey sandy mud with 6–20% well-sorted sand (Figs 3 & 4). There is very little biogenic silica in these sediments. The well-sorted sand fraction in core 72 becomes common only within the uppermost 50 cm of the core (Fig. 4). The well sorted sand fraction in core 72 is very fine grained and is rich in heavy minerals (Frederick 1991). Frederick (1991)

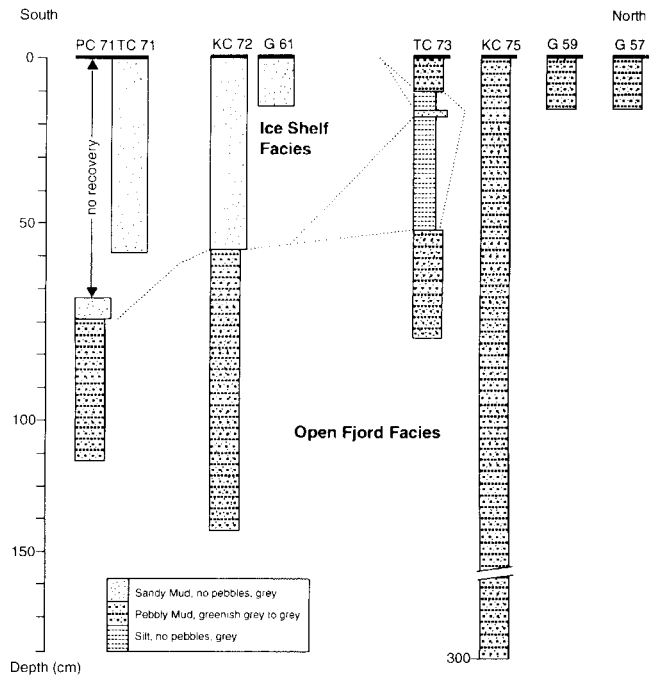


**Fig 4.** Sand content (weight percentages), total organic carbon (TOC %), foraminifera concentration (forams gm<sup>-1</sup>), % agglutinated foraminifera, and % *Neogloboquadrina pachyderma* for samples taken from Kasten cores 72.



**Fig. 5.** Cumulative weight % distributions for the sand fraction in surface grabs 57 (distal) and 61 (proximal), interpreted as ice-rafted and aeolian respectively.

and Stein (1992) concluded that the very fine grained sand in core 72 was of aeolian origin whereas the poorly sorted sand and gravel fraction in both cores 72 and 75 was of ice rafted origin. The grain size data for surface grabs 61 and 57 (Fig. 5) clearly distinguish these different sources. The variable sand content of core 72 clearly indicates that there has been a change in depositional processes in the vicinity of core 72 but not extending out to the site of core 75 (Fig. 6).



**Fig. 6.** Facies diagram for sediment cores collected in Lallemand Fjord in the vicinity of the Müller Ice Shelf. PC refers to piston core, TC refers to trigger core, KC refers to Kasten core, and G refers to grab sample.

X-rays were taken of selected piston cores and grab samples in order to access the coarsest (gravel) size fraction. The most common sediment type has a fine grained matrix with inclusions of gravel sized clasts. The sediments lack laminations and bioturbation structures. The second most common sediment type is also structureless but lacks the gravel-sized clasts. Comparison of the textural data with the x-rays demonstrates that sand-rich intervals correspond to zones that lack coarse clasts within the sediment. The distribution of the two sediment types is illustrated in Fig. 6. Those sediments which contain gravel-sized material occur at some distance from the front of the Müller Ice Shelf. Gravelly sediments are also found in the subsurface, below a depth of approximately 60 cm in cores taken adjacent to the Müller Ice Shelf (Fig. 6). The finest deposits (pebble-free silts) were found only in piston core 73 (Fig. 6).

Total organic carbon (TOC) content was determined at 10 cm intervals in both cores 72 and 75 (Figs 4 & 7). The TOC content is generally low (<0.5%) for both cores as a reflection of the polar climate and extensive seasonal sea ice cover. Core 75 has a higher TOC content than core 72 as a reflection of the more distal open marine location of core 75 (Stein 1992). Both cores show a first order trend of increasing TOC content with depth so that the TOC maximum is reached at the bottom of both cores. A slight increase in TOC is associated with the uppermost 20 cm in both cores and a slight TOC maximum is reached at a depth of 110 cm in core 75. The increase in TOC downcore in core 75 corresponds to a change in colour from grey to olive-grey at a depth of 190 cm (Stein 1992).

### Micropalaeontology

The foraminiferal records from cores 72 and 75 include planktonic, agglutinated and calcareous benthic foraminifera. A total of 47 foraminiferal taxa have been identified (43 species and 4 taxonomic groupings) from the two cores (Tables I & II). Distinct faunal trends are observed in the two cores and summarized below. Our results are consistent with those of Denny *et al.* (1992).

#### Core 75

The benthic foraminifera record in core 75 shows a significant change at c. 80 cm depth in the core. The number of benthic foraminifera per gram of sediment (forams gram<sup>-1</sup>) is consistently greater than 20 forams gram<sup>-1</sup> from 80 cm to the base of the core; above 80 cm the number of forams gram<sup>-1</sup> decreases with the lowest value at the top of the core (Fig. 7). Below 80 cm the benthic foraminifera assemblage is dominated by calcareous foraminifera; above 80 cm there is an increase in percent abundance of agglutinated foraminifera (Fig. 7). The lower, calcareous rich interval of the core (101–273 cm) is dominated by two taxa, *Bulimina aculeata* and *Fursenkoina* spp. (Fig. 8). These taxa are common on the Bellingshausen Sea and Weddell Sea continental margins (Ishman 1990, Ishman & Domack 1994, Mackensen *et al.* 1990). Other common taxa abundant

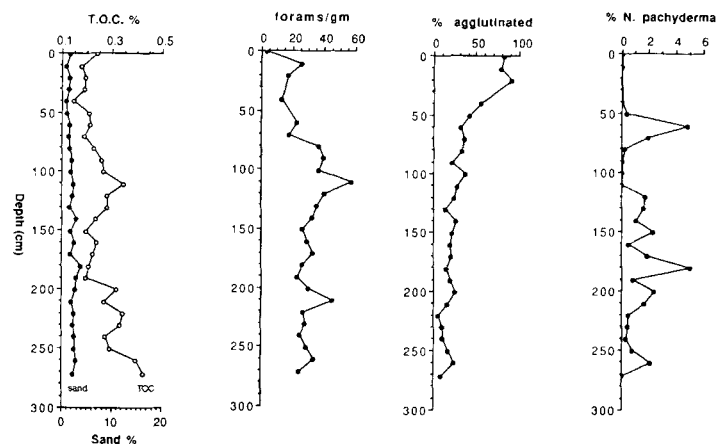


Fig. 7. Sand content (weight percentages), total organic carbon (TOC %), foraminifera concentration (forams/gm), % agglutinated foraminifera, and % *Neogloboquadrina pachyderma* for samples taken from Kasten cores 75.

in the lower unit are *Nonionella* spp. and *Miliammina* spp. (Fig. 8). Minor components (>2% and <5% in two or more samples) of the assemblage from the lower unit of core 75 are *Astrononion echolsi*, *Globocassidulina subglobosa*, *Portatrochammina eltaninae* and *Reophax ovicula* (Table I). The lower unit of core 75 is also characterized by the consistent occurrence of the planktonic foraminifera *Neogloboquadrina pachyderma* (Fig. 7).

The upper portion of core 75 (0–110 cm) is characterized by an increase in agglutinated foraminifera (Fig. 7) and an increase in the abundance of *Nonionella* spp. and *Miliammina* spp. between 101 and 51 cm (Fig. 8). This is followed by the dominance of the taxa *Miliammina* spp., *Adercotryma glomeratum*, *Textularia antarctica*, *Textularia weisneri* and *Trochammina bullata*. The upper part of core 75 (101–0 cm) has a peak abundance (>1%) of *Neogloboquadrina pachyderma* between 81 and 51 cm (Fig. 7).

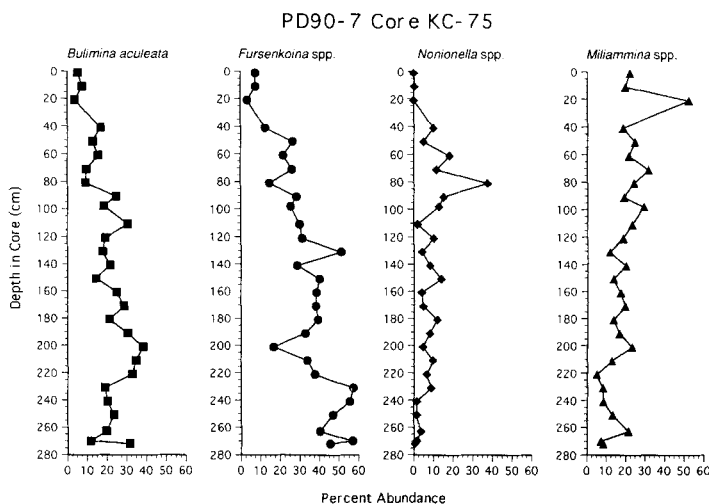


Fig. 8. Percentage abundance of the most commonly occurring benthic foraminifera from core 75.





**Table II.** Percentage abundance of foraminifera occurring in PD90-7 Core KC-72.

Sample interval (cm)	150–152	140–142	130–132	120–122	110–112	100–102	90–92	80–82	70–72	60–62	50–52	40–42	30–32	20–22	10–12	0–2
Foraminifer Count	462	316	306	312	467	468	374	336	347	289	299	251	285	305	290	269
<i>Adercotryma glomeratum</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.73	0.00	1.59	4.21	1.31	3.45	3.72
<i>Astrononion echolsi</i>	1.30	3.80	2.94	4.17	1.71	0.85	1.07	0.00	0.29	2.42	0.67	5.58	4.21	0.66	6.55	2.60
<i>Bolivina pseudopunctata</i>	3.03	0.00	0.65	5.45	0.21	5.98	5.08	4.46	0.00	1.04	0.00	0.00	0.00	0.00	0.00	1.49
<i>Bulimina aculeata</i>	27.06	9.49	1.31	9.62	10.28	17.95	28.88	7.74	8.07	23.53	26.42	5.18	18.95	7.87	9.31	2.97
<i>Cassidulina neocarinata</i>	0.00	0.00	0.00	0.64	0.43	0.00	0.00	0.00	0.00	1.38	0.33	0.00	0.00	0.33	0.00	0.00
<i>Cibicides lobatulus</i>	0.00	0.00	0.00	0.64	0.00	0.21	0.00	0.00	0.86	0.00	0.00	0.00	0.35	0.00	0.00	0.37
<i>Cibicides</i> sp.	0.00	0.00	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Conotrochammina alternans</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Cribrostomoides jefferysi</i>	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Epistominella exigua</i>	0.00	0.63	0.33	1.92	0.21	0.00	0.80	4.46	1.73	0.69	0.67	0.00	0.00	0.00	0.34	2.97
<i>Fursenkoina</i> spp.	51.95	16.14	13.07	25.00	25.91	35.26	23.53	21.73	6.92	9.00	23.08	22.71	17.19	17.38	24.14	14.13
<i>Globocassidulina subglobosa</i>	1.73	2.22	5.56	3.85	3.64	2.14	0.80	4.46	9.22	4.50	5.35	8.76	3.16	0.33	0.69	9.29
<i>Haplophragmoides parkerae</i>	0.00	0.32	0.00	0.00	0.21	0.00	0.00	0.60	1.73	0.00	0.00	1.59	0.35	0.00	7.24	1.12
<i>Laryngosigma hyalascidia</i>	0.00	0.95	0.00	0.00	0.00	0.21	0.00	0.00	0.86	0.35	0.00	0.00	0.35	0.00	0.00	0.00
<i>Miliammina</i> spp.	8.23	25.95	34.31	18.91	15.20	13.25	18.72	13.69	29.11	1.38	10.37	13.55	17.19	3.28	15.52	6.32
<i>Neogloboquadrina pachyderma</i>	0.43	0.95	1.31	3.21	5.14	8.76	3.21	0.00	3.17	1.38	5.69	6.77	4.91	1.97	0.34	0.74
<i>Nodosariids</i>	0.00	0.00	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Nonionella</i> spp.	5.41	36.08	33.01	18.59	30.19	13.68	13.10	30.36	18.73	35.64	20.07	11.95	8.42	52.46	4.14	5.95
<i>Portatrochammina antarctica</i>	0.00	0.32	0.65	0.64	0.00	0.21	0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.00
<i>Portatrochammina etaninae</i>	0.00	0.00	0.00	1.28	0.43	0.64	2.14	2.98	4.32	4.50	0.67	2.39	2.46	3.93	1.03	1.86
<i>Pullenia bulloides</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.58	0.00	0.00	0.40	0.35	0.66	0.00	0.00
<i>Pullenia salisburyi</i>	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	2.08	1.00	2.79	4.91	2.95	0.34	0.00
<i>Reophax ovicula</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.70	0.00	0.00	0.00
<i>Reophax spiculifer</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.00	0.00
<i>Reophax subdentaliniformis</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.37
<i>Stainforthia concava</i>	0.43	1.90	3.92	2.56	0.00	0.00	0.53	2.38	2.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Textularia antarctica</i>	0.00	0.32	0.33	0.00	0.21	0.00	0.27	1.79	6.92	3.81	0.00	0.00	0.00	0.00	23.79	16.36
<i>Textularia tenuissima</i>	0.00	0.32	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Textularia wiesneri</i>	0.43	0.32	1.96	1.92	1.71	0.43	0.53	3.57	0.00	2.42	0.67	8.76	7.02	4.59	0.00	27.51
<i>Trifarina earlandi</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.34	0.00
<i>Triloculina tricarinata</i>	0.00	0.00	0.00	0.00	1.93	0.00	0.00	0.00	0.00	0.00	2.01	0.00	0.00	0.00	0.00	0.37
<i>Trochammina bullata</i>	0.00	0.00	0.33	0.96	0.43	0.21	0.53	1.19	3.75	3.81	2.34	7.17	4.91	2.30	1.72	1.86
<i>Trochammina intermedia</i>	0.00	0.32	0.00	0.64	0.43	0.21	0.27	0.00	0.58	0.35	0.33	0.80	0.00	0.00	0.00	0.00
Percent Agglutinated																
Foraminifera	8.66	27.85	37.91	24.36	18.84	14.96	22.99	24.40	46.69	17.99	14.72	35.86	37.19	15.41	53.79	59.11
Percent Calcareous																
Foraminifera	91.34	72.15	62.09	75.64	81.16	85.04	77.01	75.60	53.31	82.01	85.28	64.14	62.81	84.59	46.21	40.89



100 years varied from  $0.21 \text{ cm yr}^{-1}$  to  $0.17 \text{ cm yr}^{-1}$  for cores 72 and 75 respectively (Stein 1992, Domack & Stein 1993).  $^{14}\text{C}$  ages can also be used to determine sediment accumulation rates although the time frame is on the order of thousands of years. Though the  $^{14}\text{C}$  method has generally been found to be better than  $^{210}\text{Pb}$  methods along the Antarctic Peninsula (Harden *et al.* 1992) comparative studies have yet to be done within ice-proximal fjord settings where sedimentation rates would be expected to be high. A total of nine accelerator mass-spectrometer (AMS) radiocarbon ages were obtained from cores 72 and 75 (Table III). Of these nine AMS dates, six were obtained on the acid insoluble organic carbon fraction and three were obtained on benthic foraminifera. The dates ranged from  $1945 \pm 85$  to  $4910 \pm 90$  years BP. Downcore trends in uncorrected  $^{14}\text{C}$  age are illustrated in Fig. 10 where it can be seen that there is an offset between the organic matter ages and the calcite (foram) ages. This offset is greatest in core 72 (c. 700–3000 years) and is minimal in core 75 (c. 400 years). Discrepancies between organic matter and calcite ages have been reported previously for glacial marine sediments in the Arctic (i.e. fjords of Baffin Island, Andrews *et al.* 1985) but have yet to be documented in Antarctic glacial marine sediments. Excellent agreement between organic matter and calcite ages in diatomaceous (organic-rich) pebbly muds from an Antarctic fjord has been discussed by Domack *et al.* (1993). In the organically lean sediments of Lallemand Fjord it would be expected that organic matter ages might reflect some component of reworked carbon. This effect appears to be greatest in the ice-proximal core, the one that is most lean in organic carbon (core 72). Sedimentation rates for core 72 are therefore based on calcite ages (Fig. 10). In core 75 there appears to be little offset in organic matter and calcite ages and therefore the downcore trend of organic matter ages can be used to determine the sedimentation rate (Fig. 10). Modern (surface) ages on the organic matter in both cores 72 and 75 are between  $2260 \pm 65$  and  $2590 \pm 65$  years, which is within the range of modern surface ages on organic matter reported by Harden *et al.* (1992) and Domack *et al.* (1993) for glacial marine sediments along the western side of the peninsula. These ages are c. 1000 years older than the generally accepted reservoir correction for the Antarctic Peninsula region (Harden *et al.* 1992, Domack 1992, Björck *et al.* 1991). Sedimentation rates using the  $^{14}\text{C}$  method range from  $0.12\text{--}0.13 \text{ cm yr}^{-1}$  for cores 72 and 75 respectively. It is evident that the  $^{210}\text{Pb}$  method yields rates that are greater than the rates obtained using the  $^{14}\text{C}$  method. This is consistent with the results of Harden *et al.* (1992). Therefore, for the purposes of this paper, the  $^{14}\text{C}$  chronology will be used to determine the stratigraphy of downcore events. Based upon these results it is proposed that cores 72 and 75 contain a record of the past 1250 and 2100 years respectively.

### Interpretation and discussion

We interpret the sedimentology as reflecting a relatively recent advance of the Müller Ice Shelf. This advance resulted in the deposition of a well-sorted sand-rich facies in the vicinity of the

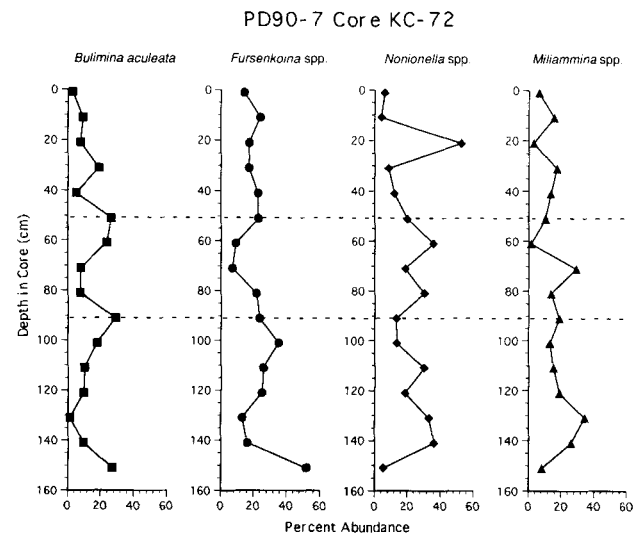


Fig. 9. Percentage abundance of the most commonly occurring benthic foraminifera from core 72.

modern calving line (Fig. 6). The sand-rich facies results from the transport of aeolian material across the surface of the ice shelf to the calving line and its deposition beneath the proximal fjord waters. Two other studies of ice shelf sedimentation in Antarctica also point out the importance of aeolian sedimentation in association with calving lines (Dunbar *et al.* 1989, Barrett *et al.* 1991). It is possible that surface meltwater plays a role in concentrating aeolian material within transverse crevasses that form just back from the calving line. We do not believe that the sand-rich intervals are the result of bottom current activity, turbid meltwater plumes, or sediment gravity flows (turbidites) because the sand does not occur in graded intervals nor are there any bottom current structures. It is also significant to note the dramatic decline in sand content versus distance from the calving line (Frederick *et al.* 1991) as compared with work done by Domack & Ishman (1993). These later data were collected from subpolar fjords, with subsurface meltwater plumes, and displayed a more gradual sand content decline with distance out into the fjord. The abrupt decrease of sand content away from the calving line reinforces the premise that the source of the well-sorted sand was not located beneath the ice shelf or at the grounding line of the ice shelf (Frederick *et al.* 1991).

Table III. Uncorrected  $^{14}\text{C}$  ages of Kasten cores 72 and 75, Lallemand Fjord.

Lab no.	Core & depth	Age (yr)	Carbon source
AA-6719	72 0–2cm	$2260 \pm 65$	organic carbon
AA-9032	72 30–32cm	$4910 \pm 90$	organic carbon
AA-9180	72 50–52cm	$1945 \pm 85$	foram. calcite
AA-9033	72 140–142cm	$4085 \pm 75$	organic carbon
AA-9181	72 150–152cm	$2735 \pm 65$	foram. calcite
AA-9034	75 0–2cm	$2590 \pm 65$	organic carbon
AA-9035	75 100–102cm	$3295 \pm 60$	organic carbon
AA-9182	75 150–152cm	$3340 \pm 90$	foram. calcite
AA-9036	75 240–242cm	$4440 \pm 80$	organic carbon

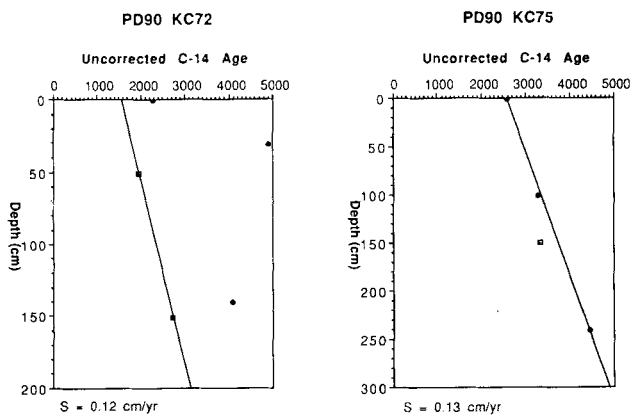


Fig. 10. Downcore trends in uncorrected  $^{14}\text{C}$  age for acid insoluble organic matter (dots) and foraminifera calcite (squares).

An absence of ice rafted debris within the sand rich facies is related to the blocking effect that the ice shelf edge has on drifting icebergs. This prevents the rafting of coarse sediment near and beneath the outer edge of the ice shelf. Ice shelves typically are free of debris except near the grounding line (Drewry & Cooper 1981, Powell 1994) so that ice rafting would not take place beneath the ice shelf itself or from ice bergs calved off the ice shelf. Out in the more open parts of the fjord icebergs from tidewater glaciers are not restricted so they can drift freely and melt, releasing their poorly sorted sediment load to the seafloor. It is important to note that meltwater is not a significant contributor to sediment input into the fjord today. Vertical profiles of salinity, temperature, and turbidity collected in Lallemand Fjord in 1990–91 revealed very little suspended particulate matter even near the bottom (Frederick 1991).

It is significant to note that the advance of the Müller Ice Shelf took place following a period of slightly higher preservation of organic carbon within the cored sediments. The subsequent period of decreased TOC preservation is a reflection of more persistent sea ice and the encroachment of glacial margins around the periphery of Lallemand Fjord. This is consistent with the observation in modern Antarctic fjords where the TOC content decreases with increasing proximity to the glacier margin (Domack & Ishman 1993). The relative abundance of mud pellet layers within the upper portion of core 75 may also indicate a period of more active sea ice rafting if the origin of the pellets is similar to that proposed for the Arctic (Reimnitz *et al.* 1993).

The greater foraminiferal variability in abundance seen in core 72 versus core 75 is explained by its ice proximal position next to the Müller Ice Shelf and the effects of this on primary productivity. The trends in the TOC records and forams  $\text{gram}^{-1}$  values for cores 72 and 75 show low values for core 72 relative to core 75. At about 71 cm the records begin to converge by a reduction in TOC and forams  $\text{gram}^{-1}$  in core 75 and an increase in forams  $\text{gram}^{-1}$  in core 72 (Figs 4 & 7). These trends suggest that the foraminiferal abundance (forams  $\text{gram}^{-1}$ ) in this region is controlled by primary productivity and organic carbon flux to

the substrate.

The dominance of the taxa *Bulimina aculeata* and *Fursenkoina* spp. in the lower interval of core 75 (80–279 cm) indicates high productivity and relatively organic-rich sediments. The higher forams  $\text{gram}^{-1}$  values in the lower interval (below 80 cm) indicate lower clastic sedimentation rates and/or higher organic carbon flux relative to the upper interval. This is supported by the geochemical data that show higher organic carbon values in this lower section of the core than the upper 101 cm. The species *Bulimina aculeata* is commonly associated with Circumpolar Deep Water (CDW) on the Bellingshausen shelf (Ishman 1990), Weddell Sea (Mackenson *et al.* 1990) and South Atlantic (Mead 1985). The high abundance of *B. aculeata* and *Fursenkoina* spp. throughout the lower section of core 75 indicates the presence of highly productive warm CDW occupying Lallemand Fjord to c. 700 yr B.P. The abundance of the planktonic foraminifer *Neogloboquadrina pachyderma*, although low (<5%), exceeds its occurrences in modern sediments on the Bellingshausen Sea margin of the Antarctic Peninsula indicating marine conditions even more open than today. This may be related to periods when sea ice cover was much reduced compared to today, allowing incursions of *N. pachyderma* into Lallemand Fjord. A decrease in the abundance of *B. aculeata* from 81–41 cm (625–315 yrs. B.P.) and significant increase in the abundance of *Nonionella* spp. indicate a progressive cooling of bottom waters, perhaps responsible for the reduced abundance of calcareous benthic foraminifera in the upper interval of core 75. This is corroborated by the distribution of *B. aculeata* in the South Atlantic where it is associated with bottom waters having temperatures  $>0^\circ\text{C}$  (Mackensen *et al.* 1993).

The foraminiferal trends in core 72 differ from those observed in core 75. A reduction in the abundance of *B. aculeata*, particularly above 41 cm, and an increase in the forams  $\text{gram}^{-1}$  values occurs at 61 cm in core 72. The decrease in *B. aculeata* suggests decreased productivity (TOC), as observed in the upper part (0–71 cm) in core 75. This may also be a factor of dilution of the TOC content in the sediments due to the increased influx of silt (Stein 1992) and sand observed for this section of core 72. However, because no noticeable change in accumulation rates are observed, we suggest that an increase in aeolian input was accompanied by a decrease in biogenic and ice-rafted debris.

The sedimentation rates as determined by the  $^{14}\text{C}$  chronology indicate that the Müller Ice Shelf advanced c. 400 years ago. This would suggest that the advance of the Müller Ice Shelf is correlative with the onset of the Little Ice Age (LIA), a widely recognized Northern Hemisphere neoglacial event. Advance of glacial margins during the LIA is also recognized from other Southern Hemisphere high latitude localities (Clapperton 1990). However, climatic conditions across Antarctica during the LIA were far from uniform. A study of ice core records for this period documents that the continent proper experienced a cooler climate during the LIA while the region in the vicinity of Siple station, including the Antarctic Peninsula, experienced warmer temperatures (Mosley-Thompson 1992, Mosley-Thompson *et al.* 1990). These published data appear to conflict with the evidence

presented here, that the Müller Ice shelf advanced during a relatively warmer interval of time. Even a modest amount of warming would not be consistent with advance of the Müller Ice Shelf as it is in retreat today, in step with the disintegration of the Wordie Ice Shelf under a recent warming trend (Doake & Vaughan 1991). However, it is important to keep in mind that an ice shelf also loses mass by undermelting in contact with warm water masses. In fact warm ocean waters can play a critical role in the mass balance of ice shelf systems (Potter & Paren 1985, Robin 1979). Today Lallemand Fjord is filled with warm CDW that has a temperature of greater than 1°C (Domack *et al.* 1992, Ishman & Domack 1994). In the absence of CDW the basal melt rates would be expected to be significantly less than they are at present. We suggest that it was an absence of CDW that contributed to the advance of glacier margins in Lallemand Fjord during the latest Holocene. A decrease in CDW in the Southern Ocean at this time may be related to reduced deep water production in the North Atlantic during the LIA, as demonstrated for glacial periods throughout the Pleistocene (Broecker & Denton 1989, Charles & Fairbanks 1992). An alternative is that the Siple ice core data are not representative of the rest of the Antarctic Peninsula and that late Holocene regional climates have varied to a greater degree than has previously been assumed. Increased accumulation accompanied by greater storm frequency may be another important factor to keep in mind.

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