

# Seasonal and water-depth variations in sediment luminescence and in sedimentation from sediment trap samples at Gerlache Strait, Antarctic Peninsula

GLENN W. BERGER<sup>1</sup>, SARA ANTE<sup>1\*</sup> and EUGENE W. DOMACK<sup>2</sup>

<sup>1</sup>Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA

<sup>2</sup>Department of Geosciences, Hamilton College, 198 College Hill Road, Clinton, NY 13323, USA

\*Present address: Chevron Corporation, 9525 Camino Media, Bakersfield, CA 93311, USA  
glenn.berger@dri.edu

**Abstract:** Sediment trap arrays were deployed in Brialmont Cove and Andvord Bay, eastern Gerlache Strait, from December 2001–March 2003. The recovered sediments (representing instantaneous deposition from the viewpoint of luminescence dating) encompass all the annual and local glaciomarine depositional processes. Magnetic susceptibility profiles were used to infer seasonality in the trap cores, and thus to select subsamples for luminescence measurements. Multi-aliquot infrared stimulated luminescence (IRSL) apparent ages were used to assess the effectiveness of ‘clock zeroing’ (by daylight) of light sensitive luminescence within fine silt polymineral samples from each trap depth. IRSL apparent ages for 24 samples indicate that the largest age-depth differences occur with the autumn season samples at both trap sites, suggesting a previously unrecognized and regional (within the Gerlache Strait) change in depositional controls in the autumn compared to other seasons. The apparent ages also indicate some differences between the fjords, and a more complex oceanographic regime at Andvord Bay than at Brialmont Cove. Dry-mass sediment fluxes varied from 0.4 to 0.7 g cm<sup>-2</sup> yr<sup>-1</sup>, with the largest flux at Brialmont Cove (~0.7 g cm<sup>-2</sup> yr<sup>-1</sup>) occurring in the bottom trap, whereas at Andvord Bay, the largest flux (~0.6 g cm<sup>-2</sup> yr<sup>-1</sup>) occurred in the middle trap (~45 m above seafloor).

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## Introduction

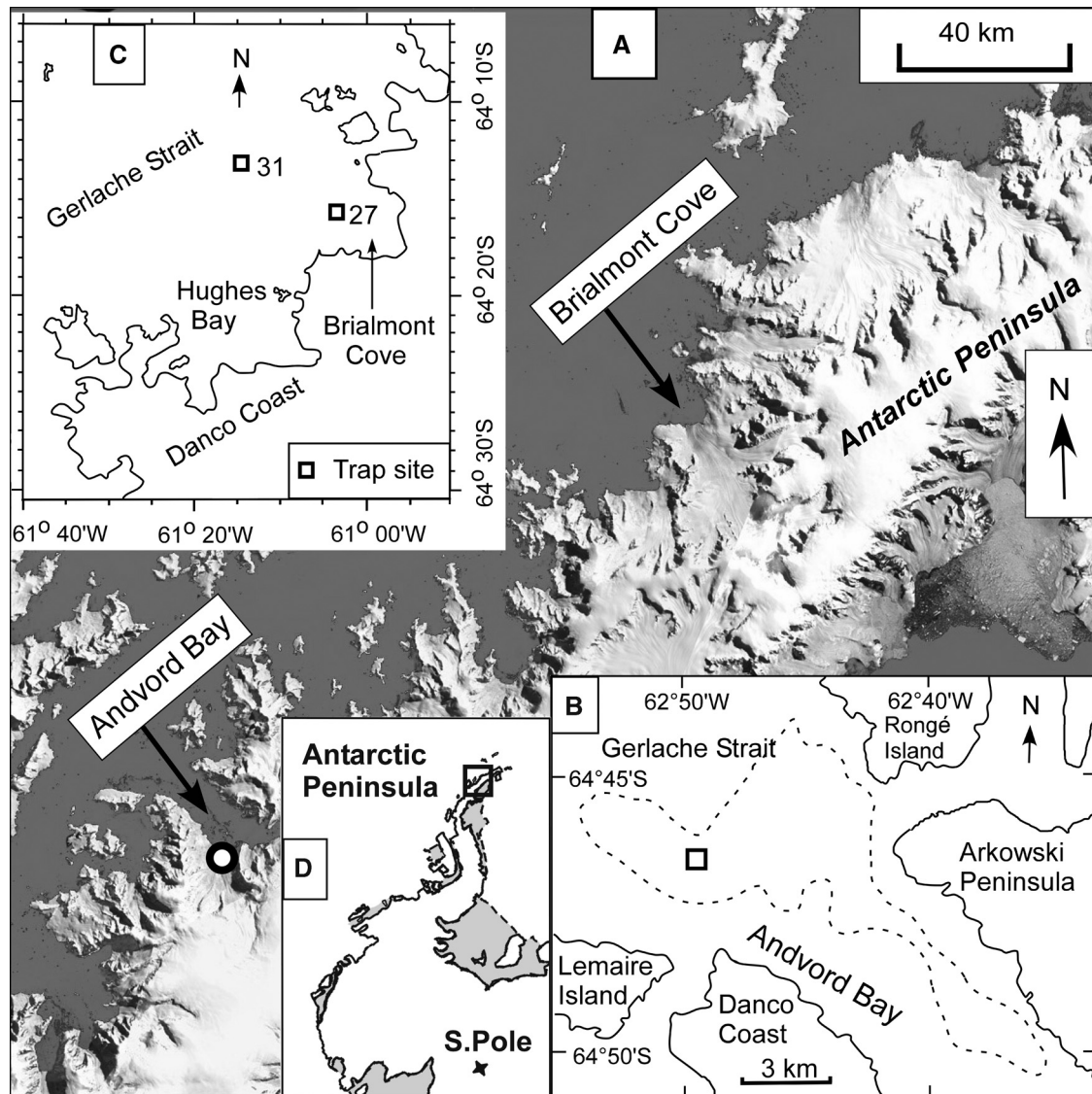
The Antarctic Peninsula has a number of fjords that act as depocentres for glaciomarine sedimentation and that have recorded detailed climatic fluctuations (Griffith & Anderson 1989, Domack & McClennen 1996, Leventer *et al.* 1996, Harris *et al.* 1999, Domack & Mayewski 1999, Smith *et al.* 1999, Gilbert 2000, Yoon *et al.* 2000, Taylor *et al.* 2001). Sediments deposited there hold a valuable record of ice sheet fluctuation and warming/cooling trends throughout the Holocene (Domack *et al.* 2003a). Also, on a ‘modern’ time scale and from an ecosystems viewpoint, “the shallows and bays of the south-western Bransfield Strait and Gerlache Strait are the nursery grounds for a host of biota, especially krill” (Zhou *et al.* 2002). Thus on both modern and long time scales, an understanding of the complex depositional processes in the region is important. For the geological time scale (Holocene and older), radiocarbon (<sup>14</sup>C) has provided the primary tool for dating these sediments, but scarcity of organic material and a large and variable <sup>14</sup>C reservoir effect along the continental shelf (e.g. Domack *et al.* 1999a, 1999b) have limited the utility of this method for some Antarctic glaciomarine sediments.

To investigate the suitability of an alternate geochronometer for such sediments, we attempted to quantify the degree by which the luminescence sediment-dating ‘clock’ (e.g.

Aitken 1985, 1998, Berger 1995, Wallinga 2002, Botter-Jensen *et al.* 2003, Lian & Roberts 2006) is zeroed by daylight in the areas around the Antarctic Peninsula. As part of this effort we tested the degree of natural daylight zeroing of light sensitive luminescence within the fine silts (4–11 μm diameter range) from sediment trap samples accumulated during *c.* 14 months at two fjord sites. Other parts of this effort involve applying luminescence sediment-dating methods to core tops and sediment suspensions from around the Peninsula. Those results are not yet published.

Sediment trap samples represent essentially instantaneous deposition from the viewpoint of luminescence sediment dating, but capture the entire annual range of depositional processes operating at different depths near two well-characterized fjords on the western side of the Antarctic Peninsula: Brialmont Cove and Andvord Bay (Fig. 1). These trap samples therefore provide the potential for us to isolate possible seasonal and spatial depositional effects on the retention of light sensitive luminescence. Magnetic susceptibility profiles of the sediment trap tubes (‘cores’ hereinafter) were utilized to infer seasonal variability within the sediments. Grain size and microprobe analyses helped to characterize the sediments.

Because the sediments studied in this project have an effectively zero age of deposition, any erroneously old apparent age results would reflect local depositional



**Fig. 1.** Maps of the locations of the sediment trap arrays within the study sites of Brialmont Cove and Andvord Bay at the Antarctic Peninsula. In inset D, the open square outlines part A. In A, the open circle within Andvord Bay denotes Lester Cove. In B, the dashed-line zone outlines the extent of the Andvord Drift deposits (after Harris *et al.* 1999). The satellite image mosaic in A is constructed from component images available from the Landsat Image Mosaic of Antarctica project (LIMA, <http://lima.usgs.gov>) (from Berger *et al.* 2009).

limitations on daylight exposure. Such limitations would involve incorporation of grains transported in darkness, whether at depth from beneath glacier termini, or at depth through bottom-current reworking processes. The sub-polar setting (*c.* 64.5°S) provides not only a much longer diurnal daylight cycle (up to 21.5 h sunrise to sunset, summer) than at lower latitudes, but also a substantial seasonal light–dark cycle with seasonal ice cover, traits not available to luminescence studies at lower latitudes. Samples from these traps might permit isolation of possible seasonal and spatial depositional effects on the retention of light sensitive luminescence. Set against the advantage of this depositional setting (long daylight exposures in summer), is the possibility

of rapid sedimentary transport and deposition in deep or turbid water, which would inhibit the resetting of the light sensitive luminescence clock (Berger 1990).

Although long-term sediment traps have been used to infer depositional processes in temperate fjords (e.g. Syvitski *et al.* 1987), and in other areas of the Antarctic Peninsula (Lallemand Fjord - Gilbert *et al.* 2003; Andvord Bay - Mammone 1992, Domack & Mammone 1993; Deception Island - Baldwin & Smith 2003, Lenn *et al.* 2003; northern Bransfield Strait - Kim *et al.* 2004), to our knowledge ours is the first use of sediment traps in any aqueous setting for the study of luminescence and its relation to depositional processes. Moreover, the more

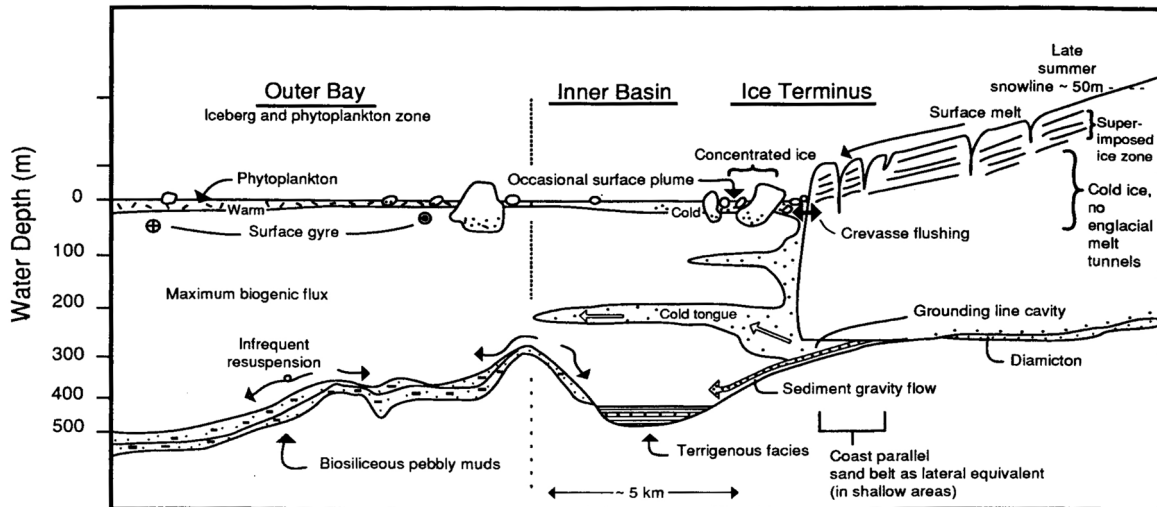


Fig. 2. Cartoon of depositional processes active in fjords along the Danco Coast as exemplified in Andvord Bay (after Domack & Ishman 1993).

northerly trap areas of Deception Island and Bransfield Strait never experience full sea ice cover, unlike the more southerly sites (this study, and Lallemand Fjord). Most details of the luminescence methods we used and of the luminescence results are presented elsewhere (Berger *et al.* 2009).

## Depositional setting

### Geology

The geology of the Antarctic Peninsula is composed of basement rocks referred to as the Trinity Peninsula Group (Barker *et al.* 1991, Anderson 1999). Brialmont Cove is bounded on the north by early Mesozoic granitoids, and on the east and south by the mid (?)–upper Palaeozoic Trinity series, which consists of sandstones, clay shales, siltstones, gritstones, and accessory conglomerates. The Trinity series also occupies the head of Andvord Bay, while the sides of the fjord are made up of diorite-dominated late Mesozoic intrusives (Grikurov 1978).

While the geology surrounding these fjords promotes the presence of quartz and feldspar grains necessary for luminescence dating, detrital grains derived from volcanic rocks are often prone to exhibit anomalous fading, which can lead to under-estimations in age. Problematic minerals include volcanic Ca-rich plagioclases (i.e. andesine, labradorite, and bytownite) and zircons (Aitken 1985, Berger 1995).

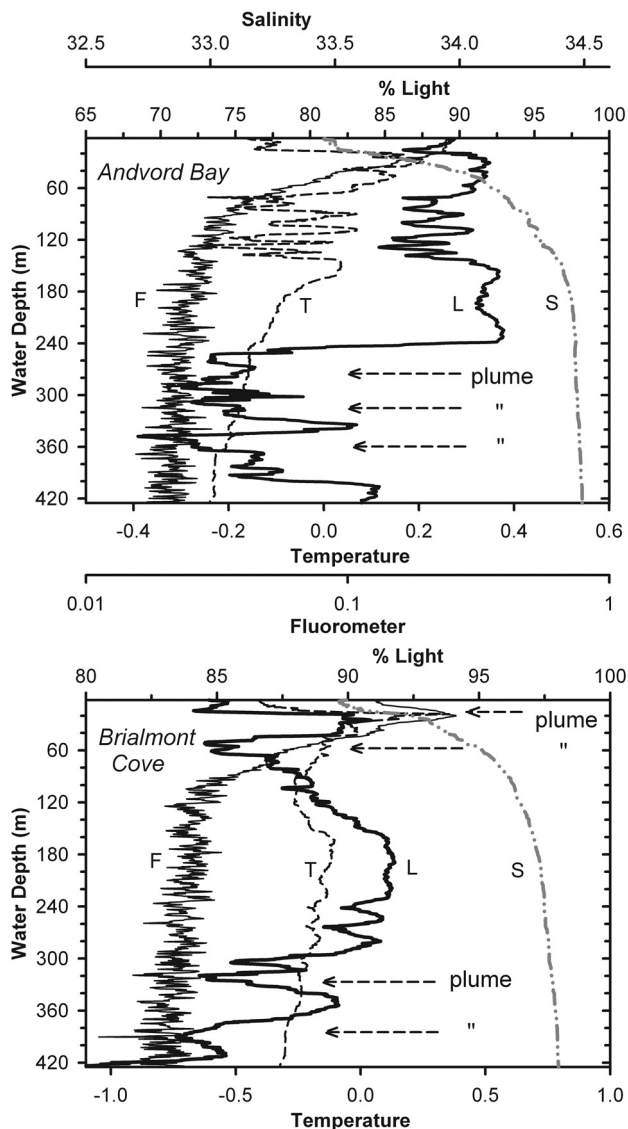
### Sedimentation

Both Brialmont Cove and Andvord Bay are sub-polar fjords characterized by near-zero summer temperatures. Whereas in temperate fjords meltwater can be transported during diurnal darkness, in a sub-polar setting any melting generally would occur most actively only during seasonal daylight.

However, the low temperatures that have characterized sub-polar fjords in historic time have allowed very little melting to occur during historic time, until the last few years. In the spring–summer season in this setting, biogenic deposition dominates terrigenous deposition (Griffith & Anderson 1989) and increases with distance from the glacier termini (Domack & McClennen 1996).

The perimeter of Andvord Bay (Fig. 1) is surrounded by tidewater glaciers (Griffith & Anderson 1989). This is classified as a complex bay system with a length to width ratio of 3.4 (Domack & Ishman 1993). Brialmont Cove (Fig. 1) is located to the north of Andvord Bay on the Danco Coast. Brialmont Cove has an open bay geometry (Domack & Ishman 1993), with a smaller length to width ratio than Andvord Bay. Sediments deposited near the glacial terminus in each of these fjords are relatively protected from ocean currents. The northern portion of the Gerlache Strait (including Brialmont Cove) is known to have very high levels of biogenic productivity (e.g. Karl *et al.* 1987, Holm-Hansen & Mitchell 1991, Domack & Ishman 1993).

At the glacier-proximal location of both fjords, deposition is controlled by the formation of what have been described as mid–deep coldwater tongues (Fig. 2). Mid–deep coldwater plumes have been directly observed with CTD (conductivity–temperature–depth–transmissometer) profiles within both fjords (Domack & Ishman 1993, Domack *et al.* 1994) and Fig. 3. These suspension plumes probably form when tidal motion lifts the glacier, entraining water beneath it. Sediment-laden water is then flushed from beneath the glacier into the water column as the tide falls, forming mid to deep coldwater tongues. These coldwater tongues can reach different heights in the water column depending on the relative density of the meltwater plumes (Domack & Ishman 1993). Studies of sediment traps in central Andvord Bay by Mammone (1992) support this conceptual model of plume formation by



**Fig. 3.** Water-depth profiles of transmissometer-light attenuation (L), temperature (T), salinity (S) and fluorometry (F) at: (top) a site within innermost Andvord Bay (Lester Cove, 430 m deep, 64°54.54'S, 62°34.94'W), and (bottom), a site within innermost Brialmont Cove (434 m deep, 64°17.63'S, 60°58.40'W). The horizontal arrows denote significant suspension plumes. The fluorometer data indicate concentrations of biogenic particles (containing chlorophyll) thus permitting recognition of the fraction of suspended particles that are not siliciclastic grains. In this case the highest concentration of biogenic particles in the upper figure occurs within the upper 20 m, where there is only a thin suspension plume, whereas in the lower figure the highest concentration occurs at the base of the surface plume with the plume itself having a relatively low concentration of such particles.

recording an increase in sediment accumulation with depth over a six-month period (October–March), the highest flux occurring at their bottom trap (441 m).

Study of the suspended particulate matter (SPM) at Brialmont Cove (Domack *et al.* 1994) determined that most particles were sand-sized floccules composed of individual grains (5–50  $\mu\text{m}$  diameter). Such floccules can be formed by flocculation (Van der Waals binding of very fine particles induced by high salinity marine water), agglomeration (attachment of organic detritus to grains), and pelletization (zooplankton faecal pellets) (Syvitski *et al.* 1987, Kim *et al.* 2004 and citations therein). Grazing zooplankton can ingest siliciclastic mineral grains of fine silt size (Kennett 1982), as shown by examination of faecal pellets from different areas (e.g. Bodungen cited in Wefer *et al.* 1988, Syvitski & Alan 1980).

Studies of sediment-water-interface ('grab-sample' core top) sediments within both fjords have shown that there is a distal limit to the extent of these plumes. Plumes appear to extend seaward only about 6 km from the head of Lester Cove (innermost Andvord Bay, Fig. 1a). This limit is generally indicated in core-top sediment by a sharp decrease in sediment grain size (from high sand percentages) with distance from the glacial terminus, toward biogenic dominated sediments (Domack & Williams 1990) further out in the fjord. At Brialmont Cove, the majority (87%) of total sediment input within the fjord was shown (Domack *et al.* 1994) to originate from midwater tongues and near-bottom turbidity currents. Bottom turbidity may reach only 3–5 km outward in the Andvord Bay fjord because of the sill present at this distance from the glacial terminus (e.g. Fig. 2). Bottom turbidity transport at Brialmont Cove is limited to < 1.5 km because of the presence of a sill about 1.7 km from the glacier terminus (Domack *et al.* 1994).

Evidence of depositional controls distinctly different from the above exists near the distal portion of Andvord Bay. Along shelf margins, basin-fill is typically the dominant style of deposition, and the largest drainage areas for glacial ice are within fjord systems (Domack *et al.* 1999b). The Andvord Drift (Harris *et al.* 1999) (Fig. 1b) is therefore an uncommon feature to be found at such close proximity to the Antarctic Peninsula. Located adjacent to Andvord Bay, the drift deposit is dominated by a fine detrital component and is thickest outside the fjord. Patterns of deposition are "consistent with sediments being eroded (or not deposited) at shallow depths (< 300 m?) and transported into deeper waters." (Harris *et al.* 1999). The depositional features observed at the Andvord Drift site (such as sediment waves, ponded sediments, and sediment drapes) are also evidence of control by deep currents. These features imply that sediments are being supplied to the drift from the Gerlache Strait, Andvord Bay, and the Aquirre and Errera channels. If so, the drift may contain a high-resolution record comprising a combination of sediment from different sources. Probably germane to our trap study, eddy-type circulation has also been observed over the Andvord Drift. Sluggish circulation here is probably due to the confluence of currents and contributes to enhanced surface productivity and the entrapment and subsequent melting of

icebergs (May *et al.* 1991, Domack & Ishman 1993). This is supported by observations of cores taken near the sediment trap locations containing muddy diatomaceous ooze with scattered pebbles (Griffith & Anderson 1989, Domack *et al.* 2003a).

Unfortunately, the very nature of these processes controlling the deposition of such a drift deposit provides a challenging environment for luminescence dating studies. Sediment deposition and reworking at depth would provide little, if any, of the daylight exposure necessary for resetting the light sensitive luminescence clock. When these traps were deployed, our working hypothesis was that a detectable contribution to deposition would be made from suspension plumes within surface and near-surface meltwater during the summer, and that deposition would be minimal or non-existent during the mostly dark winter months, when the area is covered by sea ice. However, it became apparent later that deep and bottom processes are likely the primary mechanism for sediment transport (both by bottom currents along the shelf and plumes expelled from beneath glaciers), and that deposition continues through the winter.

#### Ocean currents

The movement of ocean currents along the western side of the Antarctic Peninsula may also complicate the deposition of sediment at the two outermost sediment trap mooring locations in Fig. 1, especially because of the distance of these two trap sites from the shoreline. Three moorings were deployed, but the mooring at the near-shore site 27 (Fig. 1c) was not found.

The study area lies in the eastern zone of the Gerlache Strait, bounded on the west by the Palmer Archipelagos. To the north of the study area is the Bransfield Strait, bounded on its western side by an island group (South Shetland Islands). Along the Peninsula side of the Bransfield Strait an important current moves south-westward along the north-western side of the Antarctic Peninsula, and swings westward just north of our study area (e.g. Zhou *et al.* 2002 and fig. 1 in Domack *et al.* 2003b). This current results when surface waters from the Weddell Sea to the east of the Peninsula sweep around the northern tip of the Peninsula.

Within the Gerlache Strait (Fig. 1) is a strong surface, north-eastward flowing current (Gerlache Strait Current, Zhou *et al.* 2002) that follows the middle deep channel with speeds of 10–30 cm s<sup>-1</sup>. The surface flow exiting the Gerlache Strait forms three paths. Zhou *et al.* (2002) deployed near-surface drifters also in the Hughes Bay–Brialmont Cove area. These indicated the existence of weak surface currents and eddy-like circulations that had residence times of weeks and months. “The circulation patterns in both Bransfield and Gerlache Straits change seasonally” (Zhou *et al.* 2002). Additionally, there is also a water mass at mid–deep depths that flows southerly within the Gerlache Strait, termed the Weddell Sea

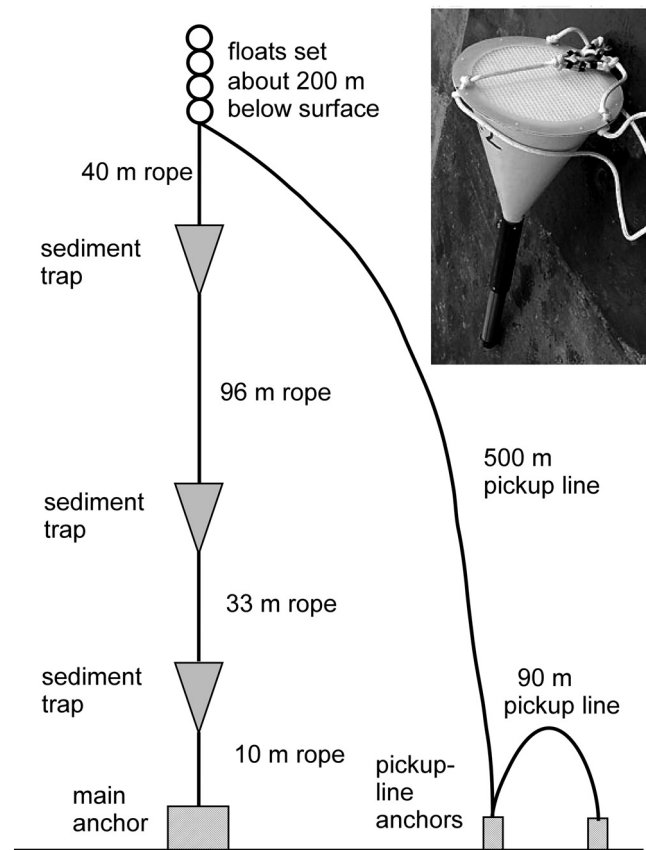


Fig. 4. Example configuration of sediment trap arrays, with a photograph (inset, credit: David Tewksbury) of a light-shielded trap tube below a baffled funnel (from Berger *et al.* 2009).

Transitional Water (WSTW) (fig. 2 in Domack *et al.* 2003b). Furthermore, Isla *et al.* (2004) deduced from a study of regional sediment cores and the preservation of biogenic components therein that in the central Gerlache Strait sediment deposition is strongly influenced by current “focusing due to lateral transport and sea floor relief”. Unfortunately, year-round seasonal data for currents (shallow and deep) within the relatively sheltered Gerlache Strait are not available.

## Experimental procedures

### Use of sediment traps

Sediment trap arrays (Fig. 4) were deployed on cruise NBP01-07 of the Antarctic research vessel *Nathaniel B. Palmer* in December 2001. Two of these moorings (Fig. 1 and site 31 in Fig. 1c) were recovered during cruise LMG03-03 of the *Lawrence M. Gould* by dragging for the 90 m pickup line. The mooring at site 27 in Brialmont Cove was not found, and was probably displaced or destroyed by icebergs. Indeed, because of such icebergs the top trap could be placed no shallower than about 200 m. Details of

**Table I.** Sediment trap arrays (Andvord Bay: 64°46.583'S; 62°49.675'W; 427 m water depth; Brialmont Cove: 64°13.249'S, 61°14.477'W, 579 m water depth) and sediment dry-mass flux. The core-barrel internal diameters are: Andvord top trap = 4.3 cm, others = 6.4 cm.

Trap	Depth (m)	Funnel ratio <sup>a</sup>	Density (g cm <sup>-3</sup> )	Linear flux <sup>b</sup> (mm yr <sup>-1</sup> )	Total flux (g cm <sup>-2</sup> yr <sup>-1</sup> )	Grains > 105 µm? <sup>c</sup>
Andvord Bay: 18 Dec 01–24 Mar 03						
Top	279	100	0.36 ± 0.03	12.32	0.44 ± 0.03	S
Middle	379	80	0.31 ± 0.04	18.50	0.57 ± 0.04	S, W, A
Bottom	416	80	0.28 ± 0.02	17.00	0.48 ± 0.03	S, SP, W
Brialmont Cove 27 Dec 01–22 Mar 03						
Top	447	80	0.36 ± 0.02	10.00	0.36 ± 0.02	S, SP, W
Middle	531	80	0.37 ± 0.02	10.50	0.39 ± 0.02	W, A
Bottom	573	80	0.41 ± 0.03	16.30	0.67 ± 0.03	W, A

<sup>a</sup>Ratio of funnel-opening area to the core-barrel internal area.

<sup>b</sup>Calculated as stated in the text. Analytical errors are at the 67% confidence level.

<sup>c</sup>Sand-size grains were sought, but only mg amounts were found, and only in some seasonal horizons (S = summer, SP = spring, W = winter, A = autumn). Seasonality determination is inferred from magnetic susceptibility profiles presented in the text, and from knowledge of the start and end of seasonality.

each array are listed in Table I. All the traps (with the exception of the Andvord Bay top trap, from Dr Rob Dunbar of Stanford University, California) were designed by Dr Robert Gilbert of Queen's University, Ontario, Canada.

Due to the expected low sedimentation rates at Andvord Bay and Brialmont Cove and the need for sufficient material for luminescence tests, we employed funnels over the core barrels (Fig. 4, inset) to amplify the accumulating sediment. However, with the use of funnels the dominant horizontal velocity component in turbulent waters can potentially resuspend sediments that have settled into the funnel. Therefore, a honeycomb-gridded baffle was placed over the tops of the traps (inset, Fig. 4 and fig. 12 in Honjo *et al.* 1992), not only to keep out large objects but also to minimize resuspension of sediment. We also used core barrels with large aspect ratios (> 7, e.g. Zajaczkowski 2002). This is the ratio of core barrel length to core barrel internal diameter. A sufficiently high aspect ratio can prevent resuspension after particles enter the tubes (Håkanson & Jansson 2002). A hypersaline solution of magnesium chloride was added to each tube before trap deployment to serve as a poison to prevent the survival of any bioturbating organisms that could settle in the traps. The collection tubes of the traps were opaque in order to prevent light exposure that would affect the sediments' luminescence properties.

After retrieval from their respective fjords, the funnel and excess PVC plastic tubing at the top of each trap (unfilled by sediments) were removed in dim amber light in a light-tight laboratory on the research vessel. Each sediment-containing core was then capped, sealed, and stored in an upright position in order to minimize disturbance of potential stratigraphy and to allow sediments to settle. These cores were shipped to Reno in an upright position. Some cores remained 'soupy' in Reno, and required an additional 10–12 months' vertical cold storage before the sediment could be extruded or the core split.

Four samples (Brialmont M1, M2, M3 and B3, identified later in Results) were removed by vertical extrusion of the

soft sediment using a customized piston, and then slicing off the desired thickness with a wire. A more consistently practicable procedure was followed for the remaining samples. The opaque plastic core walls were cut lengthwise using a hand-router saw, set to cut almost through the wall thickness. The remaining wall was cut with a box cutter. Then two, thin stainless-steel sheets were inserted together lengthwise through the cut along one side and pushed through to the opposite-side cut. At this point the two sheets were pulled apart to create two splits: an archive half and a working half. From the working half, the desired 1 cm thick intervals were removed using thin aluminium discs. The core-barrel interior diameter of the Andvord Bay top trap was smaller (4.3 cm) than that for all other traps (6.4 cm).

#### *Determination of sediment flux*

Sedimentation rates were calculated with the dry bulk weights and densities for the working core splits for each of the six sediment traps retrieved at Brialmont Cove and Andvord Bay (Ante 2005). Wet and dry weights were obtained on the aforementioned subsamples having known thickness and diameter. This information was combined with the known interior volumes of the core tubes to estimate densities. In the case of the split cores, weights were considered to comprise half of the total accumulated sediment, because the archive core halves remain unprocessed. Vertical Mass Flux was calculated from the equation  $VMF = M/tA$ , where  $A$  = core-barrel collection area,  $M$  = dry measured mass of the cylinder's contents and  $t$  = the collection period (Tennant *et al.* 2001). This flux was divided by the ratio of the area of the funnel opening to the area of the core-barrel interior cross-section.

#### *Measurement of magnetic susceptibility*

Because the sediment in the cores appeared to be structureless and homogeneous in the dim laboratory light (Berger & Kratt 2008), and to be dominantly silty to

clayey-silt in texture, and because quantitative seasonal diatom-assemblage data were not available, we relied upon along-core profiles of magnetic susceptibility (MS) as a proxy for seasonality. MS profiles along marine cores have been used as a convenient, non-intrusive, way to gather indirect information about mineralogy, grain size, and biogenic content (e.g. Andrews & Jennings 1987, Frederick *et al.* 1991, Domack & Ishman 1992, Brachfeld & Banerjee 2000). MS reflects the concentration, mineralogy and particle size of ferrimagnetic minerals (e.g. Brachfeld *et al.* 2002, Evans & Heller 2003). Several studies of bottom cores in the region have revealed that high biogenic/carbon content corresponded with low points in the MS profiles (e.g. Brachfeld *et al.* 2002, Domack *et al.* 2003a and citations therein). That is, peaks and troughs in MS profiles can represent respectively periods of relatively low and high biogenic productivity. In Gerlache Strait, for example, biogenic productivity is highest in the spring and summer (e.g. Isla *et al.* 2004 and citations therein), and minimal or non-existent during the seasons of sea ice cover and darkness. We expected that at the trap sites, high levels of biogenic flux would dilute the magnetic terrigenous portion of total flux, so that peaks and troughs in MS profiles would represent respectively periods of relatively low (winter) and high (summer) biogenic productivity.

The cores were passed (in 1 cm steps) vertically through a 9 cm diameter coil of a Bartington model MS2C magnetic susceptibility meter. We observed peaks and troughs in the MS profiles, and interpret these to represent relative seasonality. The lowered values near and at the ends of each core partly reflect the detector coil's effective sampling of space beyond the ends. The along-core positions of the coil centre are represented by the data points in the MS profiles presented below. Since we know the season of trap deployment and recovery, we can interpolate roughly the seasonality of intermediate zones in the 14 month sediment trap cores.

#### *Grain size analysis*

In glaciomarine sediments, grain size distributions can be used to infer the proportion of varying sediment components attributable to varying sources (meltwater plumes, ice rafting, aeolian, etc.). Using small (~0.13 ml) samples and a laser particle size analyser (Malvern Master Sizer-E, Hamilton College), we measured grain size distributions of bulk-sample grains for sizes up to 600  $\mu\text{m}$ . Samples were selected at ~1 cm intervals from each trap and prepared according to Warner & Domack (2002). Unfortunately, no samples from the bottom trap of Andvord Bay were analysed.

#### *Microprobe analysis*

Knowledge of the mineralogy of the fine silt samples can be useful in interpreting the luminescence signal because

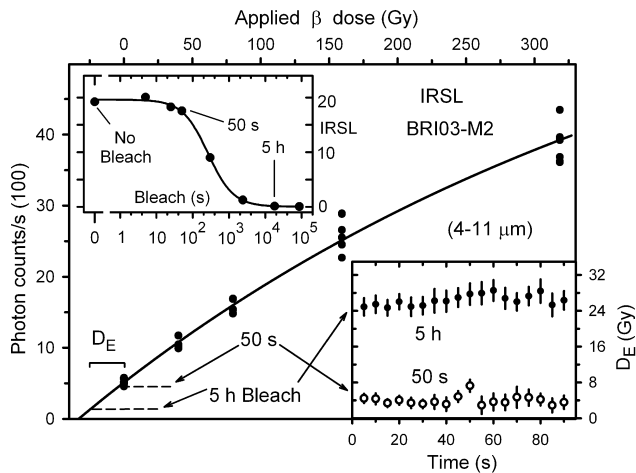
quartz and various feldspars emit signals at different wavelengths (Berger 1995, Krbetschek *et al.* 1997). Most of our dating experiments detected emissions only near 410 nm wavelengths (deep blue), wavelengths for which K-feldspars often provide a stable signal. However, our silt samples contained both quartz and feldspar grains. Therefore, to characterize our fine silt, polymineral, siliciclastic samples, microprobe analyses were performed on 'summer' and 'winter' samples from each trap to determine whether variations in feldspar concentrations were contributing to any variations in luminescence between samples.

Mineralic proportions were determined using microprobe point-count element-calibrated analysis at the University of California Davis' Department of Geology. Aliquots (1 cm diameter Al discs) of the same 4–11  $\mu\text{m}$  diameter grains used for luminescence measurements were coated with carbon and analysed with a Cameca SX100 Electron Probe Microanalyzer to determine the quartz-to-feldspar ratio and the relative proportions of Na-, K-, and Ca-feldspars, using the UC-Davis calibration procedures.

#### *Sample preparation for luminescence measurements*

Samples representing 'summer' deposition from all three Andvord Bay sediment traps exhibited a very low yield of siliciclastic grains because of the high concentration of biogenic material, such as diatoms. That is, at this site terrigenous sediment deposited during the inferred summer months was more diluted by biogenics than the sediment representing inferred winter deposition. Consequently, to obtain sufficient siliciclastic material for luminescence tests from 'summer' samples at this site, we combined adjacent 1 cm slices of sediment. These additional slices were chosen based on their positions on the magnetic susceptibility curves (presented below). For shorter cores, it was more difficult to combine samples while isolating seasonality. For example, top-trap 'summer' and 'autumn' samples from Andvord Bay are only 1 cm apart.

Fine silt size (4–11  $\mu\text{m}$  diameter range) particles were chosen for luminescence measurements because use of this size range simplifies the dosimetry in luminescence dating (Aitken 1985) and this range is part of the dominant grain size range in the Antarctic fjord depositional system. Sand grains are usually associated with ice rafted debris (IRD) and proximity to glacial termini, and such grains drop out of suspension quickly. Silt and smaller grains are carried farther horizontally in turbid waters and dispersed over a wider area (Domack & McClennen 1996) (e.g. Fig. 2), potentially providing more opportunity for daylight exposure, and thus more suited to luminescence dating than glacier-proximal sand grains. Following chemical treatments to destroy carbonates and organic matter (e.g. Berger & Doran 2001), wet filtering was performed to isolate larger grains (> 105  $\mu\text{m}$  diameters), and wet settling was used to isolate 4–11  $\mu\text{m}$  diameter siliciclastic grains.



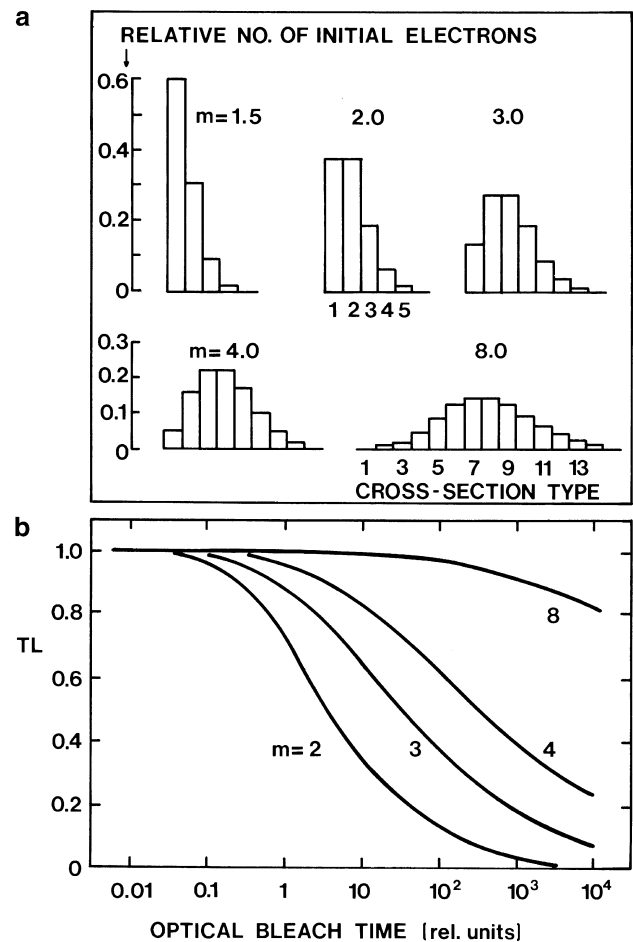
**Fig. 5.** Plots of a bleaching response (upper inset), multi-aliquot dose-response curve with 'total-bleach' intersections (centre) for the integrated first 5 s of IRSL, and the resultant  $D_E$ -time plots (lower inset) for the Brialmont Cove 'summer' sample BRI03-M2. An apparent age is calculated from the mean of the  $D_E$  values for the first several seconds (e.g. 0–40 s) of signal release (Berger *et al.* 2009). Note that the 5 h bleach IRSL intensity in the main figure is significantly larger than the 5 h intensity in the upper-left inset. This increase is caused by the thermal-transfer effect (Ollerhead *et al.* 1994). The aliquots in the bleaching response curves (upper inset and Fig. 10 below) were not heated prior to signal readout, whereas all aliquots in the  $D_E$ -measurement experiments for Brialmont Cove were heated at 155°C for two days prior to signal readout.

Only two of the samples yielded a noticeable amount of  $> 105 \mu\text{m}$  grains (about 200–500 grains) after sieving, but this was insufficient for further processing for luminescence work. Had more sand grains been available we might have attempted single-grain-quartz (e.g. Lian & Roberts 2006) photon-stimulated-luminescence (PSL, Aitken 1998) dating.

#### Luminescence measurements

A luminescence apparent age equals  $D_E/D_R$ , where  $D_E$  is palaeodose or 'equivalent dose' and  $D_R$  is dose rate. Dose rates were determined as outlined elsewhere (Berger & Doran 2001), from measurements of saturation water concentration, and of concentrations of U, Th and K. Using aliquots of 4–11  $\mu\text{m}$  diameter polymineral grains, we determined  $D_E$  values using both multi-aliquot (Aitken 1998, Berger & Doran 2001) and single aliquot PSL dating procedures (Banerjee *et al.* 2001, Watanuki *et al.* 2005). The single aliquot results revealed no clear seasonal differences, and are presented and discussed elsewhere (Berger *et al.* 2009).

To aid in choosing laboratory bleach times for the measurement of  $D_E$  values, we conducted several bleaching response experiments on samples from the Brialmont Cove traps. Groups of aliquots were exposed to 'orange-red' (560–800 nm wavelengths herein) optically filtered light



**Fig. 6.** Conceptual model of bleaching response curves for the light sensitive component of thermoluminescence (TL). This also applies to IRSL, showing: **a.** Poisson distributions of charge traps having different mean ( $m$ ) photonic cross sections, **b.** corresponding calculated bleaching response curves for a first-order-kinetics model (from Berger 1990).

(e.g. Berger & Doran 2001) to simulate the dominant colour of ambient light within sediment plumes (Berger 1990). Infrared-stimulated-luminescence (IRSL) was recorded at 30°C. Inter-sample feldspar-mass differences were normalized later by administering a post-IRSL, constant, small beta dose to six optically drained aliquots from each sample, then measuring the IRSL again.

Based on the bleaching experiments, we employed both 50 s ('short bleach') and 5 h ('long bleach') bleaching times in multi-aliquot IRSL dating experiments, as explained below. IRSL was detected in the blue (centred at 410 nm emissions). In polymineral samples, IRSL arises from only feldspars (Aitken 1998).  $D_E$  values as a function of IR stimulation time were obtained by extrapolation from dose-response luminescence curves to the intersection point with the IRSL intensity defined by either the short or long bleaching (e.g. Fig. 5).



### Rationale for use of 'short' bleaching

We used short bleaching in an attempt to isolate the youngest IRSL signals in partially zeroed polymineral grains. Each aliquot of fine silt grains contains several thousands of grains (e.g. Duller 2008). The 50 s bleaching time was chosen because for our samples this represents the approximate knee of IRSL reduction in log-log (and linear-log) plots (Berger 2006) of IRSL vs bleaching time (e.g. upper inset, Fig. 5).

The physics of the release of PSL (usually denoted OSL, 'optically-stimulated luminescence', Berger 1986), is complex and poorly understood at the atomic scale. For example, charge-traffic models of PSL vs stimulation time can invoke almost limitless numbers of atomic scale variables (e.g. Bøtter-Jensen *et al.* 2003, pp. 34–35). The shapes of the release curves vary with mineral type and stimulation wavelengths, among other variables. Two key variables are photon flux ( $\Phi$ ) and photo-ionization cross section ( $\sigma$ ). PSL is proportional to the number of light sensitive crystal traps of charges (electrons or holes). In the simplest first-order-kinetics (no re-trapping, etc.) models, the initial number of charges ( $n_{0i}$ ) decreases exponentially according to the relation  $n_i = n_{0i}e^{-(t/\tau_i)}$ , where  $t$  is the photonic stimulation time (during signal readout or during laboratory bleaching tests),  $\tau_i$  is a time constant  $= (\Phi\sigma_i)^{-1}$ , and  $i$  represents traps of a given 'type' (having the same cross-section) (e.g. Berger 1990).

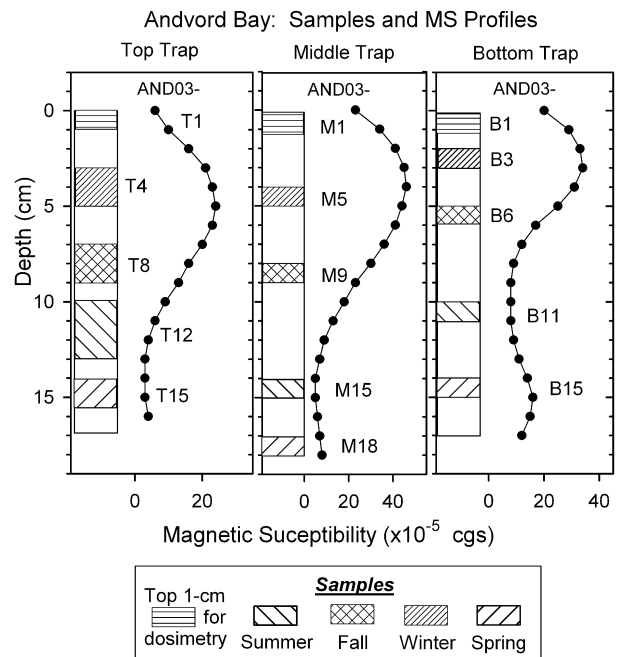
Thermally stimulated luminescence (TSL or TL) consists of a light sensitive component plus a light-insensitive component, whereas PSL consists of only a light sensitive component. In the above first-order-kinetics model, with photonic stimulation TL would reduce to a finite, non-zero level, and PSL would reduce to zero. In practice, the bleaching response signal from real samples (single minerals or mineral mixtures) appears to consist of one or more single-exponential components, but can be modelled more complexly. Whether the photonic bleaching occurs during signal readout (in the dating experiment) or during exposure to sunlight or controlled wavelength laboratory light to simulate bleaching effects under geological conditions, the bleaching curves would obey the same mathematical forms (other variables being equal).

Berger (1990) proposed a conceptual bleaching response model for TL consisting of a Poisson distribution of trap types. His calculations produced bleaching response curves for scenarios wherein a sample contained Poisson distributions of different trap types. Essentially the first-order-kinetics simulated response curves are summations of different single exponential response curves. If the sample were dominated by low 'Poisson-mean' numbers, then a bleaching curve would drop quickly on a linear-log plot. This kind of sample could be thought of as having mostly 'easily bleached' (high  $\sigma$ ) light sensitive charge traps. Other simulated samples with higher Poisson-mean numbers exhibited a delayed reduction in TL

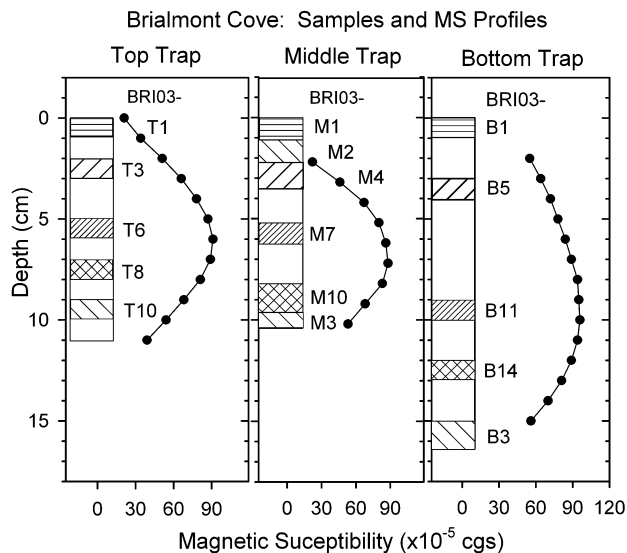
(or PSL in this discussion) (Fig. 6), with a delayed 'knee'. Conceptually then, in IRSL multi-aliquot dating a series of short laboratory 'bleaches' before or near the knee is attained could extract the age of the most readily zeroed PSL components. These would be the components yielding the youngest PSL ages from samples exposed to only a limited duration of daylight, or for a mixture of grains only some of which were exposed to sufficient daylight to empty their light sensitive charge traps.

In principle, each of the short bleach (before and near the knee) IRSL multi-aliquot dating experiments should yield nearly the same (within analytical error)  $D_E$  values, much smaller than  $D_E$  values derived from use of longer bleaching times. There is some evidence supporting this 'constancy' of short bleach  $D_E$  values in data from core-top samples around the Antarctic Peninsula (Berger, unpublished data). Unfortunately, the precision in the short bleach  $D_E$  values is lower than that for long bleaches.

For samples poorly 'zeroed' by daylight (as are our trap samples), long bleach ages would greatly exceed the true age simply because the laboratory bleaching would empty traps that were never emptied in nature (a long understood concept, e.g. Aitken 1985 and citations therein). As stated, we employed a short bleach time of about 50 s and a long bleach time of 5 h. The 50 s and 5 h bleaching times are particular to the specific optical geometries of our laboratory bleaching lamps (optical flux  $3.8 \text{ mW cm}^{-2}$ ), and the general responses of fine silt samples in our project.



**Fig. 7.** Magnetic susceptibility profiles, inferred seasons and the luminescence sample naming scheme for the Andvord Bay traps. The respective depths of the 3 traps were: 279 m (top), 379 m (middle), 416 m (bottom) (modified from Berger *et al.* 2009).



**Fig. 8.** As in Fig. 7, but for Brialmont Cove (modified from Berger *et al.* 2009).

Other geometries would yield different choices of times, but the optical fluence and the sample, not the bleaching time, determine the position of the knee.

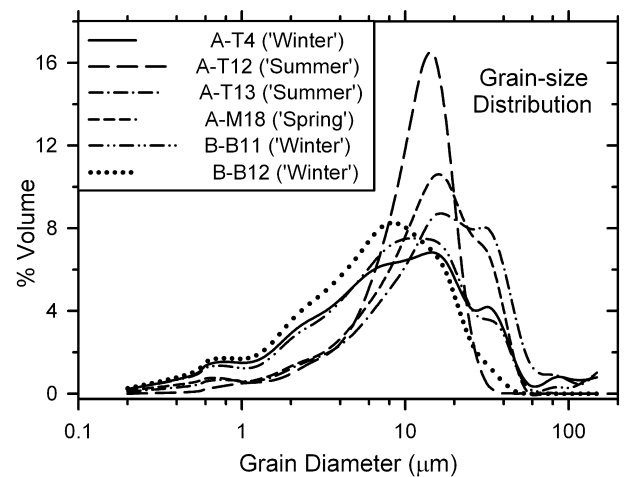
The implications of the above conceptual model can also be interpreted within the context of more recent ideas of PSL or TL ‘release components’ (e.g. Bøtter-Jensen *et al.* 2003). For example, for quartz it is now common to describe the PSL release (bleaching response) curves as consisting of 2–6 components (e.g. ‘fast’, ‘medium’, ‘slow’), each represented by single-exponential (or other) mathematical forms. Because it is now known that the photo-ionization cross sections of the various possible quartz PSL components differ by about a factor of ten from each other (e.g. Singarayer *et al.* 2005), then if similar variations occur within the polymineralic-sample IRSL of this study, the aforementioned short bleach signals should be dominated by the most light sensitive component and contain very little if any of the less light sensitive components. It would be interesting to re-formulate Berger’s (1990) model using a series of discrete-distribution time constants, rather than a Poisson distribution.

## Results

### *Magnetic susceptibility and sample selection*

The differences in MS intensities between Andvord Bay and Brialmont Cove (Figs 7 & 8) are mainly because split cores were used for MS measurements for Andvord Bay and whole cores for Brialmont Cove. To compare the two sets of MS results, the Andvord Bay measurements can be doubled.

As stated above, our samples were selected based on seasonality inferred from MS profiles. Diatom blooms of the spring and summer can dilute mineral grains enough to result in very low magnetic susceptibility levels during



**Fig. 9.** Simplex-smoothed plots of grain size distributions for selected samples that represent the range of observed distributions from the sediment traps.

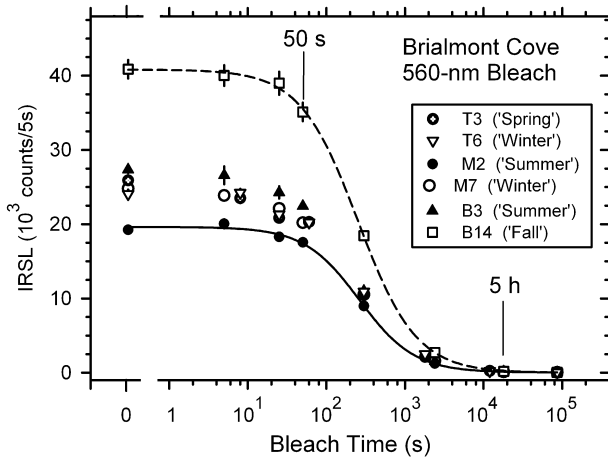
periods of high productivity. During periods of low biogenic productivity (winter), high levels of magnetic susceptibility represent relatively high concentrations of terrigenous detritus. This pattern of high and low MS with season is characteristic of top, middle, and bottom sediment traps for both Andvord Bay and Brialmont Cove. The transition from ‘spring’ to ‘summer’ (during the first few months after trap deployment) is also observable in the MS curves from all three Andvord Bay profiles, but not in profiles from Brialmont Cove. This may be due to differences in timing of peak primary productivity at the two fjords. It was assumed that this spring signal at the core base was absent for Brialmont Cove traps (deployed nine days after the Andvord Bay traps, Table I). Thus, a sample representing inferred spring deposition in this fjord was taken from the upper half of the trap cores (after the ‘winter’ MS peak, moving upward in the cores).

### *Grain size distributions*

Particle size analysis reveals very little material with diameters  $> 60 \mu\text{m}$  (Table I, Fig. 9). A broad peak in volume % is observed at  $\sim 6\text{--}20 \mu\text{m}$ , overlapping with the size range ( $\sim 4\text{--}11 \mu\text{m}$ ) chosen for luminescence analyses.

### *Mineralogy*

Samples for microprobe analysis were chosen before any luminescence results were obtained. Consequently, ‘autumn’ and ‘spring’ samples were not chosen, rather only the ‘summer’ and ‘winter’ seasons from each trap, since we supposed that the greatest variability in luminescence might be manifested between ‘summer’ and ‘winter’ seasons. The microprobe results (Berger *et al.* 2009) indicate only minor fluctuations in feldspar concentrations between ‘summer’ and ‘winter’ samples, and no seasonal pattern in the quartz concentrations.



**Fig. 10.** IRSL bleaching response curves for six selected samples from the Brialmont Cove sediment traps. Each data point represents the integrated first 5 s of IRSL (stimulated at 30°C), and is the mean of 4–6 aliquots. The curves are unweighted regression fits through the data points.

Microprobe data do show a usefully large fraction of K-feldspar (7–25%) and quartz (6–28%). For polymineral samples such as ours, K-feldspar can dominate luminescence signals recorded at emission wavelengths > 400 nm. Of course, in

our single-aliquot experiments (Berger *et al.* 2009), quartz signals dominate the < 400 nm emissions because these signals were recorded after IR stimulation, which usually minimizes feldspar emissions.

#### IRSL bleaching

Two samples from each of the Brialmont Cove traps were selected for detailed tests. As stated, the intensities were scaled between samples by second-shine normalization. The signals are reduced to background by 24 h (Fig. 10), and the knee is at about the 50 s time. There are some post-normalization intensity differences and these are discussed below.

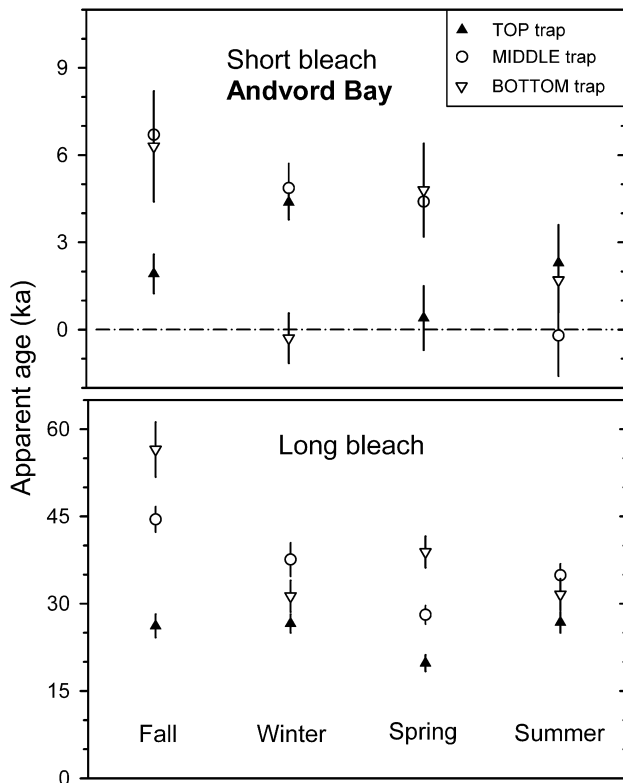
#### Apparent ages from multi-aliquot IRSL experiments

Apparent ages for fine-grained polymineral detrital sediments from both fjord sites were determined using the short and long bleach procedures (Fig. 5). These are plotted in Fig. 11 (Andvord Bay) and in Fig. 12 (Brialmont Cove), and discussed below.

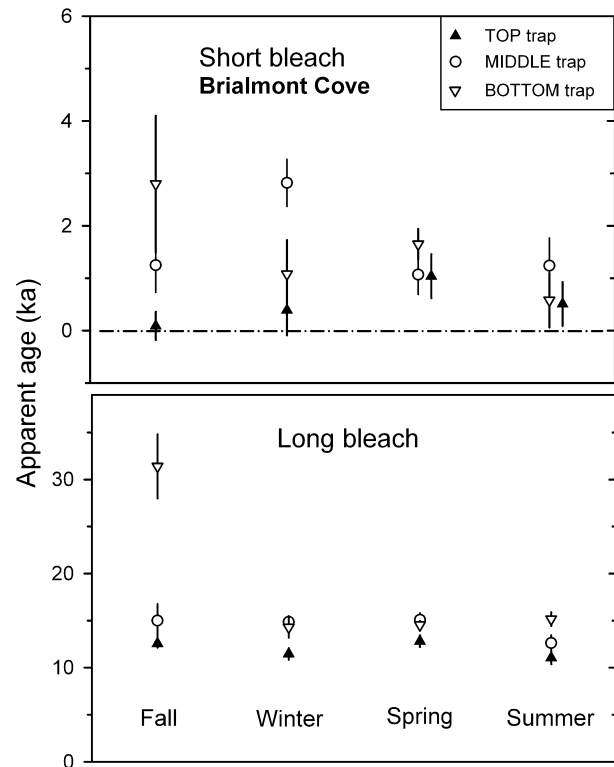
## Discussion

#### Magnetic susceptibility

The MS profiles (Figs 7 & 8) are consistent with the known occurrence of seasonal fluctuations in biogenic productivity



**Fig. 11.** Multi-aliquot short bleach and long bleach IRSL apparent age vs season for Andvord Bay trap samples. Error bars here and in Fig. 12 are  $\pm 1\sigma$  (from Berger *et al.* 2009).



**Fig. 12.** Multi-aliquot short bleach and long bleach IRSL apparent age vs season for Brialmont Cove trap samples.

at these sites. At the more southerly, polar (67°S) Lallemand Fjord on the western side of the Peninsula, MS profiles of sediment trap cores (Gilbert *et al.* 2003) were very noisy and did not exhibit any seasonal patterns. This is reasonable because in that polar setting organic surface productivity is greatly limited and consequently the majority of the year-round total flux is terrigenous (Gilbert *et al.* 2003).

#### *Sedimentation rates*

The total sediment fluxes in the top, middle and bottom traps from Andvord Bay are: 0.44, 0.57, and 0.48 g cm<sup>-2</sup> yr<sup>-1</sup>, respectively (Table I). A decrease in sediment flux between the middle and bottom traps was unexpected. If bottom currents are re-suspending sediments at depth and possibly thereby increasing the near-bottom suspension load, through the reworking of the Andvord Drift (Fig. 1b), then we would expect a larger flux in the bottom trap compared to the overlying traps. On the other hand, if the bottom currents have a high enough velocity, they could reduce the fraction of settling and re-suspended particles that might otherwise enter the bottom trap, by removing them from the local site to another part of the drift area. This suggestion is speculative because we lack any direct information on the seasonal existence and velocity of near-bottom currents. Another possible explanation might be the differential effects of faecal pellet settling, which can be quite rapid (e.g. Wefer *et al.* 1988, Kim *et al.* 2004 and citations therein). This possibility seems plausible only if most of the silt grains that can be incorporated into faecal pellets (e.g. Syvitski & Alan 1980) were horizontally transported away from the trap site before reaching the deepest trap (by the putative near-bottom current). In turn this hypothesis requires that most or all of the faecal pellets be dissolved before they reach the near bottom, thus releasing their silt particles into the water column. Again, we lack any information on the dissolution depth (e.g. Kennett 1982) of the pellicle casing of such pellets in the area.

Total sediment fluxes for our Andvord Bay samples are similar to those calculated by Mammone (1992) for central Andvord Bay sediment traps (64°49.15'S, 62°39.3'W) and for the Lallemand Fjord sediment traps of Gilbert *et al.* (2003), except that both these studies yield increased sediment flux with depth. Mammone's Andvord Bay traps collected sediment during the summer months at three depths in the water column and exhibited an increase in flux with depth ranging from g cm<sup>-2</sup> yr<sup>-1</sup> (230 m trap depth) to 0.314 g cm<sup>-2</sup> yr<sup>-1</sup> (441 m trap depth). Lallemand Fjord traps yielded total sediment fluxes (increasing with depth) between 0.17 and 0.35 g cm<sup>-2</sup> yr<sup>-1</sup>.

For Brialmont Cove, total-sediment fluxes are 0.36, 0.39 and 0.67 g cm<sup>-2</sup> yr<sup>-1</sup> for top, middle and bottom traps, respectively (Table I). The steady increase in flux with depth suggests input of sediments both between top and

middle depths (447–531 m) and between middle and bottom depths (531–573 m). These flux changes are similar to those of Mammone (1992) (central Andvord Bay) and to those of Gilbert *et al.* (2003) (Lallemand Fjord), in that both of those studies yield increased total sediment flux with depth. Our observed fluxes are 3–7 times the sediment accumulations rates (SARs) estimated from short bottom cores within the Gerlache Strait (Isla *et al.* 2004), and 10–30 times the mass fluxes determined in Bransfield Strait from 12 month sediment traps (Kim *et al.* 2004).

#### *Grain size distributions*

Although there was little sand-sized material in the trap samples, with wet sieving we detected the presence of coarse sand (1–2 mm diameters) and/or granules/pebbles (sub-angular to sub-rounded) in the horizons shown in Table I. The largest observed pebbles from Brialmont Cove ranged from 4–8 mm in diameter, while the largest pebbles from Andvord Bay trap sediments ranged from 3–5 mm in diameter. The presence of such large IRD is consistent with the scenarios of winter entrapment and spring-summer melting of icebergs in eddies over the Andvord Drift. Coarse grains may exist elsewhere in the core stratigraphy of the sediment traps; however, only samples that had been filtered (four of the 1 cm slices from each core) were examined. Nonetheless, during core splitting we did not observe any granules or pebbles in the fresh faces of core splits.

The detailed grain size analyses (only representative examples are shown in Fig. 9) reveal some differences, none of which can be associated clearly with differences in luminescence behaviour. The distribution for sample A-T12 ('summer') is unique among the many (not all shown) curves we obtained. This sample is centred on the interval 12 cm in Fig. 7. Some samples (e.g. A-T13, A-M18, A-T4) show relatively larger contributions at *c.* 40 μm than do others. Andvord Bay top-trap samples T10 and T11 (not shown) are similar to that for A-T13 except that A-T11 has a greatly reduced grain size fraction at 40 μm diameters. Some samples (e.g. B-B12, B-B11, A-T4) show relatively larger contributions of clay-size (< 4 μm) particles than do others.

Considering all the measured distributions, we observe that at Andvord Bay there is a systematically higher fraction (> 20%) of clay-size particles in the 'autumn' and 'winter' samples than in the 'summer' samples (~10%), within both the top and middle traps. This difference may reflect the dominance of diatoms only in the 'summer' horizons and their relatively smaller concentration (or absence) at other inferred seasons, or may be influenced by seasonal faecal pellet settling (expected to be dominant in the summer), or may simply reflect the longer suspension time in the water column of the preceding-summer clay-size particles not removed by faecal pellets during the

summer. Zooplankton grazers can generate faecal pellets containing silt-size and smaller mineral particles (Syvitski & Alan 1980). At Brialmont Cove there is no such seasonal variation in the percent-clay fraction, although it averages ~20% in the top trap and ~25% in the middle and bottom traps. At Brialmont Cove (we made no diatom observations for the Andvord Bay trap samples), there are diatoms in both the 'summer' and 'winter' fractions, probably a consequence of deep current re-suspension during winter of summer-bloom diatom-rich deposits in this open bay setting, but we did not estimate relative concentrations of diatoms. Certainly the bottom-sediment evidence of Isla *et al.* (2004) implies a significant deep-water horizontal translocation of bio-silica and fine silt within the Gerlache Strait.

In summary, the grain size distributions illustrate typical variation in the 8–20 µm size range, which in these settings relates most directly to the presence of diatom frustules (Warner & Domack 2002). The lower amplitude of this modal range in the 'winter' intervals suggests the presence of a greater number of siliciclastic particulates and fewer diatoms, consistent with variations in seasonal phytoplankton production and particulate sinking (e.g. Gilbert *et al.* 2003).

#### *IRSL bleaching-time behaviour*

The aforementioned normalization accounts for the differences in the concentrations of feldspars among the samples (the curves in Fig. 10 are scaled to equal IRSL intensities following a standard beta dose). Thus it is a surprise to see a large difference between the 'autumn' bottom-trap sample and all others. While the shapes of the bleach-response curves are very similar, the starting normalized IRSL is much higher for the 'autumn' bottom-trap sample. There is no significant scale difference among the other samples, except perhaps between the 'summer' and 'winter' samples (M2 and M7 respectively) in the middle trap. The simplest interpretation of the anomalous 'autumn' curve is that the silt-size feldspars in this sample carry a much larger relict luminescence than measured at the other seasons. Perhaps this means that during the 'autumn' season at this site, the feldspar silt grains arrived at the bottom trap from a different (older) source than did the silt grains in the other traps. In other words, the 'autumn' silt grains in the bottom trap at Brialmont Cove experienced a significantly different transport path or depositional process than for the other samples. As we see below, the 'autumn' samples from this bottom trap also produce a seasonal anomaly in apparent ages.

#### *Apparent ages from multi-aliquot IRSL*

The long bleach results in Figs 11 & 12 show clearly that all samples produce large (11–57 ka) overestimates of the true zero age (< 14 months).

#### *Andvord Bay*

Results for Andvord Bay (Fig. 11) suggest that our multi-aliquot short bleach procedure (Fig. 5) has isolated the true zero age from some samples. This discrimination is most consistent with all traps for the 'summer' deposition, but is also effective for the 'spring' season in the top trap and the 'winter' season in the bottom trap. This 'winter' short bleach result for the bottom trap is counter-intuitive and further research is necessary to understand this result. Generally, the Andvord Bay results indicate complex inter-seasonal differences in the daylight exposure histories of fine silt feldspars, differences that may be useful in future provenance or transport path studies of siliciclastic grains in the area of this fjord.

At the Andvord Bay site the greatest difference in inter-trap variation of short bleach and long bleach results appears to be between the 'autumn' and 'summer' seasons, rather than between the 'winter' and 'summer' seasons as we originally expected. This suggests that remnant luminescence at these sites is controlled significantly or dominantly by depositional mechanisms at depth in the water column. This agrees with regional studies that acknowledge the minor role in these sub-polar fjords played by particulate settling from surface suspensions from melting of glaciers. Recall that the Andvord Bay sediment trap array was positioned over a drift deposit (Fig. 1b). Implicitly, such a deposit indicates that depositional processes are controlled by currents at or near the bottom, where all wavelengths of daylight spectra have been highly attenuated and are unavailable for luminescence depletion. Such re-deposition (resuspension) at depth could readily result in the higher apparent ages in deeper traps that we observe for 'autumn' and 'spring'. That this increasing trend with depth does not exist for all seasons may suggest seasonal variation in depositional controls on the Andvord Drift.

#### *Brialmont Cove*

For the more geographically open Brialmont Cove, the short bleach results (Fig. 12) indicate that all top-trap samples except the 'spring' season apparently contain a detectable fraction of fine silt feldspars that have been exposed to some daylight. This inference also was drawn from the dual-wavelength bleaching-response TL curves (Berger *et al.* 2009) for top, middle and bottom traps at Brialmont Cove. Unexpectedly, the results in Fig. 12 permit the same inference to be drawn for the bottom-trap 'summer' and 'winter' seasons. We lack an understanding of the sedimentation processes that could explain this result. Oddly, the short bleach results indicate that the largest inter-seasonal variation occurs among the middle trap samples. In the long bleach results, only the bottom trap shows a large inter-seasonal variation, with the 'autumn' sample being anomalous. The long bleach Andvord Bay results (Fig. 11) for the middle and bottom traps also exhibit the oldest apparent ages in the 'autumn' season. In particular, as we saw in Fig. 10 for IRSL

bleaching response curves, it is the ‘autumn’ season that is most anomalous in the long bleach results from Brialmont Cove (Fig. 12).

#### *Implications of seasonality and depth variations*

The above apparent-age variations are unexpected. We expected to see the largest inter-seasonal variations in apparent ages between the ‘summer’ and ‘winter’ samples. Moreover, there is more overall variation in apparent age between season and depth for Andvord Bay than for Brialmont Cove. An ‘autumn’ age-depth trend is clear at both sites in the long bleach results, but is observable also in the short bleach results for the ‘spring’ and ‘autumn’ samples at Andvord Bay and for the ‘autumn’ samples at Brialmont Cove. The increase in long bleach apparent ages with trap depth must reflect an increased input at depth of grains having unbleached or poorly bleached luminescence. Even though our traps represent the mid-to-lower part of the water column, there is a significant increase in long bleach apparent ages between the top and middle traps at Andvord Bay, suggesting an at-depth influx of unbleached sediments in the part of the water column where the middle trap is located (379 m). Such an effect is small at Brialmont Cove, and may not be significant. Our results suggest a more complex oceanographic regime at Andvord Bay than at Brialmont Cove.

For Brialmont Cove, there is a large difference in total sediment flux (Table I) between the middle and bottom traps, and also a large difference in ‘autumn’ long bleach apparent ages (Fig. 12) and normalized IRSL (Fig. 10) between these two traps. This parallel association could mean that this difference in sediment flux (Table I) occurred within the ‘autumn’ season. To create such a large change in long bleach apparent ages between the middle and bottom traps (Fig. 12), and the anomalously large normalized IRSL in Fig. 10, the supposed ‘autumn’ increase in flux must have been in darkness, implying deep water input of sediment grains at this depth (573 m). If this change in apparent age with depth implies changes in depositional processes during certain seasons at this site, then a lack of apparent-age variation during other seasons may imply a lack of depositional variation with depth during those other seasons. Thus the long bleach results in Fig. 12 would imply little or no variation in depositional processes during the ‘winter’, ‘spring’ and ‘summer’ seasons at this trap site.

While the above inferences from the Brialmont Cove results in Fig. 12 and Table I are evident, for Andvord Bay any association between trap-depth differences in total flux (Table I) and trap-depth differences in apparent ages is not so evident. Perhaps the most notable feature of the Andvord Bay total flux values is the comparative increase in the middle trap, whereas the top and bottom traps have similar total fluxes. This different behaviour at the middle-trap depth (379 m) seems to be reflected in the relatively larger

seasonal variation in apparent ages (short- and long bleach, Fig. 11) from the middle trap at Andvord Bay compared to the middle-trap results at Brialmont Cove (Fig. 12). Certainly this middle-trap ‘anomaly’ at Andvord Bay is spread across three seasons (‘autumn’, ‘winter’, ‘summer’), unlike at Brialmont Cove, where there is only a bottom-trap ‘anomaly’ and that is confined to the ‘autumn’ season.

Clearly, the sedimentation processes at the trap site in Andvord Bay are more complex seasonally and with depth than are those at the trap site in Brialmont Cove. In this context it is worthwhile noting that the overall intensity of IRSL in the natural aliquots from Andvord Bay traps is ~10 times greater than that from Brialmont Cove. Fluctuations in IRSL natural intensity generally reflect variability in the daylight exposure history of grains, and therefore, a difference in sediment source or transport mechanisms. It is unlikely that this signal intensity difference is due mainly to differences in feldspar mineralogy (only feldspars respond to IR stimulation) of the suspensions between these sites because the microprobe data (Berger *et al.* 2009) show, if anything, slightly higher concentrations of feldspars in Brialmont Cove than in Andvord Bay. Therefore, this higher natural IRSL signal at the Andvord Bay site probably indicates a more limited cumulative daylight exposure at Andvord Bay, or input of grains at depth that retained a larger remnant signal.

Possible mechanisms that might cause influx of suspended particles at depth include increased tidal activity, storm activity, increased bottom currents, or putative effects on vertical transport of silt grains of faecal pellet rainout. Domack *et al.* (2003a, Fig. 10, grey scale plots) demonstrated the influence of tidal effects on sedimentation in their study of a mid-Holocene portion of a core from the Andvord Drift. “The amplitude of spring/neap tides is at a maximum in the spring and fall, with a pronounced minimum in the summer and winter” (Domack *et al.* 2003a, 219–220). Certainly at our Andvord Bay trap site, the largest trap-depth apparent-age differences occur in the ‘spring’ and ‘autumn’ samples (Fig. 11), suggestively paralleling the neap-tide variations.

Whatever the at-depth sediment transport mechanisms may be, they appear to be most effective at about 10 m above the bottom (e.g. bottom trap results, both trap sites). Our results suggest that the mechanisms producing increasing apparent age with depth in some samples (e.g. ‘autumn’) are regional (not specific to one fjord), but the effects of these mechanisms may be enhanced at the Andvord Bay site relative to the Brialmont Cove site. These mechanisms are probably linked to whatever is happening within Gerlache Strait. Sills at the southern entrance to Gerlache Strait are likely to block entry of any deep circumpolar water. As mentioned above, there is evidence (Domack *et al.* 2003b) for the presence at depth within Gerlache Strait of Weddell Sea Transitional Water water-mass movement. So, there appear to be several, superimposed variables at play here.

In order to identify a regional control within the Gerlache Strait, year-round fluctuations in depositional mechanisms throughout the water column need to be investigated. Unfortunately, autumn and winter observations of deep currents in the region are as yet unavailable to aid our understanding of these deep-trap luminescence results. Most ocean current studies in this region focus on surface water masses (Zhou *et al.* 2002), summer observations (Karl & Asper 1990, Anadón *et al.* 2002, Garcia *et al.* 2002), or the nearby minimum-sea-ice Bransfield Strait (Wefer *et al.* 1988, Niiler *et al.* 1991, Gordon *et al.* 2000, Gomis *et al.* 2002). It does appear that surface currents in Gerlache Strait are seasonally variable (Zhou *et al.* 2002), and if seasonably variable currents also exist at depth (especially near the bottom), then this could explain the observed differences in IRSL apparent ages that we observe. Lamellar structures in cores reported elsewhere in Antarctica (Maddison *et al.* 2005, 2006, Stickley *et al.* 2005) are interpreted to represent seasonal pulses in biogenic productivity. These structures may also be influenced partly by seasonal changes in sediment reworking via changes in current magnitude (Jacobs 1989).

In summary, the increase in apparent age with depth in the 'autumn' season at both trap sites as well as in the 'spring' season at the Andvord Bay site likely results from the incorporation of reworked bottom sediments at depth in the water column. Although the light sensitive luminescence from sediments in the top traps is obviously not well zeroed, for most samples it is more well zeroed (see short bleach results) than that from the middle and bottom traps. The concentration of poorly bleached grains would have to increase with depth to produce the increase in apparent age with depth that we observe. The relatively high apparent ages for bottom-trap 'autumn' samples probably manifest autumn changes in the strength or direction of sediment-reworking bottom currents along this part of the Antarctic Peninsula.

## Conclusions

As concluded by Berger *et al.* (2009), the luminescence results in Figs 11 & 12 indicate that the conventional long bleach fine silt dating procedure we used (multi-aliquot IRSL) is unsuitable for dating bottom sediments in these two fjords, and probably within the region. All long bleach apparent ages grossly over-estimate the true age (1–14 months) by 15–60 ka. On the other hand, short bleach apparent ages are closer to zero for most samples, though further research is needed to understand the utility of this procedure for dating regional bottom sediments.

Our use of sediment trap samples from different depths within the lower water column in two different fjords, and our use of two complementary optical bleaching procedures (short and long bleach) plus normalized IRSL bleaching-response behaviour indicate quantitative differences in the degree to which natural daylight has zeroed the light

sensitive luminescence during a 14 month interval. There is a strong seasonal variation in apparent ages, with 'autumn' samples evincing the largest differences from other seasons, and with 'autumn' samples revealing the largest variation in apparent ages with depth. Thus these light-sensitive luminescence results appear to provide a proxy indicator of seasonal changes in mechanisms of deposition in the lower water column at the study sites. More precise estimation of the seasonality of the horizons within the sediment trap cores would provide a fuller understanding of our results. For example, small along core samples from our cores should be examined for total and relative species concentrations of diatoms.

The luminescence results reveal both regional (within Gerlache Strait) and intra-regional (between fjords) changes in depositional controls. That the 'autumn' samples at both sites evince the largest age-depth differences, compared to other seasons, suggests a previously unrecognized regional effect. On the other hand, the IRSL natural intensities (per unit aliquot feldspar mass) and palaeodose values (Berger *et al.* 2009) differ between Andvord Bay and Brialmont Cove. Overall, the observations imply the importance of seasonal changes in currents (magnitudes and directions) for seasonal reworking of fine silts. Such seasonal reworking may influence aspects of the creation of lamellar structures in cores observed elsewhere in Antarctica.

Further investigation of depositional changes and annual deep-current trajectories for the Gerlache Strait region is needed to understand the significance of such changes for other sediment-record studies. For example, yearlong current-velocity depth-profile moorings over the Andvord Drift and elsewhere would be informative. The small contribution of surface plumes to sediment flux in this sub-polar environment places even more importance on the understanding of depositional processes at depth in the water column.

Microprobe data (Berger *et al.* 2009) do not indicate any significant seasonal, relative differences in percent feldspar mineralogy, but do show a slightly higher concentration of feldspars in Brialmont Cove traps than in Andvord Bay traps. Grain size data do indicate seasonal differences in concentrations of clay-size grains within some of the traps at both the Andvord Bay and Brialmont Cove sites.

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## References

- AITKEN, M.J. 1985. *Thermoluminescence dating*. San Diego, CA: Academic Press, 351 pp.
- AITKEN, M.J. 1998. *An introduction to optical dating*. Oxford: Oxford University Press, 262 pp.
- ANADÓN, R., ALVAREZ-MARQUES, F., FERNANDEZ, E., VARELA, M., ZAPATA, M., GASOL, J.M. & VAQUÉ, D. 2002. Vertical biogenic particle flux during austral summer in the Antarctic Peninsula area. *Deep-Sea Research II*, **49**, 883–901.
- ANDERSON, J.B. 1999. *Antarctic marine geology*. Cambridge: Cambridge University Press, 289 pp.
- ANDREWS, J.T. & JENNINGS, A.E. 1987. Influence of sediment source and type on the magnetic susceptibility of fiord and shelf deposits, Baffin Island and Baffin Bay, N.W.T. *Canadian Journal of Earth Sciences*, **24**, 1386–1401.
- ANTE, S. 2005. *Luminescence dating tests of detrital grains from sediment traps, Andvord Bay and Brialmont Cove, Antarctic Peninsula*. MS thesis, (thesis 5759), University of Nevada, Reno, 124 pp. [Unpublished].
- BALDWIN, R.J. & SMITH, K.L. 2003. Temporal dynamics of particulate matter fluxes and sediment community response in Port Foster, Deception Island, Antarctica. *Deep-Sea Research II*, **50**, 1707–1725.
- BANERJEE, D., MURRAY, A.S., BØTTER-JENSEN, L. & LANG, A. 2001. Equivalent dose estimation using a single aliquot of polymineral fine grains. *Radiation Measurements*, **33**, 73–94.
- BARKER, P.R., DALZIEL, I.W.D. & STOREY, B.C. 1991. Tectonic development of the Scotia Arc Region. In TINGEY, R.J., ed. *Antarctic geology*. Oxford: Oxford University Press, 215–248.
- BERGER, G.W. 1986. Dating Quaternary deposits by luminescence - recent advances. *Geoscience Canada*, **13**, 15–21.
- BERGER, G.W. 1990. Effectiveness of natural zeroing of the thermoluminescence in sediments. *Journal of Geophysical Research*, **95**, 12 375–12 397.
- BERGER, G.W. 1995. Progress in luminescence dating methods for Quaternary sediments. In RUTTER, N.W. & CATTO, N.R., eds. *Dating methods for quaternary deposits*. : Geological Association of Canada, 81–104.
- BERGER, G.W. 2006. Trans-Arctic-Ocean tests of fine-silt luminescence sediment dating provide a basis for an additional geochronometer for this region. *Quaternary Science Reviews*, **25**, 2529–2551.
- BERGER, G.W. & DORAN, P.T. 2001. Luminescence-dating zeroing tests in Lake Hoare, Taylor Valley, Antarctica. *Journal of Paleolimnology*, **25**, 519–529.
- BERGER, G.W. & KRATT, C. 2008. LED laboratory lighting. *Ancient TL*, **26**, 9–11.
- BERGER, G.W., ANTE, S. & DOMACK, E. 2009. Luminescence from glaci-marine sediment-trap samples at the Antarctic Peninsula. *Quaternary Geochronology*, 10.1016/j.quageo.2009.01.10.
- BØTTER-JENSEN, L., MCKEEVER, S.W.S. & WINTLE, A.G. 2003. *Optically stimulated luminescence dosimetry*. Amsterdam: Elsevier, 350 pp.
- BRACHFELD, S.A. & BANERJEE, S.K. 2000. Rock-magnetic carriers of century-scale susceptibility cycles in glacial-marine sediments from the Palmer Deep, Antarctic Peninsula. *Earth and Planetary Science Letters*, **176**, 443–455.
- BRACHFELD, S.A., BANERJEE, S.K., GUYODO, Y. & ACTON, G.D. 2002. A 13,200 year history of century to millennial scale paleoenvironmental change magnetically recorded in the Palmer Deep, western Antarctic Peninsula. *Earth and Planetary Science Letters*, **194**, 311–326.
- DOMACK, E.W. & ISHMAN, S. 1992. Magnetic susceptibility of Antarctic glacial marine sediments. *Antarctic Journal of the United States*, **27**(5), 64–65.
- DOMACK, E.W. & ISHMAN, S. 1993. Oceanographic and physiographic controls on modern sedimentation within Antarctic fjords. *Geological Society of America Bulletin*, **105**, 1175–1189.
- DOMACK, E.W. & MAMMONE, K.A. 1993. Modern sedimentation within Andvord Bay, Antarctic Peninsula. *Antarctic Journal of the United States*, **28**, 97–98.
- DOMACK, E.W. & MAYEWSKI, P.A. 1999. Bi-polar ocean linkages: evidence from late-Holocene Antarctic marine and Greenland ice-core records. *The Holocene*, **9**, 247–251.
- DOMACK, E.W. & MCCLENNEN, C.E. 1996. Accumulation of glacial marine sediments in fjords of the Antarctic Peninsula and their use as late Holocene paleoenvironmental indicators. *Antarctic Research Series*, **70**, 135–154.
- DOMACK, E.W. & WILLIAMS, C.R. 1990. Fine structure and suspended sediment transport in three Antarctic fjords. *Antarctic Research Series*, **50**, 71–89.
- DOMACK, E.W., FOSS, D.J.P., SYVITSKI, J.P.M. & MCCLENNEN, C.E. 1994. Transport of suspended particulate matter in an Antarctic fjord. *Marine Geology*, **121**, 161–170.
- DOMACK, E.W., BURNETT, A. & LEVENTER, A. 2003b. Environmental setting of the Antarctic Peninsula. *Antarctic Research Series*, **79**, 1–13.
- DOMACK, E.W., HALL, B. & HAYES, J.M. 1999a. Accurate Antarctic dating techniques sought by Quaternary Community. *Eos Transactions AGU*, **80**, 591–596.
- DOMACK, E.W., TAVIANI, M. & RODRIGUEZ, A. 1999b. Recent sediment remolding on a deep shelf, Ross Sea: implications for radiocarbon dating of Antarctic marine sediments. *Quaternary Science Reviews*, **18**, 1445–1451.
- DOMACK, E.W., LEVENTER, A., ROOT, S., RING, J., WILLIAMS, E., CARLSON, D., HIRSHORN, E., WRIGHT, W., GILBERT, R. & BURR, G. 2003a. Marine sedimentary record of natural environmental variability and recent warming in the Antarctic Peninsula. *Antarctic Research Series*, **79**, 205–224.
- DULLER, G.A.T. 2008. Single grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. *Boreas*, **37**, 589–612.
- EVANS, M.E. & HELLER, F. 2003. *Environmental magnetism: principles and applications of enviromagnetics*. San Diego, CA: Academic Press, 382 pp.
- FREDERICK, B.C., DOMACK, E.W. & MCCLENNEN, C.E. 1991. Magnetic susceptibility measurements in Antarctic glacial-marine sediment from in front of the Müller Ice Shelf, Lallemand Fjord. *Antarctic Journal of the United States*, **26**, 126–128.
- GARCIA, M.A., CASTRO, C.G., RIOS, A.F., DOVAL, M.D. & ROSON, G. 2002. Water masses and distribution of physico-chemical properties in the western Bransfield Strait during austral summer 1995/96. *Deep-Sea Research II*, **49**, 585–602.
- GILBERT, R. 2000. Environmental assessment from the sedimentary record of high-latitude fjords. *Geomorphology*, **32**, 295–314.
- GILBERT, R., CHONG, A., DUNBAR, R.B. & DOMACK, E.W. 2003. Sediment trap records of glaci-marine sedimentation at Müller Ice Shelf, Lallemand Fjord, Antarctic Peninsula. *Arctic, Antarctic and Alpine Research*, **35**, 24–33.
- GOMIS, D., GARCIA, M.A., LOPEZ, O. & PASCUAL, A. 2002. Quasi-geostrophic 3D circulation and mass transport in the western Bransfield Strait during austral summer 1995/96. *Deep-Sea Research II*, **49**, 60–621.



- GORDON, A.L., MENSCH, M., DONG, Z., SMETHIE, JR, W.M. & BETTENCOURT, J. 2000. Deep and bottom water of the Bransfield Strait eastern and central basins. *Journal of Geophysical Research*, **105**, 11 337–11 346.
- GRIFFITH, T.W. & ANDERSON, J.B. 1989. Climatic control of sedimentation in bays and fjords of the northern Antarctic Peninsula. *Marine Geology*, **85**, 181–204.
- GRIKUROV, G.E. 1978. *Geology of the Antarctic Peninsula*. New Delhi: Amerind Publishing Co, 140 pp.
- HÅKANSON, L. & JANSSON, H. 2002. *Principles of lake sedimentology*. Caldwell, NJ: Blackburn Press, 308 pp.
- HARRIS, P.T., DOMACK, E.W., GILBERT, R. & LEVENTER, A. 1999. Andvord drift: a new type of inner shelf, glacial marine deposystem from the Antarctic Peninsula. *Geology*, **27**, 683–686.
- HOLM-HANSEN, O. & MITCHELL, B.G. 1991. Spatial and temporal distribution of phytoplankton and primary production in the western Bransfield Strait region. *Deep-Sea Research*, **38**, 961–980.
- HONJO, A., SPENCER, D. & GARDNER, W. 1992. A sediment intercomparison experiment in the Panama Basin. *Deep-Sea Research*, **39**, 333–358.
- ISLA, E., MASQUÉ, P., PALANQUES, A., GUILLÉN, J., PUIG, P. & SANCHEZ-CABEZA, J.A. 2004. Sedimentation of biogenic constituents during the last century in western Bransfield and Gerlache Straits, Antarctica: a relation to currents, primary production, and sea floor relief. *Marine Geology*, **209**, 265–277.
- JACOBS, S.S. 1989. Marine controls on modern sedimentation on the Antarctic continental shelf. *Marine Geology*, **85**, 121–153.
- KARL, D.M. & ASPER, V.L. 1990. Racer: particle flux measurements during the 1989–1990 austral summer. *Antarctic Journal of the United States*, **25**, 167–169.
- KARL, D., TIEN, G., TILBROOK, B., BAILIFF, M.D., NAWROCKI, M., TAYLOR, G. & HABERSTROH, P. 1987. RACER: seasonal changes in the downward flux of biogenic matter. *Antarctic Journal of the United States*, **22**(5), 157–158.
- KENNETT, J.P. 1982. *Marine geology*. Englewood Cliffs, NJ: Prentice-Hall, 787 pp.
- KIM, D., KIM, D.-Y., KIM, Y.-J., KANG, Y.-C. & SHIM, J. 2004. Downward fluxes of biogenic material in Bransfield Strait, Antarctica. *Antarctic Science*, **16**, 227–237.
- KRBETSCHKEK, M.R., GÖTZE, J., DIETRICH, A. & TRAUTMANN, T. 1997. Spectral information from minerals relevant for luminescence dating. *Radiation Measurements*, **27**, 695–748.
- LENN, Y.-D., CHERESKIN, T.K. & GLATTS, R.C. 2003. Seasonal and tidal variability in currents, stratification and acoustic backscatter in an Antarctic ecosystem at Deception Island. *Deep-Sea Research II*, **50**, 1665–1683.
- LEVENTER, A., DOMACK, E.W., ISHMAN, S.E., BRACHFELD, S., MCCLENNEN, C.E. & MANLEY, P. 1996. Productivity cycles of 200–300 years in the Antarctic Peninsula region: understanding linkages among the sun, atmosphere, oceans, sea ice, and biota. *Geological Society of America Bulletin*, **108**, 1626–1644.
- LIAN, O.B. & ROBERTS, R.G. 2006. Dating the Quaternary: progress in luminescence dating of sediments. *Quaternary Science Reviews*, **25**, 2449–2468.
- MADDISON, E.J., PIKE, J., LEVENTER, A. & DOMACK, E.W. 2005. Deglacial seasonal and sub-seasonal diatom record from Palmer Deep, Antarctica. *Journal of Quaternary Science*, **20**, 435–446.
- MADDISON, E.J., PIKE, J., LEVENTER, A., DUNBAR, R., BRACHFELD, S., DOMACK, E.W., MANLEY, P. & MCCLENNEN, C. 2006. Post-glacial seasonal diatom record of the Mertz Glacier Polynya, East Antarctic margin. *Marine Micropalaeontology*, **60**, 66–88.
- MAMMONE, K.A. 1992. *Modern particle flux and productivity in Andvord Bay, Antarctica*. BA thesis, Hamilton College, Clinton, NY, 98 pp. [Unpublished].
- MAY, S.E., MCCLENNEN, C.E. & DOMACK, E.W. 1991. Diatom assemblages within surface waters of Andvord Bay, Antarctica. *Antarctic Journal of the United States*, **26**(5), 112–115.
- NIILER, P.P., AMOS, A. & HU, J.-H. 1991. Water masses and 200 m relative geostrophic circulation in the western Bransfield Strait region. *Deep-Sea Research*, **38**, 943–959.
- OLLERHEAD, J., HUNTLEY, D.J. & BERGER, G.W. 1994. Luminescence dating of the Buctouche Spit, New Brunswick. *Canadian Journal of Earth Sciences*, **31**, 523–531.
- SINGARAYER, J.S., BAILEY, R.M., WARD, S. & STOKES, S. 2005. Assessing the completeness of optical resetting of quartz OSL in the natural environment. *Radiation Measurements*, **40**, 13–25.
- SMITH, R.C., AINLEY, D., BAKER, K., DOMACK, E., EMSLIE, S., FRASER, B., KENNETT, J., LEVENTER, A., MOSLEY-THOMSON, E., STAMMERJOHN, S. & VERNET, M. 1999. Historical observations and paleoecological records reveal ecological transitions in the Antarctic Peninsula region. *Bioscience*, **49**, 393–404.
- STICKLEY, C.E., PIKE, J., LEVENTER, A., DUNBAR, R., DOMACK, E.W., BRACHFELD, S., MANLEY, P. & MCCLENNEN, C. 2005. Deglacial ocean and climate seasonality in laminated diatom sediments, MacRobertson Shelf, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **227**, 290–310.
- SYVITSKI, J.P.M. & ALAN, G.L. 1980. Sediment ingestion by *Tigriopus californicus* and other zooplankton: mineral transformation and sedimentological considerations. *Journal of Sedimentary Research*, **50**, 869–880.
- SYVITSKI, J.P.M., BURRELL, D.C. & SKEI, J.M. 1987. *Fjords: processes and products*. New York: Springer, 379 pp.
- TAYLOR, F., WHITEHEAD, J. & DOMACK, E. 2001. Holocene paleoclimate change in the Antarctic Peninsula: evidence from the diatom, sedimentary and geochemical record. *Marine Micropalaeontology*, **41**, 25–43.
- TENNANT, D.A., BAKER, E.T., PAULSON, A.J., FEELY, R.A. & LEBON, G. 2001. Long-term studies of particulate flux on and near the Juan de Fuca Ridge. *NOAA Technical Memorandum OAR*, PMEL-118.
- WALLINGA, J. 2002. Optically stimulated luminescence dating of fluvial deposits: a review. *Boreas*, **31**, 303–322.
- WARNER, N.R. & DOMACK, E.W. 2002. Millennial to decadal-scale change during the Holocene in the Palmer Deep, Antarctica, as recorded by particle size analysis. *Paleoceanography*, **17**, 10.1029/2000PA000602.
- WATANUKI, T., MURRAY, A.S. & TSUKAMOTO, S. 2005. Quartz and polymineral luminescence dating of Japanese loess over the last 0.6 Ma: comparison with an independent chronology. *Earth and Planetary Science Letters*, **240**, 774–789.
- WEFER, G., FISCHER, G., FUETTERER, D. & GERSONDE, R. 1988. Seasonal particle flux in the Bransfield Strait, Antarctica. *Deep-Sea Research*, **35**, 891–898.
- YOON, H.I., PARK, B.-K., KIM, Y. & KIM, D. 2000. Glaciomarine sedimentation and its paleoceanographic implications along the fjord margins in the South Shetland Islands, Antarctica during the last 6000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **157**, 189–211.
- ZAJĄCZKOWSKI, M. 2002. On the use of sediment traps in sedimentation measurements in glaciated fjords. *Polish Polar Research*, **23**, 161–174.
- ZHOU, M., NIILER, P.P. & HU, J.-H. 2002. Surface currents in the Bransfield and Gerlache Straits, Antarctica. *Deep-Sea Research I*, **49**, 267–280.