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The sediment infill of subglacial meltwater channels on the West Antarctic continental shelf

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A B S T R A C T

Subglacial meltwater plays a significant yet poorly understood role in the dynamics of the Antarctic ice sheets. Here we present new swath bathymetry from the western Amundsen Sea Embayment, West Antarctica, showing meltwater channels eroded into acoustic basement. Their morphological characteristics and size are consistent with incision by subglacial meltwater. To understand how and when these channels formed we have investigated the infill of three channels. Diamictons deposited beneath or proximal to an expanded grounded West Antarctic Ice Sheet are present in two of the channels and these are overlain by glaciomarine sediments deposited after deglaciation. The sediment core from the third channel recovered a turbidite sequence also deposited after the last deglaciation. The presence of deformation till at one core site and the absence of typical meltwater deposits (e.g., sorted sands and gravels) in all three cores suggest that channel incision pre-dates overriding by fast flowing grounded ice during the last glacial period. Given the overall scale of the channels and their incision into bedrock, it is likely that the channels formed over multiple glaciations, possibly since the Miocene, and have been reoccupied on several occasions. This also implies that the channels have survived numerous advances and retreats of grounded ice.

Introduction

Recent analyses of satellite data have demonstrated the movement of considerable volumes of water beneath today's Antarctic ice sheets (Gray et al., 2005; Wingham et al., 2006; Fricker et al., 2007) potentially in well-organized channelized systems (Wingham et al., 2006; Siegert et al., 2007). In addition, the flow of water from one basin (subglacial lake) to another is thought to be sporadic and inherently unstable (Wingham et al., 2006). Since basal meltwater facilitates ice motion through increased sliding or sediment deformation, a clear understanding of the magnitude and rates of subglacial meltwater movement is important for our understanding of ice stream dynamics and ice sheet stability.

At present our knowledge of the subglacial hydrology of ice sheets is largely theoretical (e.g., Alley, 1989; Walder and Fowler, 1994, Ng, 2000; Carlson et al., 2007; Siegert et al., 2007), with observational data limited to a handful of boreholes, and a few radar and seismic studies (e.g., Engelhardt et al., 1990; Engelhardt and Kamb, 1997; King et al., 2004; Smith et al., 2007; Murray et al., 2008). However, a small number of studies, from presently ice-free areas on land and on the continental shelf have documented large subglacial drainage systems (Sugden et al., 1991; Lowe and Anderson, 2002, 2003; Ó Cofaigh et al., 2002; Denton and Sugden, 2005; Lewis et al., 2006; Domack et al., 2006) relating to periods when the ice sheet was expanded or dynamically different. In addition there is also evidence for at least one large meltwater outburst event (jökulhlaup) that occurred near Casey Station in East Antarctica, in 1985 (Goodwin, 1988). Due to the relative inaccessibility of the ice–bed interface it is therefore essential to identify whether outbursts of subglacial meltwater occurred in the past, and if so how frequent they were, by mapping their imprint on morphological and sedimentological records (Siegert et al., 2007).

Thus far, most studies have focused largely on the morphology of meltwater channels and the impact of subglacial drainage on ice flow (e.g., Domack et al., 2006; Lewis et al., 2006). However, sediments recovered from within the channels have the potential to reveal important information on channel genesis and drainage processes. For example, it has been suggested that hyperconcentrated flows associated with catastrophic discharge of water deposit massive and graded sands and gravels (Ó Cofaigh, 1996; Cutler et al., 2002; Fisher and Taylor, 2002). In general however, the sediment facies associated with subglacial drainage networks is comparatively under-studied (Benn and Evans, 1998). This is particularly the case in Antarctica where only one other study has been undertaken (e.g., Lowe and Anderson, 2003). In order to investigate the sedimentary signature of subglacial meltwater channels further we describe the sediment infill of cores retrieved from three well-defined channels on the continental shelf in the western Amundsen Sea Embayment (ASE) (Larter et al., 2007). These channels are similar in scale to those previously documented by Lowe and Anderson (2002, 2003) in the eastern ASE

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(offshore Pine Island Bay, PIB) yet the channels contain a contrasting sedimentary infill. We discuss the significance of this finding and its implications for the age of the channels and the processes by which channels may be filled.

Geomorphological and sedimentological signature of subglacial meltwater in Antarctica

To date, meltwater channels have been recognised at the presently ice-free margin of the East Antarctic Ice Sheet (EAIS) along the Soya Coast (Sawagaki and Hirakawa, 1997) and at three locations in the Dry Valleys (Sugden et al., 1991, 1999; Denton and Sugden, 2005; Lewis et al., 2006). Additional offshore drainage networks have been identified at two locations on the western Antarctic Peninsula shelf (Ó Cofaigh et al., 2002, 2005; Domack et al., 2006) and in PIB in the eastern ASE (Lowe and Anderson, 2002, 2003).

One of the most spectacular channel systems occurs in the western Wright Valley (Dry Valleys) where an impressive ca. 50-km-long network of channels, up to 600 m wide and 250 m deep, has been observed (the 'Labyrinth'; Denton and Sugden, 2005). The area is characterised by anastomosing channels and canyons cut into Ferrar Dolerite, which have longitudinal profiles with reverse gradients and abrupt termination/initiation points (Denton and Sugden, 2005; Lewis et al., 2006). The channel floors contain very little sediment, interpreted as a result of catastrophic water discharge within the channels (with estimates in the order of $1.6–2.2 \times 10^6$ m^3 s^{-1}) and/or subsequent freeze-on beneath the overriding ice (Lewis et al., 2006). It has been suggested that the channels in the Dry Valleys were formed by episodic and catastrophic drainage of one or more inland subglacial lakes (Sugden et al., 1991; Denton and Sugden, 2005; Lewis et al., 2006). For the Labyrinth, the last phase of channel incision has been constrained by ^{40}Ar/^{39}Ar dating of volcanic ash to the mid-Miocene (ca. 14.4–12.4 Ma) (Lewis et al., 2006).

Sawagaki and Hirakawa (1997) have mapped smaller scale erosional features (e.g., sichelwannen) on streamlined roche moutonnées, transverse ridges and drumlins (referred to as tadpole rocks) along the Soya Coast of Lützow-Holm Bay. They have suggested that the large-scale bedforms, although initially the result of glacial abrasion and plucking, have been subsequently shaped by subglacial meltwater erosion in the form of sheet floods. While it is likely that some of the features mapped by Sawagaki and Hirakawa (1997) reflect the influence of subglacial meltwater, the idea that sheet floods form bedrock drumlins remains controversial (Clarke et al., 2005; Evans et al., 2006a).

On the continental shelf west of the Antarctic Peninsula, Domack et al. (2006) have imaged a network of anastomosing channels, levees and 'lake deltas' that they have linked to the development, and subsequent drainage, of a subglacial lake basin ('Palmer Deep'). Domack et al. (2006) have suggested that the 800-m-deep lake formed as grounded ice expanded across the shelf during the last glacial maximum (LGM) and capped the deep inner shelf basin. Subsequent thickening of the ice over Palmer Deep and continued input of glacial meltwater via channels cut into the 'Palmer Deep Outlet Sill' is thought to have increased the hydrostatic pressure in the basin, leading to an eventual breach of the sill and drainage of the lake. Domack et al. (2006) suggested that the evacuation of water is likely to have enlarged the channels cut into the sill resulting in an impressive system of channels 200–500 m wide and 100–300 m deep. They also speculate that drainage of the lake may have initiated enhanced ice stream flow in the adjacent Hugo Island Trough through increased bed lubrication. This idea is consistent with recent observations from the Recovery Glacier (e.g., Bell et al., 2007), which show that the onset of glacier acceleration is related to the presence of subglacial lakes and their influence on the glacial thermal regime.

Ó Cofaigh et al. (2002, 2005) documented large channels cut into bedrock on the inner and middle continental shelf in Marguerite Bay, west of the Antarctic Peninsula. The channels form a crudely anastomosing system and are characterised by overdeepening along their thalwegs. They measure up to 15 km in length and 1.5 km in width, and reach depths up to 200 m. According to the authors, the channels indicate evacuation of channelized subglacial meltwater across the hard bed of the ice stream and are likely to be a product of erosion over several glacial cycles. However, Ó Cofaigh et al. (2002) observed no meltwater channels in soft sediment on the outer shelf, concluding that subglacial meltwater may have evacuated through (i) a distributed system at the ice/till interface (cf. Kamb, 2001), (ii) a network of small 'canals' (Walder and Fowler, 1994) below the resolution of their multibeam swath bathymetry data, or (iii) the subglacial till layer. The first hypothesis seems to be less likely, because Ó Cofaigh et al. (2005) found no meltwater sediments in cores from the outer shelf trough.

Lowe and Anderson (2002) mapped a complex system of subglacial meltwater channels cut into bedrock in PIB in the eastern ASE (Fig. 1). They identified various types of channels ranging from large tunnel valleys (15 km long, 2 km wide) to smaller anastomosing channels within cavities (2–14 km long, 0.2–1 km wide) and linear channels linking cavities and channels (1–10 km long, 0.5–1 km wide). A single piston core (PC46) was collected from one of the larger channels and recovered two graded sands and gravel units with pebble-to-cobble-sized clasts separated by an olive-gray clay unit. The trigger core from site PC46 retrieved olive-gray to brown clay and mud, which contains dropstones and a few microfossils (mainly arenaceous foraminifera). The clayey to muddy deposits have low shear strength (ca. 2 kPa) and form the typical postglacial sedimentary drape in inner PIB (Kellogg and Kellogg, 1987; Lowe and Anderson, 2002; Larter et al., 2007). Lowe and Anderson (2003) interpreted the clays at site PC46 as meltwater-plume deposits originating from the front of Pine Island Glacier, while they attributed the graded sands and gravels to many short-lived catastrophic outbursts of subglacial water associated with channel incision. The authors found graded deposits in only one core, but on the basis of frequent occurrence of loose gravel in core catcher samples and highly reflective internal layering on a single-channel seismic profile near the front of Pine Island Glacier they speculated it may be more widespread. Conversely, they also suggested that the absence of a widespread sand and gravel layer within PIB would imply that the bedload was completely removed from the channels and transferred down-glacier by the overriding ice. The material must have been deposited within either the deformation till on the outer shelf or gravity flow sediments on the continental slope.

In summary, large subglacial drainage systems (tunnel valleys, Nye channels and linked-cavity systems) eroded into bedrock have been mapped at several locations in East and West Antarctica, typically at the ice sheet margin. These features indicate that significant volumes of meltwater were transferred to the margins in the past, which is likely to have influenced ice flow. Furthermore, although distributed drainage networks and 'canals' have been proposed for ice resting on deformable sediment (e.g., Walder and Fowler, 1994; King et al., 2004), no conclusive evidence (see Alonso et al. (1992) and Wellner et al. (2006), who describe a mid-shelf tunnel valley in the Ross Sea eroded into sedimentary substrate) has been found for meltwater evacuation routes in soft sediment on the Antarctic continental shelf. However, this may reflect the fact that these features are not preserved following deglaciation or are below the resolution of our imaging techniques (e.g., Evans et al., 2006b). Additional geomorphological and geological information is clearly required in order to help understand the rates, magnitudes and drainage routes of subglacial water flow beneath the Antarctic ice sheets.

Regional setting of the Amundsen Sea Embayment

The Amundsen Sea continental shelf is located between 100°W and 135°W on the Pacific margin of Antarctica. The WAIS drains into the ASE

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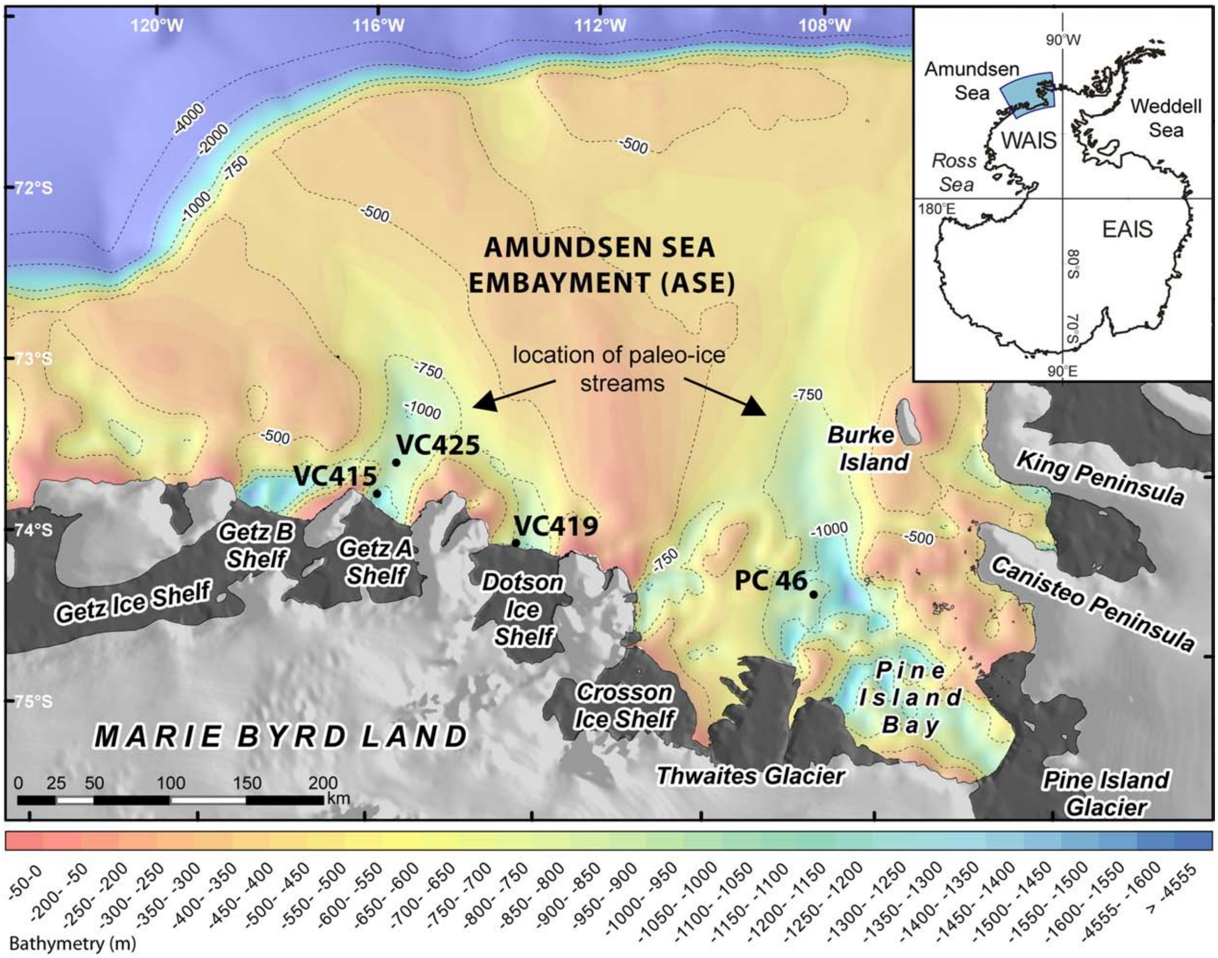

Figure 1. Bathymetry of the ASE derived from a new compilation of echo sounding data (Nitsche et al., 2007). Inset shows the location of the ASE in Antarctica. Black dots show the location of the sediment cores. The location of PC46 (analysed by Lowe and Anderson (2002, 2003)) is also shown. The bathymetry of this core site is shown in greater detail in Figure 5.

via several major fast-flowing ice streams: Pine Island Glacier, Thwaites Glacier and Smith Glacier, all of which have undergone dramatic thinning (Shepherd et al., 2004) and in some cases (e.g., Pine Island Glacier) grounding line retreat (Rignot, 1998) over the past decade. The bathymetry of the ASE is characterised by deep inner shelf basins in the western ASE (north of the Getz and Dotson Ice Shelves) and the eastern ASE (north of Pine Island and Thwaites Glaciers), which are connected to shallower troughs on the mid-shelf and represent the paleo-drainage pathways of the WAIS at the LGM (Fig. 1) (Lowe and Anderson, 2002; Evans et al., 2006b; Larter et al., 2007; Nitsche et al., 2007). Inner PIB is characterised by a deep bathymetric trough cut into bedrock, which contains meltwater channels and 'cavities' (bathymetric deeps), together with drumlins and P-forms (Lowe and Anderson, 2002, 2003). This trough might be connected to a much shallower trough on the outer shelf to the NW that exhibits streamlined subglacial bedforms and extends to the continental shelf edge (Fig. 1) (Evans et al., 2006b).

Similarly, the western ASE is characterised by three deep (ca. 1600 m water depth) inner shelf troughs cut into acoustic basement in front of the Getz and Dotson ice shelves (referred to as Dotson, Getz A and Getz B troughs) (Fig. 1). Within 70 km of the Dotson/Getz ice fronts these troughs merge northwards into a single trough containing highly elongate mega-scale glacial lineations (elongation ratio 40:1) that shoals gradually towards the shelf edge (Larter et al., 2007; Nitsche et al., 2007). These inner shelf troughs are characterised by a range of erosional landforms including small gouges, bedrock lineations, bedrock highs, drumlins and streamlined drumlinoid ridges, as well as tunnel valleys, cavities and meltwater channels (Larter et al., in press). The high elongation of some of these bedforms on the inner, mid, and outer shelf implies that ice extended to the shelf edge at the LGM and was drained by grounded, fast-flowing ice streams (Fig. 1) (see Anderson et al., 2002; Lowe and Anderson, 2002; Evans et al., 2006b; Larter et al., in press). The post-LGM deglacial chronology of the ASE indicates that the ice sheet margin had retreated to the shelf near Burke Island (Fig. 1) by ca. 16,000 ^{14}C yr BP, to the present-day positions in PIB by ca. 10,000 ^{14}C yr BP, and in the Getz region by ca. 14,000 ^{14}C yr BP (Anderson et al., 2002; Lowe and Anderson, 2002). The present study focuses on sediment cores recovered from three channels located in the Dotson and Getz A troughs (Fig. 1). A larger network of anastomosing channels in the Getz B trough are discussed in more detail elsewhere (see Larter et al., in press).

Methods

Marine geophysical and geological data from the western ASE presented in this paper were acquired during cruise JR141 of the RRS *James Clark Ross* (*JCR*) and expedition ANT-XXIII/4 of RV *Polarstern* (*PS*) in 2006 (Larter et al., 2007). On JCR geophysical data were collected using a Kongsberg-Simrad EM120 multibeam echo sounding system which has a 1°×1° beam configuration and emits 191 beams, with frequencies in the range 11.25 to 12.75 kHz and, on *PS*, using an Atlas Hydrosweep DS-2 system with 59 beams at 15.5 kHz. Multibeam data were processed and gridded with a 50-m cell size using MB-System software (Caress et al., 1996), and displayed using Generic Mapping Tools (GMT; Wessel and Smith, 1991). Navigation data were acquired using differential GPS, which in combination with an accurate vessel motion system provides a spatial accuracy of reflection points of better than 5 m.

Sediment cores were recovered on RSS *JCR* using a vibrocorer with a maximum penetration depth of 6 m. Physical properties (magnetic susceptibility, wet bulk density, and P-wave velocity) were measured on whole core (VC415) using a GEOTEK multisensor core logger (MSCL) and are used primarily to identify facies types. Magnetic susceptibility (MS), used here as a proxy for terrigenous vs. biogenic content of the sediment (i.e., low values equate to low biogenic content), was additionally measured on split cores (VC419, VC425) with a BARTINGTON MS2E point sensor. MS data can therefore be used to distinguish between sediments deposited in subglacial (>terrigenous material) or hemipelagic (>biogenic material) settings. After splitting, the cores were photographed, and grain size, sedimentary structures, bed contacts, and texture of the sediments were described. Additional information on sedimentary structures was obtained from x-radiographs. Shear strength measurements were performed every 10–20 cm using a hand-held shear vane. Shear strength provides a measure of the stiffness of the sediment and is used here to help distinguish between subglacially and proglacially deposited diamictons (e.g., Hillenbrand et al., 2005). Individual sediment samples were taken from the sediment cores at intervals of 10- to 20-cm core depth and dried to obtain sediment water content. For grain size analyses sediment samples were disaggregated in deionised H_2O and then passed through a 2 mm and a 63 μm sieve. The proportions of the mud (<63 μm), sand (>63 μm–2 mm) and gravel (>2 mm) fractions were determined on the basis of weight.

Results

Three vibrocores were collected from clearly defined channels, imaged on multibeam swath bathymetric data north of the eastern Getz and Dotson ice shelves in the western ASE (Figs. 1 and 2). A key objective of the coring was to investigate the nature of the channel sediment fill. The three channels targeted for coring are up to 4050 m long, 500 m wide and 60 m deep, and are characterised by a curvilinear to sinuous form, reverse long-axis gradients and undulating thalwegs. All three channels are incised into acoustic basement (Fig. 2 and Table 1).

VC415

VC415 was collected from a channel between two seabed highs north of the eastern Getz Ice Shelf (Fig. 2a). The channel (918 m below sea level) has a shallow undulating thalweg and is convex-up

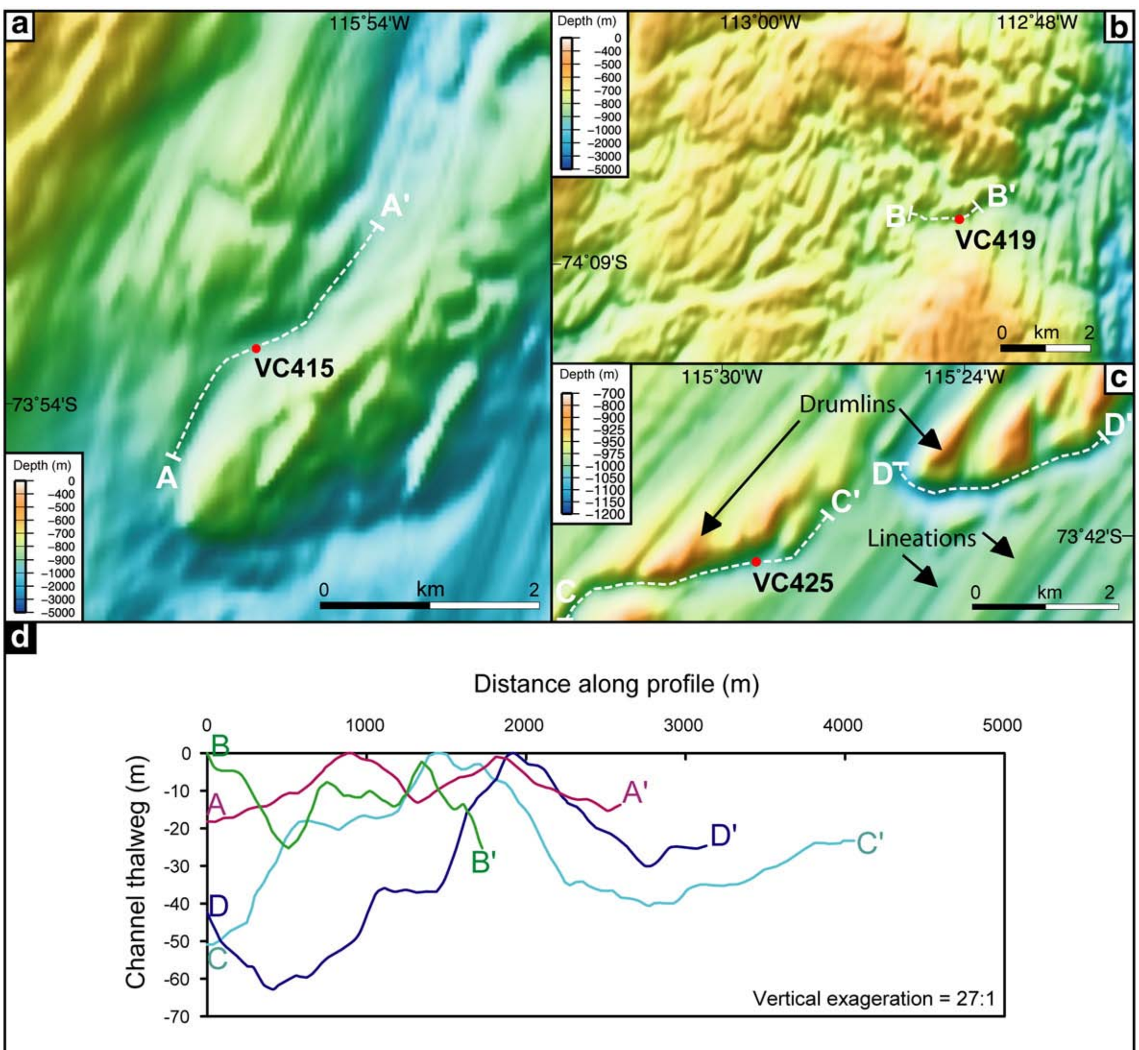

Figure 2. Swath bathymetry data showing meltwater channels and the location of core sites (red dots), (a), VC415, (b), VC419 and (c), VC425. (d) Longitudinal profiles for meltwater channels (A–A′, B–B′, C–C′, and D–D′). Depths are relative to the shallowest point on each profile. Data were collected aboard RRS *James Clark Ross* in January–February 2006 using a Kongsberg-Simrad EM120 (12 kHz) multi-beam swath bathymetry system and processed using MB-System software and gridded at cell sizes of 50 m.

Table 1
Channel dimensions and core site information

Longitudinal Profile	Channel dimensions (m)			Core site			Water depth (m) at core site	Core recovery (m)
	Length	Width	Depth		Lat. (deg/min)	Long. (deg/min)		
A–A′	2600	200–500	60	VC415	73°53.7464′S	115°55.8676′W	918	4.34
B–B′	1900	400–500	60	VC419	74°08.4965′S	112°51.3838′W	806	4.79
C–C′	4050	200–450	60	VC425	73°42.1764′S	115°29.1620′W	1020	5.08
D–D′	3200	200–450	60					

in long profile (Fig. 2d and Table 1). VC415 recovered a grey (5Y 4/1) massive, 2.7-m-thick terrigenous diamicton at its base (Figs. 3a and 4a). The unit is characterised by low water content (<20%) and high and variable MS values ($150–250\times10^{-5}$ SI Units) and high proportions of sand and gravel (Figs. 3a and 4a). Cobbles up to 6 cm (*a*-axis) are present and are typically rounded to sub-angular. Shear strength decreases from 25 kPa at the bottom of the unit to <5 kPa towards the transition between the diamicton and an overlying terrigenous sandy mud. The overlying unit consists of 0.6 m of horizontally stratified sandy muds and gravels (Fig. 4b), with high MS values (Fig. 3a). Shear strength remains low (<5 kPa) while water content increases upwards in the unit (20–40%) (Fig. 3a). The upper 1.0 m of the recovered sedimentary sequence consist of a massive, bioturbated diatom-bearing (i.e., 15–30% diatoms) (1.0–0.3 m) to diatomaceous (i.e., 50–100% diatoms) (0.3–0 m) sandy mud, which is characterised by low shear strength and MS values, and by low sand and gravel contents.

VC419

Core VC419 was retrieved from a WSW-ENE trending channel located ca. 9300 m north of the present Dotson Ice Shelf front in a region of glacially scoured bedrock (Figs. 1 and 2b). The channel (806 m below sea level) has a gently undulating thalweg with a long-axis bathymetry varying between 792 and 817 m below sea surface (topographic variation and channel depths of up to 25 m; Figs. 2b and d). Core VC419 recovered a sequence of homogenous, purely terrigenous silty-clay beds (predominantly 5Y 5/1 grey) intercalated with six discrete, 6–70 cm thick, terrigenous sand and/or gravel layers (predominantly 5Y 4/1 dark grey) (Fig. 3b). The two gravel-bearing coarse-grained layers (4.35–3.93 m and 3.45–2.78 m; Fig. 3b) have sharp basal boundaries, are normally graded, and are capped by finely laminated sand and silt layers (Figs. 3b and 4d, e). The top 0.30 m of the upper sandy gravel layer is strongly bioturbated (Fig. 4c). The upper three coarse-grained layers are also slightly bioturbated, have sharp basal boundaries and consist of well-sorted muddy sand. Shear strength is relatively low (ca. 5 kPa) throughout the sequence and is slightly higher at the base of the unit (ca. 10 kPa). Arenaceous and calcareous benthic foraminifera occur between 3.83 and 3.80 m within the basal sandy gravel layer.

VC425

Core VC425 was recovered from a channel (1020 m below sea level) north of the eastern Getz Ice Shelf, which crosscuts or is crosscut by a mixture of drumlins and attenuated glacial lineations (Figs. 2 and 3c). The long-axis channel morphology undulates and is characterised by abrupt channel termination/initiation points that are locally linked to the grooves of neighbouring subglacial bedforms. The basal sediments at site VC425 consist of a dark grey (5Y 4/1) terrigenous, 2.28-m-thick, massive to moderately stratified diamicton with low water content (<20%) and shear strength (<5 kPa) and relatively high MS values (generally over 300×10^{-5} SI Units; Figs. 3c and 4f, g). The diamicton is overlain by 2.8 m of diatomaceous to diatom-bearing mud. A discrete diatom ooze layer occurs between 24.9 and 2.45 m. Shear strength remains low (<5 kPa) while water content increases up core (40–60%) (Fig. 3c).

Interpretation

The channels in the western ASE (Fig. 2) are cut into acoustic basement that is interpreted as bedrock in seismic profiles from this area (Wellner et al., 2001; Lowe and Anderson, 2002). On the basis of an in-situ granite rock recovered in a nearby dredge sample and granodiorite samples collected at sea level from nearby Wright Island (Werner et al., 2007), we consider the bedrock to be mainly granitic, although we cannot rule out the possibility that there may be deformed sedimentary rocks in this area. Several characteristics suggest that the channels were formed by subglacial meltwater under hydrostatic pressure, such as their overall dimensions, incision into bedrock, undulating long-axis profiles and reverse gradients as well as straight to slightly sinuous forms (Fig. 2) (see Sugden et al., 1991; Booth and Hallet, 1993; Lewis et al., 2006). This suggests significant amounts of subglacial meltwater flowed beneath the WAIS in this region during the past.

VC415

The sedimentary sequence recovered at site VC415 reflects the transition from a subglacial environment to an ice-proximal setting and then to post-glacial glaciomarine conditions and is similar to those described elsewhere on the Antarctic continental shelf (e.g., Bartek and Anderson, 1991; Licht et al., 1999; Domack et al., 1999; Hillenbrand et al., 2005). The diamicton is interpreted as a deformation till deposited at the base of a fast-flowing ice stream during the LGM and differs from lithologically similar glaciomarine sediments, such as sub-ice shelf diamictons and glaciogenic debris flow deposits, by higher shear strength and MS values and higher concentrations of coarse-grained components (e.g., Licht et al., 1999; Hillenbrand et al., 2005). The stratified sandy mud (‘transitional unit’) was probably deposited in a glaciomarine environment proximal to the grounding line of the ice stream, subsequent to its retreat from the core site. The diatomaceous sandy mud reflects deposition in a seasonally open-marine setting, distal from the ice front. This interpretation is based on the presence of diatoms, the low concentration of coarse-grained material, high water content, low shear strength, and the occurrence of bioturbation.

VC419

Core VC419 contains 6 discrete sand/gravel layers resembling deposits in the eastern ASE that have been attributed to outburst floods associated with channel incision. However, we do not consider them as sediments transported and deposited by sub- or proglacial meltwater streams. The five layers have sedimentological properties, such as sharp basal boundaries with normal grading, that are typical for gravitational down-slope transport (Lowe, 1982; Bartek and Anderson, 1991). Accordingly, we interpret the layers as grain-flow deposits and coarse-grained turbidites, which were probably re-deposited from topographic highs forming the flanks

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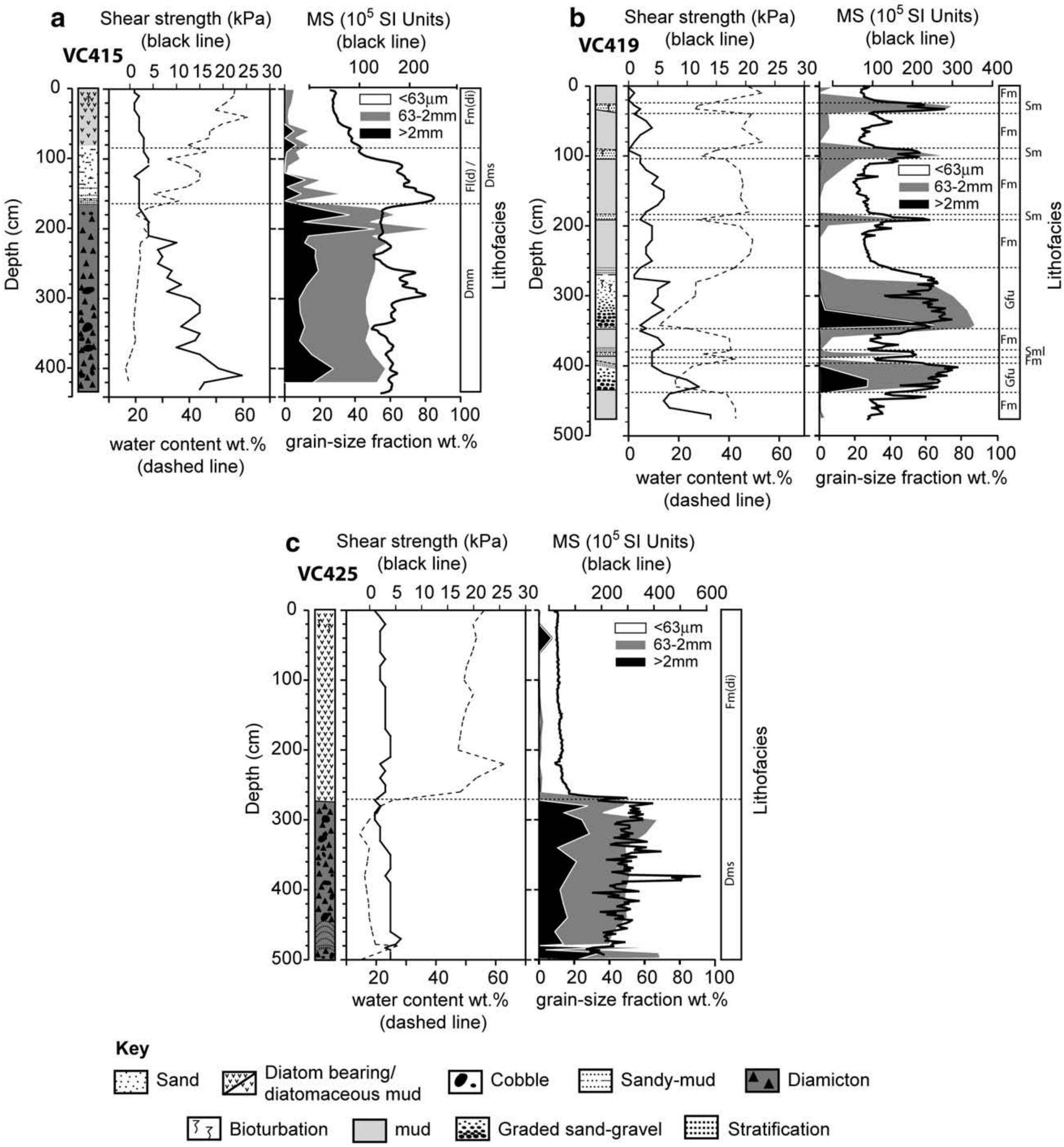

Figure 3. Generalised core logs and proxy data for (a) VC415, (b) VC419 and (c) VC425 showing shear strength, water content, magnetic susceptibility (MS), grain size data and simplified lithofacies logs (left). Lithofacies codes: Dmm (massive diamicton), Dms (stratified diamicton), Fm(di) (massive mud, diatom bearing/diatomaceous), Fl (laminated sandy mud ± (g) gravel), Fm (massive silty-clay/mud), Sm (massive sand), Gfu (normally graded gravel).

of the channel since the LGM. Our interpretation is supported by the presence of calcareous benthic foraminifera in the basal sandy gravel layer of core VC419. *In situ* surface sediments from the deep inner shelf basins in the Amundsen Sea and the nearby Bellingshausen Sea are virtually carbonate-free (Hillenbrand et al., 2003) as a result of their location below the carbonate compensation depth (CCD). The CCD on the Antarctic continental margin is often multibathyal (e.g., Anderson, 1999), and its water depth on the inner shelf is typically shallower than 500 m (e.g., Li et al., 2000). Therefore, we expect that the water depth of site VC419 (806 m) is well below the CCD. The occurrence of calcareous foraminifera in the basal sandy gravel layer at this site therefore implies reworking and rapid burial of sediments from shallower water depths by grain flows and/or turbidity currents.

VC425

The sequence recovered at site VC425 is similar to that from site VC415. Because of the diamicton's low shear strength and its moderate stratification (particularly at its base) at site VC425, we interpret this diamicton as a glaciomarine sediment deposited under perennial sea-ice cover or an ice shelf proximal to the grounding line (Licht et al., 1999; Hillenbrand et al., 2005). As in core VC415 the diatomaceous/diatom-bearing mud was probably deposited in an open marine

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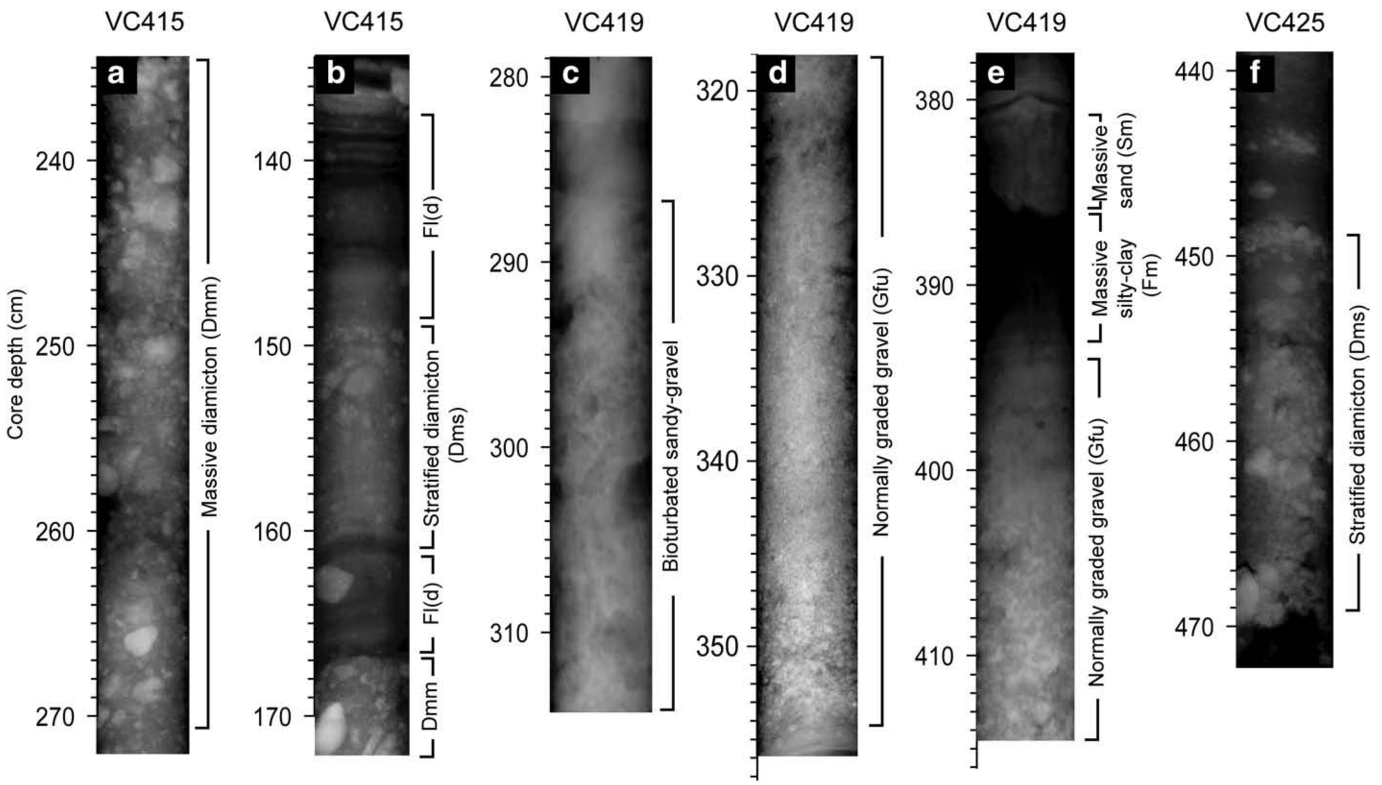

Figure 4. X-radiographs of selected sediment facies. (a) Massive subglacial diamicton (Dmm) and (b) finely laminated sandy muds (Fl) with gravel (Flg) and stratified diamicton (Dms) from VC415 (c) bioturbated graded sand unit and (d) normally graded gravel–sand facies (Gfu) with sharp basal boundary (ca. 347 cm), (d) graded gravel–sand unit overlain by a massive mud unit (Fm) (ca. 394–387 cm) and sand unit (Sm) (ca. 387–378 cm) from VC419 (e) stratified diamicton (Dms) from VC425.

environment once the ice front had retreated. We assume that the onset of glaciomarine sedimentation at sites VC415 and VC425 roughly coincided with ice retreat from the inner shelf in the eastern ASE between 16,000 and 10,000 ^{14}C yr BP (Lowe and Anderson, 2002) and from the shelf north of the western Getz Ice Shelf at ca. 14,000 ^{14}C yr BP (Anderson et al., 2002).

Discussion

We have presented new swath bathymetry illustrating well-defined channels carved into bedrock in the western ASE. The features are similar in scale to those described elsewhere in Antarctica (e.g., Sugden et al., 1991; Lowe and Anderson, 2002, 2003; Ó Cofaigh et al., 2002; Domack et al., 2006) and specifically those identified in inner PIB. In addition, we also provide sedimentological information for three cores recovered directly from these offshore channels. Two of the cores (VC415, VC425) recovered subglacial diamictons deposited beneath and/or proximal to grounded ice. These deposits are overlain by glaciomarine muds reflecting the seasonally open marine conditions of the present interglacial. The third sediment core (VC419) recovered a turbidite sequence most likely to have been deposited after deglaciation. While the presence of subglacial deposits within subglacial meltwater channel systems is not uncommon (Ó Cofaigh, 1996), their presence is unexpected in the context of previous work in the ASE and therefore warrants further discussion.

Significance of channel infill

Despite extensive research on the sediment infill of subglacial meltwater channels and tunnel valleys in other previously glaciated regions (e.g., Piotrowski, 1994; Eyles and McCabe, 1989; Ehlers and Linke, 1989; Huuse and Lykke-Andersen, 2000; Eyles and de Broekert, 2001; Kluiving et al., 2003; Lonergan et al., 2006; Jørgensen and Sandersen, 2006) only one other study by Lowe and Anderson (2003) described the sediment infill of meltwater channels on the Antarctic continental shelf. Their core PC46, located in a deep channel in inner PIB (Figs. 1 and 5), recovered a thick unit of graded sand and gravels overlain by terrigenous mud. Lowe and Anderson (2003) interpreted the graded coarse-grained sediments as bedload deposited by highly dynamic subglacial meltwater streams, which were active during the last glacial period, and the terrigenous muds as deposits of recent (deglaciation to present) meltwater plumes unrelated to channel incision, which originated from the ice front of Pine Island Glacier. We observe similar sediments in the western ASE, namely graded sands and gravels overlain by muddy sediment. In accordance with Lowe and Anderson (2003), we assume that the terrigenous muds were deposited by post-glacial meltwater plumes emanating from the ice shelves and glaciers draining into the ASE today. However, we interpret the underlying graded sands and gravels as down-slope deposits rather than being subglacial meltwater deposits related to channel incision.

Previous work on channel infills has shown that intermittent subglacial drainage may result in lenses of sorted sediments (e.g., Eyles et al., 1982; Shaw, 1987; Evans et al., 1995), while other studies on what are interpreted to have been Pleistocene outburst events of the Laurentide ice sheet point to an association with graded deposits, imbricated boulder-sized clasts, cross-stratified gravels and gravel bars (e.g., Cutler et al., 2002; Smith, 2006). The latter sediment types however, are typically deposited down flow of channel incision or on the channel interfluves. We offer two explanations for the apparent absence of subglacial meltwater deposits in our study area. Firstly, it is possible that meltwater deposits lie directly below deformation till and were not recovered by coring. At present, we cannot test whether gravel/boulder-rich deposits exist beneath the till in core VC415 because of the insufficient resolution of the available geophysical data (mainly TOPAS acoustic sub-bottom profiles). We also note that survival of deposits associated with meltwater erosion is difficult to achieve under an eroding ice stream but could occur below an ice

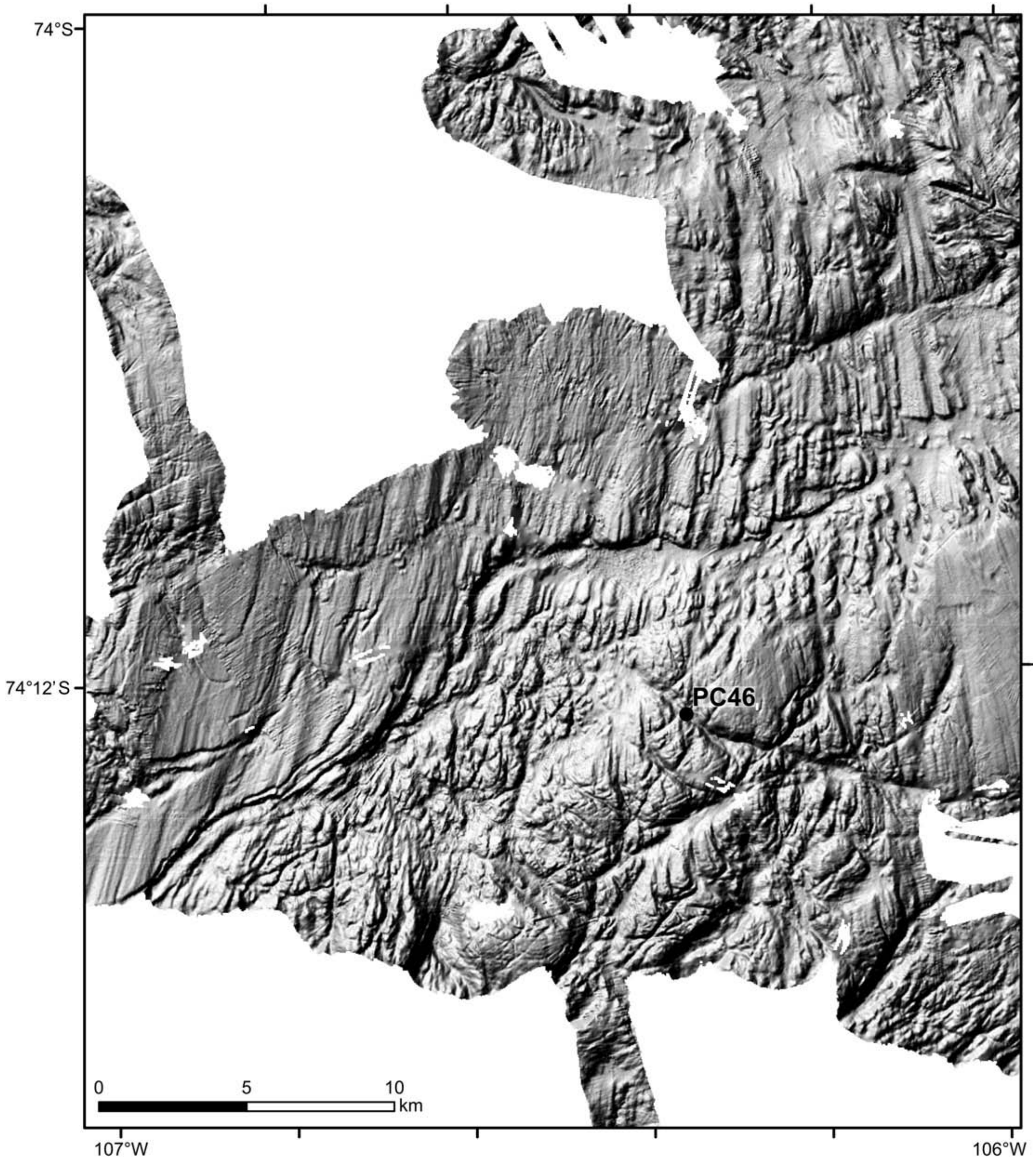

Figure 5. Swath bathymetry data showing location of PC46 analysed by Lowe and Anderson (2003). Location of PC46 in Amundsen Sea Embayment is shown in Figure 1. Swath bathymetric data has been re-gridded using NPB9902/0001 data (Lowe and Anderson, 2002) and new data collected on ANT-XX III/4 in 2006 (Larter et al., 2007). Data gridded at 30×30 m using UTM zone 13S projection.

sheet with net accumulation, perhaps when the ice sheet was advancing (e.g., Fisher and Taylor, 2002). Secondly, any deposits associated with channel incision might have subsequently been reworked into the till and redistributed across the shelf or they were flushed out from the channel during their formation. Of the two scenarios, we consider it most likely that deforming bed conditions would incorporate and/or redistribute loosely consolidated sands and gravels across the shelf, although future work should attempt to test this hypothesis.

The absence of a deformation till above the coarse-grained deposits at site PC46 in PIB is also significant, because it indicates that grounded ice did not subsequently override the channel infill during the last glacial cycle. This could imply that the coarse-grained deposits at site PC46 were deposited during or after the deglaciation and therefore have a proglacial origin, like those at core site VC419. A proglacial origin for the fine grained-sediments is certainly consistent with additional sedimentological data from inner PIB which reveal the presence of thick (>9 m) terrigenous mud and pebble deposits (Kellogg and Kellogg, 1987; Lowe and Anderson, 2002; Larter et al., 2007). Deposition in such settings are typically high (e.g., ~10 cm/yr in Antarctic Peninsula fjords: Domack and McClennen, 1996) reflecting high sedimentation rates at the grounding line, which in this case are probably related to high basal melt rates of glacier tongues and ice shelves by intrusion of warm Circumpolar Deepwater (CDW). Thus, an alternative interpretation for the sediments in PC46 is that they reflect a combination of both slope processes and deposition at the grounding line, when ice was much closer to the core site, rather than subglacial processes related to channel incision.

How old are meltwater channels in the western ASE?

Subglacial meltwater channels have been documented at several sites on the Antarctic shelf, yet their ages are uncertain due to limitations in dating techniques. In some instances this has led to models that suggest the subglacial meltwater channels formed during the LGM as part of a continuum from erosional landforms on the inner shelf to depositional landforms on the mid-to-outer shelf (e.g., Wellner et al., 2001, 2006).

While we cannot directly date incision of the channels in the western ASE, the presence of deformation till in one of the channels indicates that the channels ceased to act as conduits for meltwater at least prior to the overriding by a grounded ice stream at the LGM (ca. 18,000 ^{14}C yr BP). The presence of the deformation till within one of the channels also indicates that the channels themselves have been overridden by a wet-based eroding ice sheet, and hence it is possible that they survived numerous advances and retreats of grounded ice. Given the overall scale of the channels and their incision into granitic bedrock, we agree with the interpretations of Lowe and Anderson (2003) and Ó Cofaigh et al. (2002) and suggest the channels probably formed over multiple glaciations, possibly since the Miocene, and have been reoccupied on several occasions, most recently during the LGM. If this is the case and the meltwater channels represent an inherited landscape, then it could also have implications for the production rates and volumes of meltwater required for their formation.

The large scale of meltwater features in the western ASE indicates a long history of erosion, which in turn raises questions about how they were formed and where the water came from. It has been suggested that the amount of meltwater needed to erode such deep channels is more than can be accounted for by melting produced by subglacial friction and geothermal heating (Sugden et al., 1991). Instead several authors have envisaged a large meltwater source somewhere up-glacier, such as a subglacial lake (Sugden et al., 1991; Denton and Sugden, 2005; Lewis et al., 2006; Lowe and Anderson, 2003). The presence of subglacial lakes has become increasingly evident beneath the modern-day Antarctic Ice Sheets (Siegert et al., 2005) with recent analysis of satellite altimetric data showing rapid discharge of water from one subglacial lakes to another (Gray et al., 2005; Wingham et al., 2006; Fricker et al., 2007). This indicates that subglacial basins may be connected hydrologically, perhaps by a single conduit or a system of conduits (Wingham et al., 2006). It also provides a potential mechanism by which subglacially stored water is exported to the ice-sheet margin, which might also leave an imprint on the geomorphological record. Estimates of peak discharge between these lakes are 40–50 m^3 s^{-1} (Fricker et al., 2007; Wingham et al., 2006). For comparison, this rate is substantially lower than the peak discharge inferred for subglacial meltwater channels in the Dry Valley's (e.g., 1.6–2.2 × 10^6 m^3 s^{-1}, Lewis et al., 2006), which are similar in scale to some of the channels we imaged in the western ASE. However, if, as we speculate, the channels in the western ASE formed over several millions of years, then it is possible they reflect multiple outbursts of water from relatively small subglacial basins or even steady-state processes (e.g., Boulton and Hindmarsh, 1987).

The next logical question, therefore, is whether storage basins (i.e., subglacial lakes) exist up-glacier of these regions. In the eastern ASE the Byrd Subglacial Basin and Bentley Subglacial Trench have been identified as possible storage areas for subglacial meltwater (e.g., Lowe and Anderson, 2003) and repeated outburst of water from these basins might explain the geomorphic features observed in Pine Island Bay. To date, similar-sized basins have not been imaged up-glacier of the Dotson and Getz systems, but this might simply reflect the lack of detailed aero-geophysical data in this region. It is also possible that the deep troughs north of the Dotson and Getz ice shelves acted as sites for meltwater storage in the past. Advance and retreat of grounded ice over these basins, during several glacial cycles, might have resulted in periodic storage and discharge of meltwater (e.g., Alley et al., 2006).

One final scenario that should also be borne in mind is whether active volcanism beneath the WAIS has led to the production and episodic release of subglacial meltwater. The WAIS lies over a crustal rift and has several volcanoes that outcrop at its surface (Winberry and Anandakrishnan, 2004). In addition, a number of subglacial volcanic centres have been inferred from geophysical data (Blankenship et al., 1993; Behrendt et al., 1998). Recently Corr and Vaughan (2008) discovered evidence for a subglacial volcanic eruption within the Pine Island Glacier watershed that last erupted during the late Holocene, approximated 2200 yr ago. To put this in context, the eruption of Grímsvötn in Iceland in 1996, a similar magnitude eruption to the one described by Corr and Vaughan (2008), melted 3 km^2 of ice that was subsequently released at a peak discharge of about 50 × 10^3 m^3 s^{-1}, although this was only sustained for a few days (Snorrason et al., 1997). Thus, one hypothesis to test with future work is whether continuous or episodic production of meltwater via subglacial volcanism contributed to the observed geomorphic record in the ASE.

Conclusions

We have analysed three sediment cores recovered from channels in the western Amundsen Sea Embayment (ASE). The overall size and morphological characteristics of the channels are consistent with formation by subglacial meltwater but the specific processes leading to their formation remain unclear (e.g., steady state, catastrophic or polygenetic). Two of the analysed cores contain sediments deposited below or close to grounded ice, while the third core recovered a turbidite sequence deposited later than the ice retreat from the shelf. While the presence of glacial tills and down-slope deposits is not uncommon in tunnel valley systems (e.g., Piotrowski, 1994), it differs from previous work in the ASE. Lowe and Anderson (2003) found graded deposits in PIB that they interpreted as bedload related to subglacial meltwater erosion. We have explored several different possibilities to account for the lack of subglacial meltwater deposits in the western ASE. It is possible that they lie directly beneath the glacial deposits in the western ASE or that they were subsequently incorporated into the till as grounded, streaming ice overrode the channel (as suggested for the eastern PIB). The absence of deformation till above the graded deposits in PIB could imply that the sediments were deposited in a proglacial setting proximal to the grounding line, unrelated to channel formation.

Despite uncertainties about age of the channels we consider it most likely that they formed over multiple glacial cycles and have been subsequently overridden by streaming ice, although we cannot completely rule out the hypothesis that they were formed during several phases of the last glacial period. There is a growing need for more data on channel morphology, channel infill and how this relates to channel activity as well as evidence on and off the shelf for subglacial meltwater processes. As yet we have found no evidence for meltwater channels in our detailed swath bathymetry data from elsewhere on the Amundsen Sea continental shelf. This could suggest that subglacial meltwater evacuation was achieved through Darcian flow within the till layer (e.g., King et al., 2004; Murray et al., 2008) but is occurring at a scale below the resolution of our geophysical data or the evidence has subsequently been obliterated by ice sheet advance. It is also necessary that future work draws a clear distinction between those sediments deposited proximal to the grounding line that are related to subglacial meltwater and those that are related to channel incision beneath an ice sheet, since the physics and processes involved in each differ greatly. Future modeling studies should also focus on the conditions and times-scales under which these channel systems form.

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References

Alley, R.B., 1989. Water-pressure coupling of sliding and bed deformation: I. Water system. J. Glaciol. 35, 108–118.

Alley, R.B., Dupont, T.K., Parizek, B.R., Anandakrishnan, S., Lawson, D.E., Larson, G.J., Evenson, E.B., 2006. Outburst flooding and the initiation of ice-stream surges in response to climate cooling: a hypothesis. Geomorphology 75, 76–89, doi:10.1016/j.geomorph.2004.01.011.

Alonso, B., Anderson, J.B., Díaz, J.I., Bartek, L.R., 1992. Pliocene–Pleistocene seismic stratigraphy of the Ross Sea: evidence for multiple ice sheet grounding episodes. In: Elliot, D.H. (Ed.), Contributions to Antarctic Research III. Antarct. Res. Ser., 57, pp. 93–103.

Anderson, J.B., 1999. Antarctic Marine Geology. Cambridge University Press, Cambridge, p. 289.

Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S., Mosola, A.B., 2002. The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review. Quat. Sci. Rev. 21, 49–70.

Bartek, L.R., Anderson, J.B., 1991. Facies distribution resulting from sedimentation under polar interglacial climatic conditions within a high-latitude marginal basin, McMurdo Sound, Antarctica. Spec. Pap. — Geol. Soc. Am. 261, 27–49.

Behrendt, J.C., Finn, C.A., Blankenship, D.D., Bell, R.E., 1998. Aeromagnetic evidence for a volcanic caldera complex beneath the divide of the West Antarctic ice sheet. Geophys. Res. Lett. 25, 4385–4388.

Bell, R.E., Studinger, M., Shuman, C.A., Fahnestock, M.A., Joughin, I., 2007. Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. Nature 445, 904–907, doi:10.1038/nature05554.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London, p. 734.

Blankenship, D.D., Bell, R.E., Hodge, S.M., Brozena, J.M., Behrendt, J.C., Finn, C.A., 1993. Active volcanism beneath the West Antarctic ice sheet and implications for ice-sheet stability. Nature 361, 526–529.

Booth, D.B., Hallet, B., 1993. Channel networks carved by subglacial water: observations and reconstruction in the eastern Puget Lowland of Washington. Geol. Soc. Amer. Bull. 105, 671–683.

Boulton, G.S., Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: rheology and geological consequences. J. Geophys. Res. 92, 9059–9082.

Caress, D.W., Spitzak, S.E., Chayes, D.N., 1996. Software for multibeam sonars. Sea Technol. 37, 54–57.

Carlson, A.E., Jenson, J.W., Clark, P.U., 2007. Modeling the subglacial hydrology of the James Lobe of the Laurentide Ice Sheet. Quat. Sci. Rev. 26, 1384–1397, doi:10.1016/j.quascirev.2007.02.002.

Clarke, G.K.C., Leverington, D.W., Teller, J.T., Dyke, A.S., Marhsall, S.J., 2005. Fresh arguments against the Shaw megaflood hypothesis. A reply to comments by David Sharpe on "Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200 BP cold event". Quat. Sci. Rev. 24, 1533–1541.

Corr, H.F.J., Vaughan, D.G., 2008. A recent volcanic eruption beneath the West Antarctic ice sheet. Nat. Geosci. 1, 122–125, doi:10.1038/ngeo106.

Cutler, P.M., Colgan, P.M., Mickelson, D.M., 2002. Sedimentologic evidence for outburst floods from the Laurentide Ice Sheet margin in Wisconsin, USA: implications for tunnel-channel formation. Quat. Int. 90, 23–40.

Denton, G.H., Sugden, D.E., 2005. Meltwater features that suggest Miocene ice-sheet overriding of the Transantarctic Mountains in Victoria Land, Antarctica. Geogr. Ann. 87A, 67–85.

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. In: Ross, R., Hoffman, E., Quetin, L. (Eds.), Foundations for Ecosystem Research West of the Antarctic Peninsula, Antarctic Research Series, vol. 70. American Geophysical Union, Washington D.C., pp. 135–154.

Domack, E.W., Jacobson, E.A., Shipp, S., Anderson, J.B., 1999. Late Pleistocene–Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: Part 2. Sedimentologic and stratigraphic signature. Geol. Soc. Amer. Bull. 111, 1517–1536.

Domack, E., Amblas, D., Gilbert, R., Brachfeld, S., Camerlenghi, A., Rebesco, M., Canals, M., 2006. Subglacial morphology and glacial evolution of the Palmer Deep outlet system, Antarctic Peninsula. Geomorphology 75, 125–142.

Ehlers, J., Linke, G., 1989. The origin of deep buried channels of Elsterian age in NW Germany. J. Quat. Sci. 4, 255–265.

Engelhardt, H., Kamb, B., 1997. Basal hydraulic system of a West Antarctic ice stream: constraints from borehole observations. J. Glaciol. 43, 207–230.

Engelhardt, H., Humphrey, N., Kamb, B., Fahnestock, M., 1990. Physical conditions at the base of a fast moving Antarctic ice stream. Science 248, 57–59.

Evans, D.J.A., Owen, L.A., Roberts, D., 1995. Stratigraphy and sedimentology of Devensian (Dimlington Stadial) glacial deposits, east Yorkshire, England. J. Quat. Sci. 10, 241–265.

Evans, D.J.A., Rea, B.R., Hiemstra, J.F., Ó Cofaigh, C., 2006a. A critical assessment of subglacial mega-floods: a case study of glacial sediments and landforms in south-central Alberta, Canada. Quat. Sci. Rev. 25, 1638–1667.

Evans, J., Dowdeswell, J.A., Ó Cofaigh, C., Benham, T.J., Anderson, J.B., 2006b. Extent and dynamics of the West Antarctic Ice Sheet on the outer continental shelf of Pine Island Bay during the last glaciation. Mar. Geol. 230, 53–72.

Eyles, N., de Broekert, P., 2001. Glacial tunnel valleys in the Eastern Goldfields of Western Australia cut below the Late Paleozoic Pilbara ice sheet. Palaeogeogr. Palaeoclimatol. Palaeoecol. 171, 29–40.

Eyles, N., McCabe, A.M., 1989. Glaciomarine facies within subglacial tunnel valleys—the sedimentary record of glacioisostatic downwarping in the Irish Sea Basin. Sedimentology 36, 431–448.

Eyles, N., Sladen, J.A., Gilroy, S., 1982. A depositional model for stratigraphic complexes and facies superimposition in lodgement tills. Boreas 11, 317–333.

Fisher, T.G., Taylor, L.D., 2002. Sedimentary and stratigraphic evidence for subglacial flooding, south-central Michigan, USA. Quat. Int. 90, 87–115.

Fricker, H.A., Scambos, T., Bindschadler, R., Padman, L., 2007. An active subglacial water system in West Antarctica mapped from space. Science 315, 1544–1548, doi:10.1126/science.1136897.

Goodwin, I.D., 1988. The nature and origin of a jökulhlaup near Casey Station, Antarctica. J. Glaciol. 34 (116), 95–101.

Gray, L., Joughin, I., Tulaczyk, S., Spikes, V.B., Bindschadler, R., Jezek, K., 2005. Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. Geophys. Res. Lett. 32, L03501, doi:10.1029/2004GL021387.

Hillenbrand, C.-D., Grobe, H., Diekmann, B., Kuhn, G., Futterer, D., 2003. Modern glaciomarine environment and its sedimentary record in the Bellingshausen and Amundsen Seas (West Antarctica). Mar. Geol. 193, 253–271.

Hillenbrand, C.-D., Baesler, T.A., Grobe, H., 2005. The sedimentary record of the last glaciation in the western Bellingshausen Sea (West Antarctica): implications for the interpretation of diamictons in a polar-marine setting. Mar. Geol. 216, 191–204, doi:10.1016/j.margeo.2005.01.007.

Huuse, M., Lykke-Andersen, H., 2000. Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. Quat. Sci. Rev. 19, 1233–1253.

Jørgensen, F., Sandersen, P.B.E., 2006. Buried and open tunnel valleys in Denmark — erosion beneath multiple ice sheets. Quat. Sci. Rev. 25, 1339–1363, doi:10.1016/j.quascirev.2005.11.006.

Kamb, B., 2001. Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion. In: Alley, R.B., Bindschadler, R.A. (Eds.), The West Antarctic Ice Sheet: Behavior and Environment. American Geophysical Union, Antarct. Res. Ser., vol. 77, pp. 157–199.

Kellogg, T.B., Kellogg, D.E., 1987. Recent glacial history and rapid ice stream retreat in the Amundsen Sea. J. Geophys. Res. 92, 8859–8864.

King, E.C., Woodward, J., Smith, A.M., 2004. Seismic evidence for a water-filled canal in deforming till beneath Rutford Ice Stream, West Antarctica. Geophys. Res. Lett. 31, L20401, doi:10.1029/2004GL020379.

Kluiving, S.J., Bosch, J.H.A., Ebbing, J.H.J., Mesdag, C.S., Westerhoff, R.S., 2003. Onshore and offshore seismic and lithostratigraphic analysis of a deeply incised Quaternary buried valley-system in the Northern Netherlands. J. Appl. Geophys. 53, 249–271.

Larter, R.D., Gohl, K., Hillenbrand, C.-D., Kuhn, G., Deen, T.J., Dietrich, R., Eagles, G., Johnson, J.S., Livermore, R.A., Nitsche, F.O., Pudsey, C.J., Schenke, H.-W., Smith, J.A., Udintsev, G., Uenzelmann-Neben, G., 2007. West Antarctic Ice Sheet change since the Last Glacial Period. EOS Transact., American Geophysical Union 88, 189–190.

Larter, R.D., Graham, A.G.C., Gohl, K., Kuhn, G., Hillenbrand, C.-D., Smith, J.A., Deen, T.J., Livermore, R.A., Schenke, H.-W., in press. Subglacial bedforms reveal complex basal regime in a zone of paleo-ice stream convergence, Amundsen Sea Embayment, West Antarctica. Geology.

Lewis, A.R., Marchant, D.R., Kowalewski, D.E., Baldwin, S.L., Webb, L.E., 2006. The age and origin of the Labyrinth, western Dry Valleys, Antarctica: evidence for extensive middle Miocene subglacial floods and freshwater discharge to the Southern Ocean. Geology 34, 513–516, doi:10.1130/G22145.1.

Li, B., Yoon, H.-I., Park, B.-K., 2000. Foraminiferal assemblages and $CaCO_3$ dissolution since the last deglaciation in the Maxwell Bay, King George Island, Antarctica. Mar. Geol. 169, 239–257.

Licht, K.J., Dunbar, N.W., Andrews, J.T., Jennings, A.E., 1999. Distinguishing subglacial till and glacial marine diamictons in the western Ross Sea, Antarctica: implications for a Last Glacial Maximum grounding line. Geol. Soc. Amer. Bull., 111, 91–103.

Lonergan, L., Maidment, S.C.R., Collier, J.S., 2006. Pleistocene subglacial tunnel valleys in the central North Sea basin: 3-D morphology and evolution. J. Quat. Sci. 21, 891–903.

Lowe, D.R., 1982. Sediment gravity flows: II — depositional models with special reference to the deposits of high density turbidity currents. J. Sediment. Petrol. 41, 168–186.

Lowe, A.L., Anderson, J.B., 2002. Reconstruction of the West Antarctic ice sheet in Pine Island Bay during the Last Glacial maximum and its subsequent retreat history. Quat. Sci. Rev. 21, 1879–1897.

Lowe, A.L., Anderson, J.B., 2003. Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica. J. Glaciol. 49, 125–138.

Murray, T., Corr, H., Forieri, A., Smith, A.M., 2008. Contrasts in hydrology between regions of basal deformation and sliding beneath Rutford Ice Stream, West Antarctica, mapped using radar and seismic data. Geophys. Res. Lett. 35, L12504, doi:10.1029/2008GL033681.

Ng, F.S.G., 2000. Canals under sediment-based ice sheets. Ann. Glaciol. 30, 146–152.

Nitsche, F.O., Jacobs, S.S., Larter, R.D., Gohl, K., 2007. Bathymetry of the Amundsen Sea continental shelf: implications for geology, oceanography, and glaciology. Geochem., Geophys., Geosystems, 8, Q10009, doi:10.1029/2007GC001694.

Ó Cofaigh, C., 1996. Tunnel valley genesis. Prog. Phys. Geogr. 20, 1–19.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., Morris, P., 2002. Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf. Geophys. Res. Lett. 29, 41–1–41-4, doi:10.1029/2001.GL014488.

Ó Cofaigh, C., Dowdeswell, J.A., Allen, C.S., Heimstra, J.F., Pudsey, C.J., Evans, J., Evans, D.J.A., 2005. Flow dynamics and till genesis associated with marine based Antarctic palaeo-ice streams. Quat. Sci. Rev. 24, 709–740.

Piotrowski, J.A., 1994. Tunnel-valley formation in Northwest Germany — geology, mechanisms of formation and subglacial bed conditions for the bornhoved tunnel valley. Sediment. Geol. 89, 107–141.

Rignot, E.J., 1998. Fast recession of a West Antarctic Glacier. Science 281, 549–551.
Sawagaki, T., Hirakawa, K., 1997. Erosion of bedrock by subglacial meltwater, Soya Coast, East Antarctica. Geogr. Ann. 79, 223–238.
Shaw, J., 1987. Glacial sedimentary processes and environmental reconstruction based on lithofacies. Sedimentology 34, 103–116.
Shepherd, A., Wingham, D., Rignot, E., 2004. Warm ocean is eroding West Antarctic Ice Sheet. Geophys. Res. Lett. 31, L23402.
Siegert, M.J., Carter, S., Tabacco, I.E., Popov, S., Blankenship, D.D., 2005. A revised inventory of Antarctic subglacial lakes. Antarct. Sci. 17, 453–460.
Siegert, M.J., Le Brocq, A., Payne, A., 2007. Hydrological connections between Antarctic subglacial lakes and the flow of water beneath the East Antarctic Ice Sheet. In: Hambrey, M.J., Christoffersen, P., Glasser, N.F., Hubbard, B.P. (Eds.), Glacial Sedimentary Processes and Special Publication #39. International Association of Sedimentologists, pp. 3–10.
Smith, L., 2006. Stratigraphic evidence for multiple drainings of glacial Lake Missoula along the Clark Fork River, Montana, USA. Quat. Res. 66, 311–322.
Smith, A.M., Murray, T., Nicholls, K.W., Makinson, K., Aðalgeirsdóttir, G., Behar, A.E., Vaughan, D.G., 2007. Rapid erosion, drumlin formation, and changing hydrology beneath an Antarctic ice stream. Geology 35, 127–130, doi:10.1130/G23036A.1.
Snorrason, Á., Jónsson, P., Pálsson, S., Árnason, S., Sigurðsson, O., Víkingsson, S., Sigurðsson, Á., Zóphóníasson, S., 1997. Hlaupið á Skeiðarársandi haustið 1996. Útbreiðsla, rennsli og aurburður. In: Haraldsson, H. (Ed.), Vatnajökull. Gos og hlaup 1996. Iceland Public Roads Administration, Reykjavík, Iceland, pp. 79–137.
Sugden, D.E., Denton, G.H., Marchant, D.R., 1991. Sub-glacial meltwater channel systems and ice sheet overriding, Asgard Range, Antarctica. Geogr. Ann. 73, 109–121.
Sugden, D.E., Summerfield, M.A., Denton, G.H., Wilch, T.I., McIntosh, W.C., Marchant, D.R., Rutford, R.H., 1999. Landscape development in the Royal Society Range, southern Victoria Land, Antarctica: stability since the mid-Miocene. Geomorphology 28, 181–200.
Walder, J.S., Fowler, A., 1994. Channelised subglacial drainage over a deformable bed. J. Glaciol. 40, 3–15.
Wellner, J.S., Lowe, A.L., Shipp, S.S., Anderson, J.B., 2001. Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: implications for ice behaviour. J. Glaciol. 47, 397–411.
Wellner, J.S., Heroy, D.C., Anderson, J.B., 2006. The death mask of the Antarctic ice sheet: comparison of glacial geomorphic features across the continental shelf. Geomorphology 75, 157–171.
Werner, R., Daniel, K., Hauff, F., Veit, A., 2007. Composition and evolution of Cenozoic volcanic complexes and the crystalline basement of Marie Byrd and Ellsworth Land. In: Gohl, K. (Ed.), The Expedition ANTARKTIS-XXIII/4 of the Research Vessel 'Polarstern' in 2006. Reports of Polar and Marine Research, 557. Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, pp. 67–83.
Wessel, P., Smith, W.H.F., 1991. Free software helps map and display data. EOS Transact., American Geophysical Union 72, 445–446.
Winberry, J.P., Anandakrishnan, S., 2004. Crustal structure of the West Antarctic rift system and Marie Byrd Land hotspot. Geology 32, 977–980.
Wingham, D.J., Siegert, M.J., Shepherd, A., Muir, A.S., 2006. Rapid discharge connects Antarctic subglacial lakes. Nature 440, 1033–1036.