Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

Seismic and geomorphic records of Antarctic Ice Sheet evolution in the Ross Sea and controlling factors in its behaviour

JOHN B. ANDERSON[1]*, LAUREN M. SIMKINS[1], PHILLIP J. BART[2], LAURA DE SANTIS[3], ANNA RUTH W. HALBERSTADT[1], ELISABETTA OLIVO[3] & SARAH L. GREENWOOD[4]

[1]*Department of Earth Sciences, Rice University, Houston, TX, USA*

[2]*Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA, USA*

[3]*Osservatorio Geofisco Sperimentale, B90 Grotto Gigante 42/C, 34010 Saonico, Trieste, Italy*

[4]*Department of Geological Sciences, Stockholm University, 10691 Stockholm, Sweden*

**Correspondence:* *johna@rice.edu*

Abstract: A robust collection of seismic and geomorphic data is used to examine the evolution of the Antarctic Ice Sheet within the Ross Sea Embayment. We use geomorphic data to reconstruct Last Glacial Maximum and post-Last Glacial Maximum ice sheet drainage and demonstrate retreat behaviours for the East Antarctic and West Antarctic sectors of the ice sheet. Using this framework, we then use seismic data and chronostratigraphic information from drill cores to reconstruct the long-term evolution of the ice sheet. Early ice sheet evolution during the Late Oligocene was characterized by isolated ice caps on bathymetric highs, followed by an interval of sediment infilling of rift basins and the development of more subdued relief in the eastern Ross Sea than in the western Ross Sea. Both ice sheets have experienced multiple episodes of expansion across the continental shelf since the Middle Miocene, with the frequency increasing during the Plio-Pleistocene. We conclude that seafloor bathymetry has been the principal control on ice sheet palaeodrainage and retreat behaviour since at least the middle Miocene, demonstrated by broad West Antarctic ice streams loosely guided by south to north cross-shelf troughs, whereas East Antarctic ice streams were funnelled through troughs that merge and converge around banks.

The Ross Sea Embayment is the largest catchment for the Antarctic Ice Sheet and drains multiple ice streams and outlet glaciers of both the East Antarctic Ice Sheet (EAIS) and the West Antarctic Ice Sheet (WAIS) (Fig. 1). As a result of numerous research cruises over the past four decades, the deglaciated continental shelf in the Ross Sea is the most thoroughly studied offshore region of Antarctica, with more seismic and multibeam data and sediment core coverage than any other region (Fig. 2). A relatively thick Neogene stratigraphic sequence provides a unique opportunity to examine the past behaviour of both the EAIS and the WAIS, as well as to explore the interactions between the two sectors of the Antarctic Ice Sheet and the factors regulating their behaviour on different timescales.

An upcoming Integrated Ocean Drilling Program drilling leg (Expedition 374) in the Ross Sea will include a number of sites on the deglaciated continental shelf and continental rise. The Ross Sea drill sites will complement results from the Deep Sea Drilling Project (DSDP) Leg 28, which focused on drilling the truncated succession of basinward-dipping strata on the continental shelf (Fig. 3). Core recovery at these sites was low, especially in clast-rich glacial and glacio-marine deposits, which hindered the interpretation of the recovered material. Even with advances in drilling technology since DSDP Leg 28, there are still issues with core recovery in clast-rich deposits; therefore it will be crucial to place these sites in the context of other data, in particular seismic data that provide sufficient stratigraphic resolution for correlation to drill core.

The stratigraphic succession on the Ross Sea continental shelf has been deeply eroded by multiple ice sheet advances, resulting in late Paleogene through Neogene strata being located at or near the seafloor (Fig. 3). High-resolution seismic surveys

From: Le Heron, D. P., Hogan, K. A., Phillips, E. R., Huuse, M., Busfield, M. E. & Graham, A. G. C. (eds) 2019. *Glaciated Margins: The Sedimentary and Geophysical Archive.* Geological Society, London, Special Publications, **475**, 223–240.
First published online April 17, 2018, https://doi.org/10.1144/SP475.5
© 2019 The Author(s). Published by The Geological Society of London. All rights reserved.
For permissions: http://www.geolsoc.org.uk/permissions. Publishing disclaimer: www.geolsoc.org.uk/pub_ethics

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

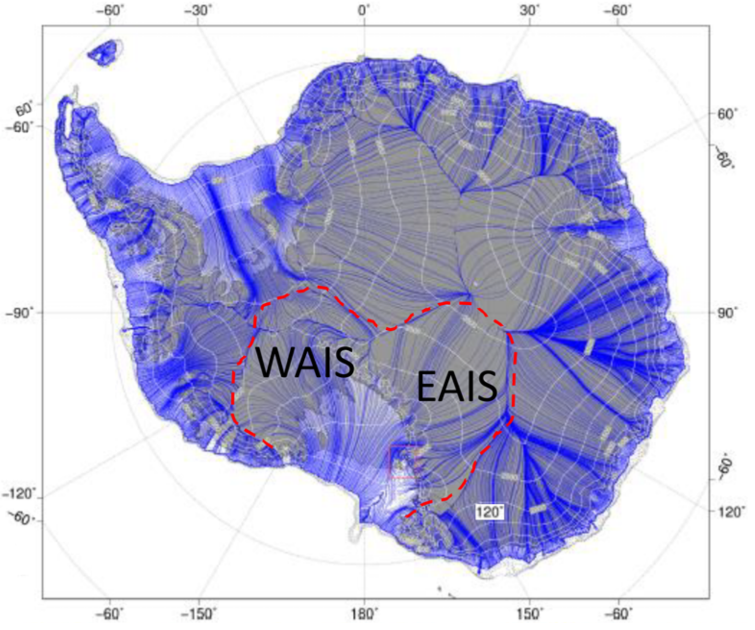


Fig. 1. The Ross Embayment drainage basin, outlined by the red dashed line, is the largest glacial drainage basin in Antarctica. Both the East and West Antarctic ice sheets drain here, with the catchment expanding by *c.* 30% during the Last Glacial Maximum. The blue lines represent flow lines. LGM configuration modified from Golledge *et al.* (2013). EIAS, East, Antarctic Ice Sheet; WAIS, West Antarctic Ice Sheet.

that image these strata allow for close correlation between seismic facies and the lithofacies within drill cores (Anderson & Bartek 1992; Alonso *et al.* 1992; De Santis *et al.* 1995). Seismic data processing allows us to infer petrophysical properties from the acoustic wave propagation velocity in sedimentary units (e.g. the degree of compaction and the fluid and gas content), which can aid in the interpretation of depositional histories (Accaino *et al.* 2005; Böhm *et al.* 2009). Glacial unconformities record ice advances across the continental shelf and can be used to map their extent and thus the extent of grounded ice. Biostratigraphic information from drill cores provides temporal constraints on episodes of ice sheet advance and retreat (e.g. Anderson & Bartek 1992; Alonso *et al.* 1992). The most recent glacial unconformity is typically situated within 20 m of the seafloor and is associated with ice advance across the continental shelf during the Last Glacial Maximum (LGM). Above the LGM unconformity, shallow sub-bottom acoustic data, sediment cores and glacial landforms preserved on the seafloor provide a detailed record of ice sheet advance and retreat (e.g. Shipp *et al.* 1999; Mosola & Anderson 2006; Halberstadt *et al.* 2016).

We first discuss the behaviour of the EAIS and the WAIS during and since the LGM based on recent analyses of geomorphic features on the continental shelf (Greenwood *et al.* 2012; Anderson *et al.* 2014; Halberstadt *et al.* 2016; Lee *et al.* 2017). We then explore the older record of glaciation in the region based on results from the application of a recently updated seismic facies classification scheme, which builds on earlier seismic data and more recent surveys in the Ross Sea (e.g. Shipp *et al.* 1999; Chow & Bart 2003; Mosola & Anderson 2006), augmented by results from seismic facies analyses in the Antarctic Peninsula (Bart & Anderson 1995, 1996; Vanneste & Larter 1995; Smith & Anderson 2010). By coupling records from the most recent glacial cycle with the Neogene record, we aim to understand how the EAIS and the WAIS interacted and which factors influenced their behaviour on different timescales. Some important questions we will address are: (1) what is the record of early EAIS and WAIS advance onto the continental shelf; (2) has the frequency and extent of advance and retreat varied between the two ice sheets; and (3) how representative is the LGM and post-LGM advance and retreat history of the ice sheets' deeper time evolution and behaviour? These questions will provide a synthesis of constraints for numerical models that require a knowledge of long-term ice sheet evolution.

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington
on October 7, 2021

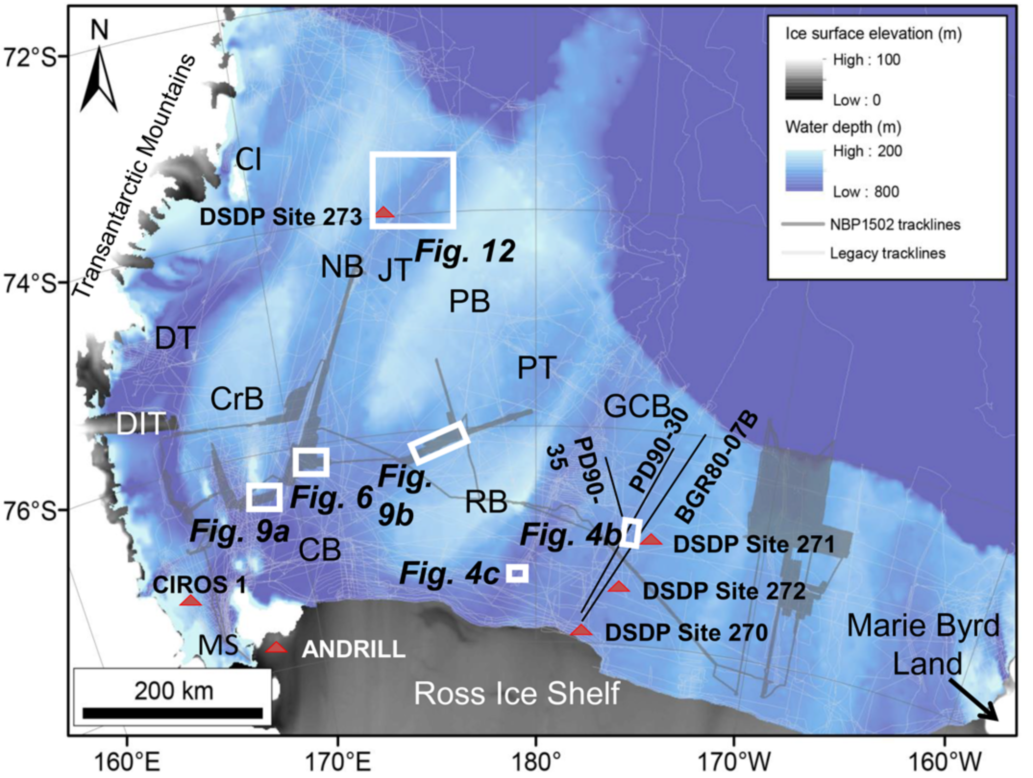


Fig. 2. Bathymetric map of the Ross Sea region with drill site locations and locations of seismic lines referred to in text. Thin white lines are legacy seismic lines acquired over the past four decades. Also shown are locations of figures with multibeam images. CB, Central Basin; CI, Coulman Island; CrB, Crary Bank; DT, Drygalski Trough; DIT, Drygalski Ice Tongue; GCB, Glomar Challenger Basin; JT, JOIDES Trough; MS, McMurdo Sound; NB, Northern Basin; PB, Pennell Bank; PT, Pennell Trough; RB, Ross Bank.

Last Glacial Maximum

A continental shelf-wide unconformity marks the LGM surface of erosion by the expanded ice sheet (Shipp *et al.* 1999; Mosola & Anderson 2006; Halberstadt *et al.* 2016) (Fig. 4a). With little sediment cover, the bathymetry of the modern seafloor reflects the relief on this surface, which is characterized by three broad, interconnected troughs separated by banks in the western Ross Sea and more subdued swells separating three large, discrete troughs in the eastern Ross Sea (Fig. 2). Till rests directly on this surface and is characterized by a semi-transparent to chaotic acoustic reflection character

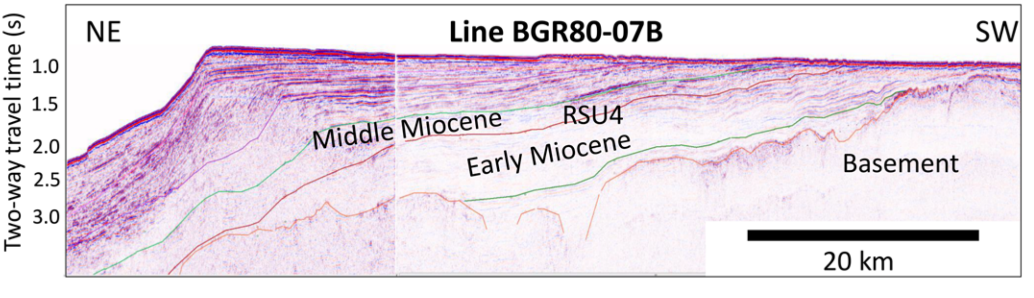


Fig. 3. Seismic profile BGR-07B illustrating seaward-dipping Cenozoic strata of the continental shelf. See Figure 2 for line location.

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington
on October 7, 2021

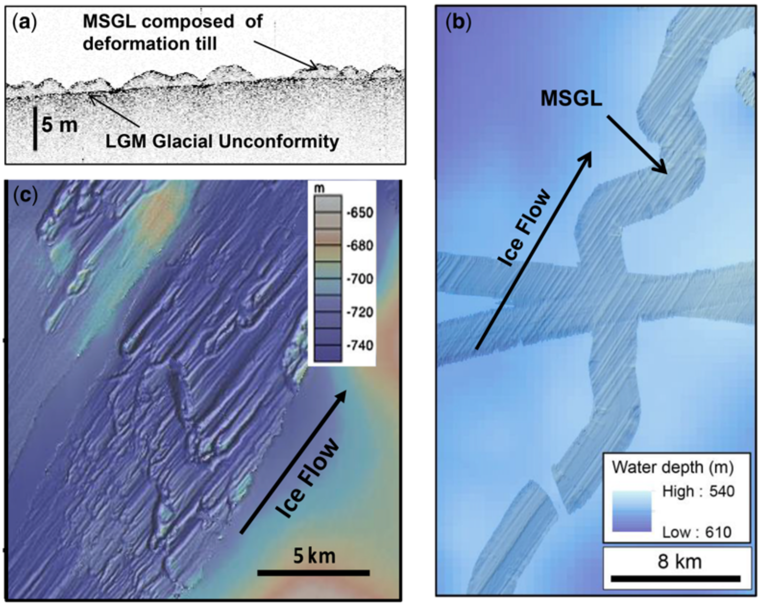


Fig. 4. Geomorphic features used to determine ice flow direction. (**a**) CHIRP sub-bottom profile showing deformation till associated with mega-scale glacial lineation resting on Last Glacial Maximum glacial unconformity. (**b**) Multibeam image showing MSGL. (**c**) Multibeam image showing drumlinoids. See Figure 2 for location. LGM, Last Glacial Maximum; MSGL, mega-scale glacial lineation.

(Fig. 4a). The tills vary in thickness, ranging from 1 to 20 m thick, with the greatest thickness within troughs and the thinnest on banks, with local variabilities in thickness associated with mega-scale glacial lineations (MSGLs; Fig. 4a, b).

The widespread occurrence and the orientations of subglacial landforms on the Ross Sea continental shelf, along with results from till provenance studies (Anderson *et al.* 1984; Licht *et al.* 2005; Farmer *et al.* 2006; Farmer & Licht 2016), provides compelling evidence that both the EAIS and the WAIS advanced across the continental shelf during the LGM, with the EAIS draining into the western Ross Sea and the WAIS draining into the eastern Ross Sea (Shipp *et al.* 1999; Mosola & Anderson 2006; Bart & Cone 2012; Bart & Owolana 2012; Anderson *et al.* 2014; Halberstadt *et al.* 2016). The WAIS extended to the continental shelf break, as evidenced by MSGLs (Mosola & Anderson 2006; Halberstadt *et al.* 2016), whereas the EAIS terminated on the outer shelf more than 100 km from the continental shelf break within palaeoglacial troughs (Fig. 5a).

Detailed palaeodrainage reconstruction of the EAIS and the WAIS is possible for the LGM and subsequent deglaciation because the glacial landforms mapped in multibeam swath bathymetry data provide a record of ice sheet expansion and retreat from the continental shelf (Shipp *et al.* 1999; Mosola & Anderson 2006; Bart & Cone 2012; Bart & Owolana 2012; Greenwood *et al.* 2012; Halberstadt *et al.* 2016; Lee *et al.* 2017). The ice sheet palaeodrainage during the LGM is based on linear features, mainly MSGLs (Fig. 4b). MSGLs are characterized by high parallel conformity, which makes them ideally suited to palaeodrainage reconstruction (Clark 1993; Stokes & Clark 2001; Spagnolo *et al.* 2014). Most MSGLs in the Ross Sea have amplitudes of 1–9 m and minimum lengths of *c.* 1–10 km and are associated with a massive seismic facies and diamicton lithofacies interpreted as deformation till (Shipp *et al.* 1999; Ó Cofaigh *et al.* 2002, 2007; Heroy & Anderson 2005) (Fig. 4a). In marine settings, MSGLs most commonly occur within troughs (e.g. Livingstone *et al.* 2012). This, along with their association with modern ice streams (King *et al.* 2009), leads to the interpretation that MSGLs record the presence of streaming ice overlying deformable sedimentary substrates.

Other less common and smaller (lengths of hundreds of metres to a few kilometres) streamlined subglacial features include drumlins, megaflutes, and crag and tail structures (Shipp *et al.* 1999; Anderson *et al.* 2014; Halberstadt *et al.* 2016). These features coexist and have width to length scales that overlap, hence they are lumped into a single category of drumlinoids (Fig. 4c). Around the Antarctic continental margin, drumlinoids are typically formed on

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington
on October 7, 2021

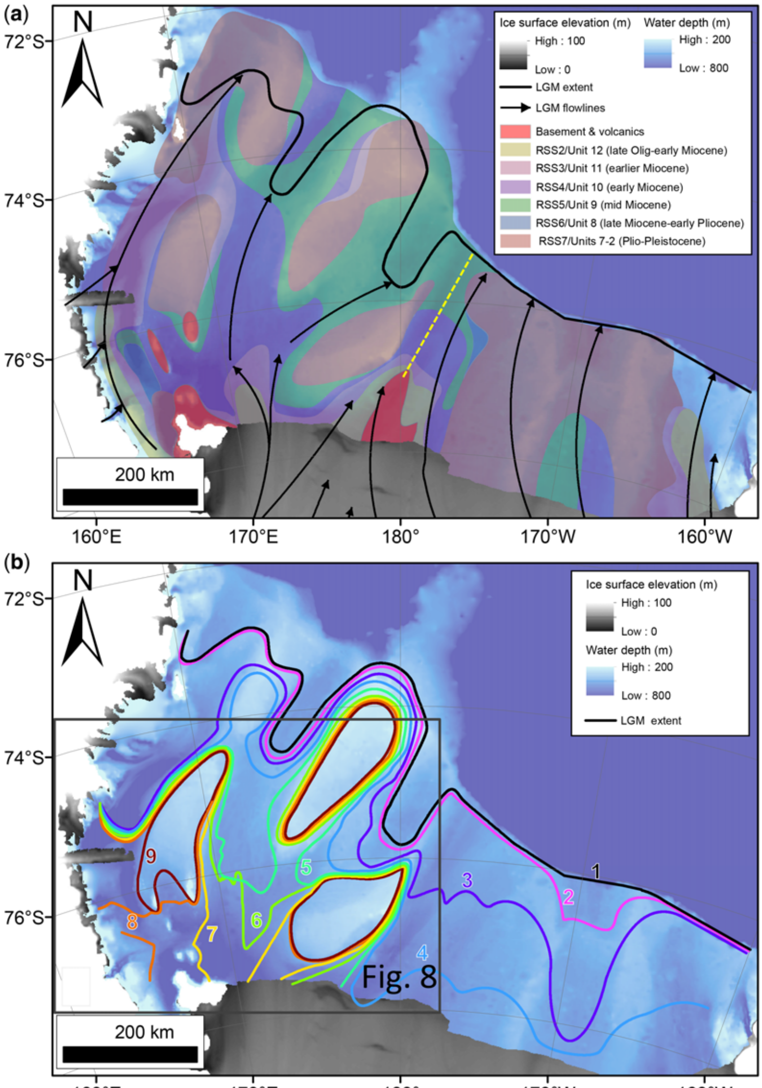


Fig. 5. (**a**) Last Glacial Maximum grounding line extent and palaeodrainage based on subglacial lineations (see Fig. 4) shown in the context of the seismically defined substrate. Yellow dashed line is the rough boundary between the East Antarctic Ice Sheet and the West Antarctic Ice Sheet. (**b**) Stages of grounding line retreat (1–9) showing ice retreat controlled by seafloor bathymetry. After Halberstadt *et al.* (2016). Inset shows location for Figure 8. LGM, Last Glacial Maximum.

crystalline bedrock and mark a zone of acceleration from hard beds, which are more resistant to flow, to soft sediment deforming beds (Anderson 1999; Wellner *et al.* 2002; Larter *et al.* 2009). This is consistent with their occurrence in the Ross Sea, where drumlinoids are restricted to coastal areas and the inner part of the Glomar Challenger Basin, where crystalline bedrock is exposed at or near the seafloor (Figs 2 & 4c).

Post-Last Glacial Maximum deglaciation

Geomorphic features formed during ice sheet retreat include ice-marginal landforms formed at palaeogrounding line positions, including grounding zone wedges (GZWs) and recessional moraines (Fig. 6). Recessional moraines are small (<5 m in amplitude) symmetrical features with generally linear crest lines. They result from deposition at the grounding

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

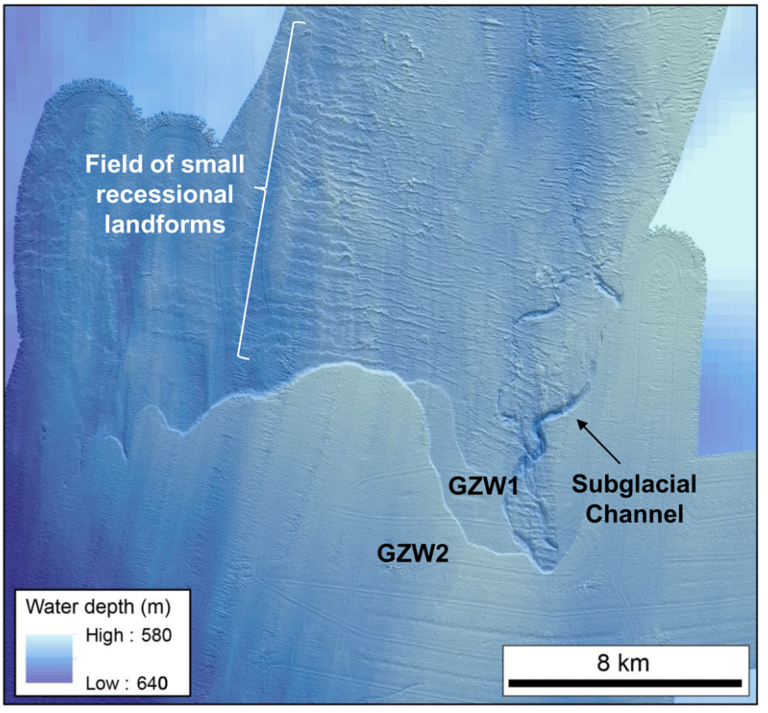


Fig. 6. Multibeam image showing ice sheet recessional features (moraines and grounding zone wedges). This example shows two stacked grounding zone wedges, with a younger wedge (GZW2) on top of the older wedge GZW1. A large subglacial channel occupies an embayment in the grounding zone wedges. See Figure 2 for location.

line and/or by the ploughing of sediment in front of the ice. Fields of closely spaced moraines are generally believed to record relatively continuous and rhythmical grounding line retreat (Fig. 6).

GZWs are asymmetrical, depositional features characterized by relatively steep foreset slopes (Fig. 7a). Prograding foreset beds, seen on some seismic profiles (e.g. Anderson 1999; Dowdeswell & Fugelli 2012; Batchelor & Dowdeswell 2015) (Fig. 7b) are often overprinted by glacial lineations observed to the topset–foreset break (e.g. Bart & Owolana 2012; Jakobsson *et al.* 2012). This indicates the seaward growth of GZWs by the overriding ice sheet and a distinct boundary between grounded and ungrounded ice. Thus they reflect episodes of grounding line stability and re-advance during an overall retreat phase of the ice sheet from the continental shelf. GZWs vary widely in size, up to 200 m in height and 100 km in length, which reflects the duration of grounding line stability and/or the rate of sediment supply to the grounding line. Larger GZWs commonly have sinuous foreset slopes (Fig. 6), which results from variable rates of sediment delivery to the grounding line from the subglacial environment. Composite GZWs, which consist of two or more stacked wedges (Fig. 6), can exceed 200 m in thickness and indicate oscillations of the grounding line (Dowdeswell & Fugelli 2012; Bart *et al.* 2017).

Landform assemblages in the western Ross Sea and the eastern Ross Sea reflect different styles of retreat of the EAIS and the WAIS, respectively. The main recessional features in the eastern Ross Sea are large-scale (tens of metres thick) GZWs, which are confined to glacial troughs. They vary in number and spacing between troughs, which indicates different ice stream retreat histories (Mosola & Anderson 2006; Bart & Owolana 2012). They are separated by well-preserved MSGLs; small-scale recessional landforms are rare. This indicates large grounding line retreat events of tens of kilometres in distance, punctuated by episodes of stability marked by the growth of large GZWs. This retreat behaviour is consistent with a low profile ice sheet retreating across a landward-deepening continental shelf with no major bathymetric pinning points (Mosola & Anderson 2006; Halberstadt *et al.* 2016). In addition, the WAIS flowed mainly across unconsolidated Plio-Pleistocene sediment (Fig. 5a), which is thought to have facilitated bed deformation and the rapid flow typical of modern ice streams.

Drygalski Trough in the far western Ross Sea is a deep trough bounded to the west by the

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

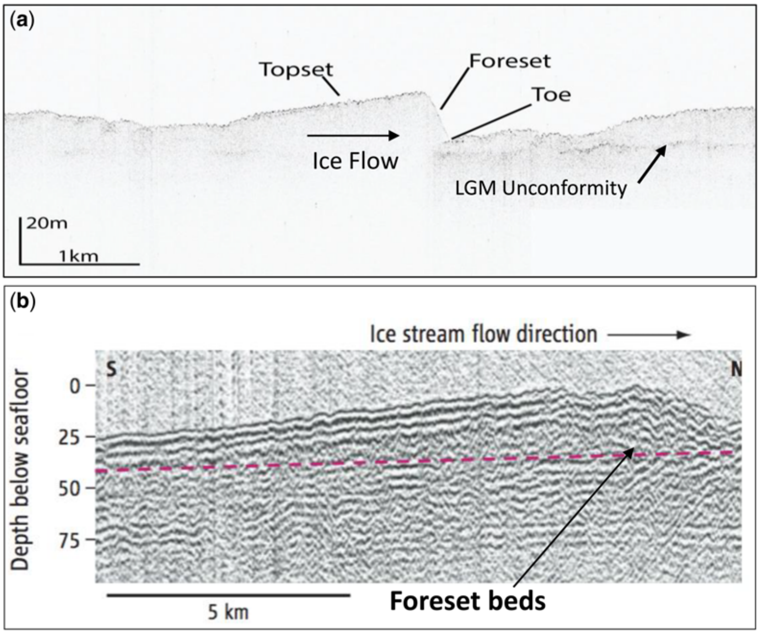


Fig. 7. (**a**) CHIRP sub-bottom profile crossing grounding zone wedge. (**b**) High-resolution seismic profile through grounding zone wedge resting on glacial unconformity (dashed red line). Note foreset bedding. LGM, Last Glacial Maximum.

Transantarctic Mountains and to the east by banks (Fig. 2). The northern part of the trough, north of the Drygalski Ice Tongue (Fig. 2), is dominated by MSGLs and only one major GZW, which marks the LGM position of the grounding line just north of Coulman Island (Figs 2 & 5a). The southern portion of the trough, south of the Drygalski Ice Tongue, contains only subtle streamlined features and small clusters of back-stepping wedges, which record ice retreat towards the west and north (Fig. 5b), back into outlets of the Transantarctic Mountains (Greenwood *et al.* 2012; Anderson *et al.* 2014; Jones *et al.* 2015; Halberstadt *et al.* 2016; Lee *et al.* 2017).

Elsewhere in the western Ross Sea, the seafloor is dominated by closely spaced small-scale (<10 m amplitude) retreat features, including recessional moraines and GZWs (Fig. 6). MSGLs occur only in isolated patches and on the topsets of GZWs and typically have amplitudes of only a few metres. The dominance of ice-marginal recessional landforms indicates rhythmic grounding line retreat characterized by small-magnitude grounding line migrations. Individual ice streams show complex retreat patterns, which were regulated by bathymetry, specifically large banks (Figs 5b & 8) (Shipp *et al.* 1999; Halberstadt *et al.* 2016). This palaeodrainage pattern indicates that the EAIS maintained a steep ice surface profile during retreat, generally preventing large-scale retreat events (tens of kilometres). The small size of GZWs and moraines in the western Ross Sea suggests that episodes of grounding line stability lasted only decades to centuries (Simkins *et al.* 2017). This is in contrast with centennial to millennial episodes of grounding line stability in the eastern Ross Sea, punctuated by larger magnitude retreat events (Bart *et al.* 2017). During the late stages of retreat, the ice sheet migrated up the flanks of banks, which later supported individual ice rises (Shipp *et al.* 1999; Anderson *et al.* 2014) (Figs 5b & 8). These ice rises were connected by an extensive ice shelf, which ultimately collapsed in the late Holocene, marking the final deglaciation of the continental shelf (Yokoyama *et al.* 2016).

At least two extensive subglacial channel networks have been identified in the western Ross Sea, which connect to palaeogrounding line positions based on superposition relationships between channel segments and ice-marginal landforms (Figs 6 & 9). One of these channels occurs within a narrow portion of Pennell Trough and was active when the ice stream flowed across a topographic high situated between the Pennell and Ross banks (Fig. 9b). Another palaeochannel extends for >150 km around southern Crary Bank into JOIDES Trough (Figs 6 & 9a) and was sourced from subglacial lakes, which stored water generated in an area of geologically recent volcanism and elevated geothermal heat (Simkins *et al.* 2017). Focused flow within the

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

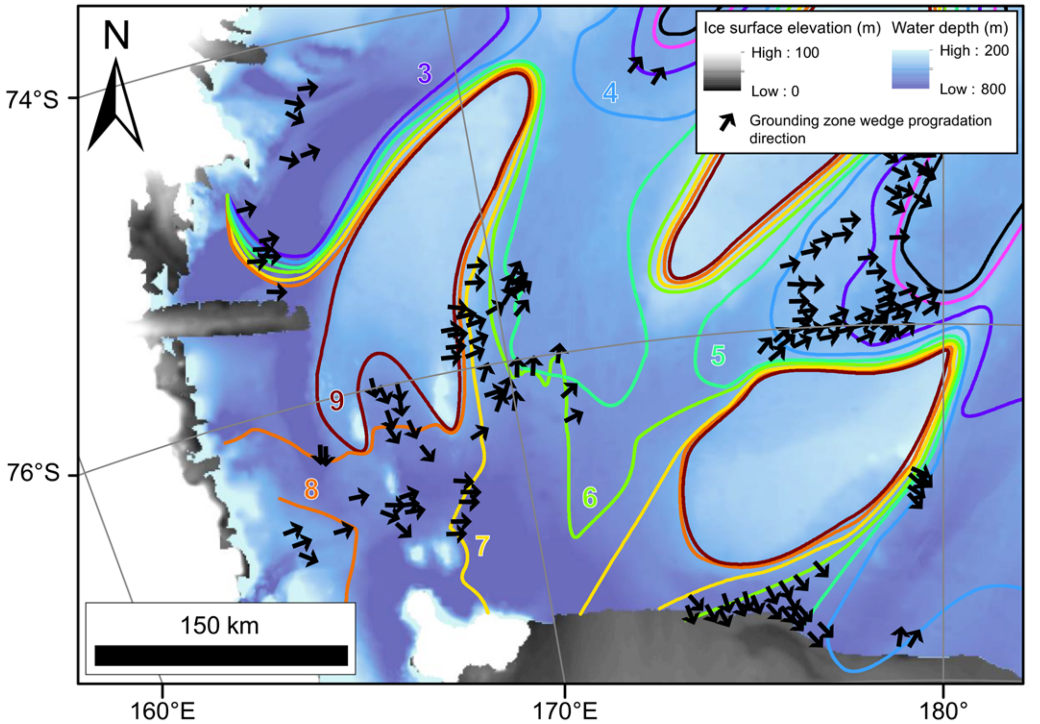


Fig. 8. Palaeodrainage during post-Last Glacial Maximum ice sheet retreat showing complex drainage in the western Ross Sea controlled by the shelf bathymetry (from Halberstadt *et al.* 2016). Note manner in which the ice sheet withdraws onto banks, resulting in the creation of individual ice rises. See Figure 5 for location. LGM, Last Glacial Maximum.

channel is believed to have reduced sediment delivery to the grounding line, which requires dispersive water flow to maintain the deformation till conveyer belt (Simkins *et al.* 2017). This, in turn, resulted in the formation of grounding line embayments and the development of pronounced grounding line sinuosity (Fig. 6). These channels are large enough to be imaged in higher resolution seismic data and they are associated with a distinct and widespread sorted terrigenous silt lithofacies, which is interpreted as a meltwater deposit (Prothro *et al.* 2018).

Pre-Last Glacial Maximum ice sheet history

Geomorphological features preserved on the seafloor provide a compelling picture of ice sheet advance and retreat from the continental shelf and different flow behaviour of the EAIS and the WAIS since the LGM. Pre-LGM continental shelf records, however, are not capable of resolving the smaller scale landforms that allow us to reconstruct detailed palaeodrainage and retreat patterns. We must rely on other methods for interpreting the older stratigraphic record of ice sheet behaviour. In general, lithofacies provide the most direct evidence of glacial history, but the similarity between subglacial and glacimarine diamictons sampled at sparsely cored drill sites can limit environmental interpretations and cannot alone be used to assess regional changes ice sheet behaviour. However, seismic data provide support for lithofacies interpretations and valuable information about the extent of lithofacies and bounding surfaces, and thus the magnitude of ice sheet growth and decay on the continental shelf. Seismic data can also provide important information about large-scale sediment transport patterns by allowing us to reconstruct glacial trough axes and determine sediment progradation directions using correlations across gridded seismic profiles. The correlation of seismic records to drill cores provides lithological and chronological ages and thus the seismic stratigraphic framework necessary for examining the long-term climatic and oceanographic history of the region.

High-resolution seismic surveys rely on higher frequency seismic sources capable of yielding metre-scale vertical and horizontal resolution and are thus capable of near outcrop-scale seismic facies

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

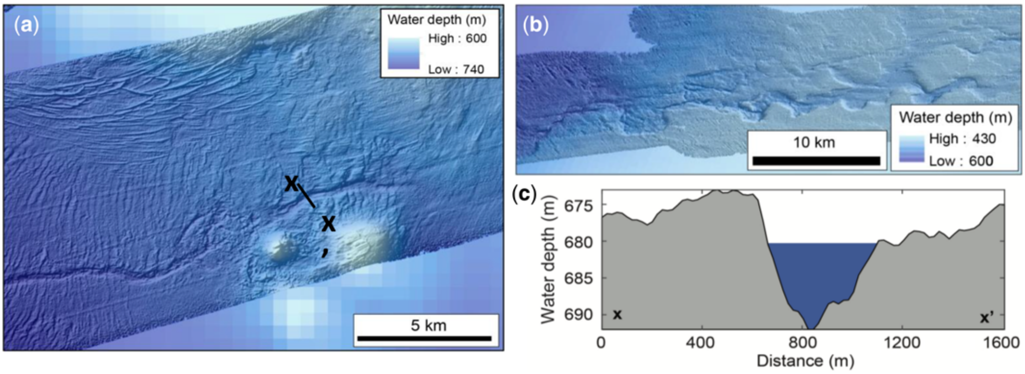


Fig. 9. (**a**, **b**) Two large meltwater channels on the western Ross Sea continental shelf (see Fig. 2 for locations). (**c**) Profile across one of these channels illustrating that it is large enough to be imaged in higher resolution seismic data.

analysis. For marine seismic data acquisition, the horizontal resolution is mainly controlled by ship speed and line spacing. High-resolution seismic surveys on the Antarctic continental margin have included sparkers (e.g. Banfield & Anderson 1995), deep-tow boomer (Vanneste & Larter 1995), water guns (e.g. Bart & Anderson 1995) and small (50 in^3) chamber Generator Injector air guns (e.g. Shipp *et al.* 1999; Bart 2003; Bart & Cone 2012; Smith & Anderson 2010). For the most part, these data were acquired using single-channel acquisition systems and the relatively short (<500 m) hydrophone streamers necessary for data acquisition in ice-covered waters.

In addition to the energy source, the recording system is crucial in acquiring high-resolution seismic data. Longer streamers (500–3000 m or more) record multiple reflections from the same stratigraphic layer. The different traces are then summed to obtain a clearer signal and to recognize unreal mirror reflectors. This technique allows the accurate analysis of the acoustic wave propagation velocity across different sedimentary units (e.g. Böhm *et al.* 2009). Different velocity values are generally used to infer the occurrence of fluids and gas and to convert the two-way travel time to depth in seismic sections. In the Ross Sea, the extensive data coverage allows a comparison of high-frequency, single-channel seismic data and multichannel seismic data (Fig. 10), thus providing the stratigraphic resolution needed for seismic facies analysis and a reasonable correlation of seismic units and bounding surfaces to drill core.

Belknap & Shipp (1991) provide a framework for high-resolution seismic facies analysis of glaciomarine strata based on: (1) the intensity of acoustic contrast bounding surfaces; (2) internal reflection configuration; and (3) the external shape of an identified grouping of similar reflections. Their work was expanded by Shipp *et al.* (1999), who conducted a combined geomorphological and high-resolution seismic facies analysis of LGM and post-LGM deposits in the Ross Sea. The study of Shipp *et al.* (1999) included a comparison of Generator Injector airgun records with CHIRP sub-bottom profiler data. They recognized five seismic facies based on the external geometry, the bounding surface amplitude, the intensity of the internal acoustic signature, the geometry of internal reflections and associations with geomorphic features. The correlation of seismic facies to the lithofacies encountered in sediment cores showed reasonable agreement (Domack *et al.* 1999). We have refined the Shipp *et al.* (1999) seismic facies classification scheme using results from seismic surveys on the Antarctic Peninsula continental shelf (Bart & Anderson 1995, 1996; Smith & Anderson 2010) and a re-analysis of Ross Sea data (lines Polar Duke 1990, NBP94, NBP95 and NBP99-02) in our seismic facies classification (Fig. 11). These surveys include lines that pass over the DSDP Leg 28 drill sites (Fig. 2), thus providing an additional opportunity to relate seismic and lithofacies and augment the results from previous studies (Anderson & Bartek 1992; Brancolini *et al.* 1995; De Santis *et al.* 1995).

Oligocene–Early Miocene

Major changes in continental shelf and slope bathymetry occurred throughout the Cenozoic, as reconstructed from reverse post-rift modelling of multichannel seismic data (De Santis *et al.* 1999). This provides a crucial framework for examining ice sheet evolution through a period of bathymetric changes extending back to the late Oligocene, beyond which the stratigraphic record is poorly sampled.

During the Late Oligocene and Early Miocene, the eastern Ross Sea was a deep rift basin with

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

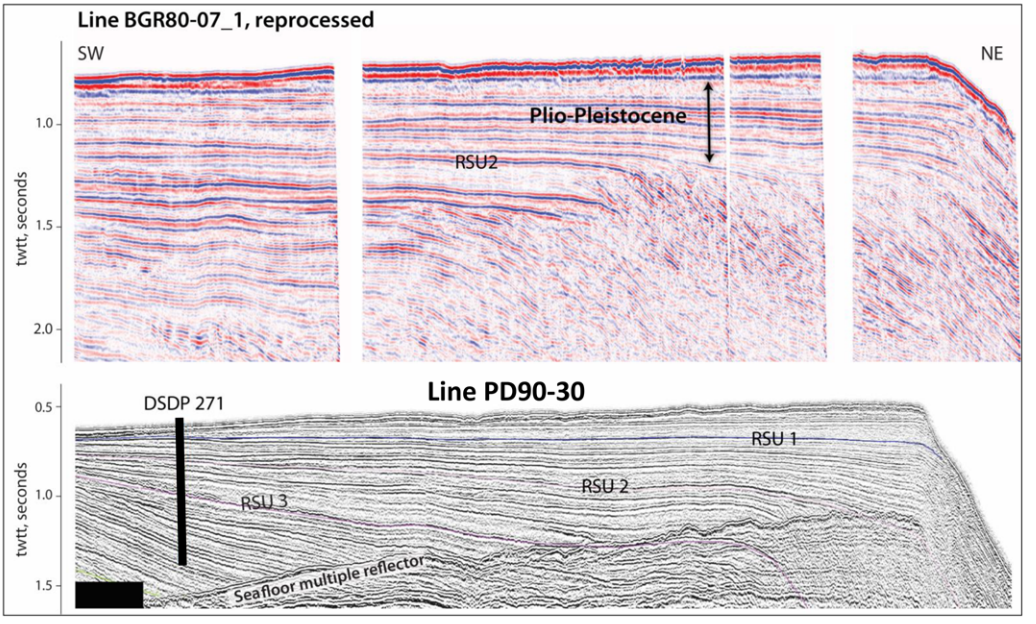


Fig. 10. Comparison of multichannel seismic profile BGR80-07 and high-resolution seismic profile PD90-30. Combined datasets similar to these are used for seismic facies analysis and the correlation of seismic stratigraphic surfaces to drill core, in this case DSDP Site 271.

isolated highs (Cooper *et al.* 1991). Upper Oligocene–lower Miocene strata are characterized by an overall stratigraphic architecture similar to lower latitude continental margins, indicating eustatically driven deposition and erosion of the continental shelf (Hinz & Block 1984; Cooper *et al.* 1991; Bartek *et al.* 1996). Seismic records show U-shaped palaeoglacial valleys along the flanks of banks (Fig. 12), suggesting localized glaciation (De Santis *et al.* 1995, 1999; Bartek *et al.* 1996; Sorlien *et al.* 2007). These observations are supported by the occurrence of diamictons within Late Oligocene and Early Miocene deposits at DSDP Site 270 in the eastern Ross Sea and DSDP Site 273 in the western Ross Sea, which have been interpreted as till and/or grounding line-proximal glacio-marine deposits (Fig. 2; Hayes & Frakes 1975; Barrett 1975; Anderson 1999). CIROS-1, which was drilled on the coastal shelf in the far western Ross Sea, sampled relatively thick Late Oligocene diamictons and thin diamicton beds of Early Oligocene age. Attempts to map unconformities away from these highs were unsuccessful, so the extent of Oligocene glaciation remains uncertain (Anderson & Bartek 1992; De Santis *et al.* 1995; Bartek *et al.* 1996). On the far eastern side of the Ross Sea, the Roosevelt Basin contains a succession of sediment-filled troughs up to 20 km across and 100–150 m deep. These strata are truncated by an unconformity with relief suggestive of a glacial origin (Sorlien *et al.* 2007). Chronostratigraphic correlation to DSDP Site 270 is tenuous, but suggests that these features predate 20 Ma.

Results from the Antarctic Drilling Program (ANDRILL) in the southwestern Ross Sea (Fig. 2) showed that ice was grounded at the drill site at least three times (19.4, 18.6 and 17.6 Ma) during the Early Miocene (Fielding *et al.* 2011), but the extent of glaciation remains uncertain. DSDP Leg 28 Sites 270, 272 and 273 all recovered Early Miocene deposits containing diamictons. Seismic profiles across these drill sites show massive wedges with foreset bedding and lenticular, acoustically massive units with chaotic reflection patterns resting on glacial unconformities (Fig. 11). Thus there is strong evidence for widespread ice sheet advance onto the continental shelf during the Early Miocene. Unfortunately, biostratigraphic constraints for the DSDP sites is too poor to allow the correlation of these ice sheet expansions to the ANDRILL record.

Middle–Late Miocene

A major, apparently shelf-wide, unconformity (RSU4, Fig. 3) separates Early Miocene and Middle Miocene strata and is interpreted as recording a major advance of the ice sheet across the continental shelf (Cooper *et al.* 1991). Prior to this time, tectonic

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

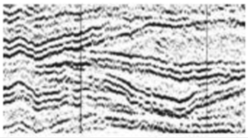
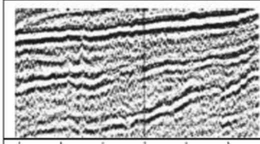
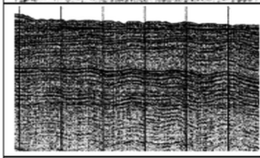
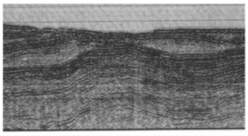
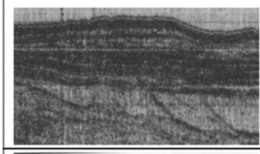
Acoustic character	Description	Interpretation
	Stacked, lenticular units with chaotic character draped by thin acoustically layered units. Cut and fill character. Occurs in nearshore mountainous areas and on bank flanks	Small troughs formed by outlet glaciers filled with till and capped by glacio-marine deposits (Bart and Anderson, 1995;1996; Smith and Anderson, 2009)
	Stacked, laterally extensive alternating acoustically layered and massive chaotic reflection pattern.	Alternating proximal and distal glacio-marine deposits. High velocity reflectors result from sediment compaction below glacial unconformities (Böhm et al., 2009; Accaino et al., 2005, Solheim et al., 1991)
	Alternating laminated and massive tabular units	Interbedded open marine (laminated) and glacio-marine deposits (Anderson and Bartek, 1992; De Santis et. al, 1995)
	Lenticular, acoustically massive units with chaotic reflection pattern resting on glacial unconformity	Grounding zone wedge (till tongues of Anderson and Bartek, 1992).
	Wedges with foreset bedding resting on glacial unconformity	Grounding zone wedges (Anderson and Bartek, 1992; Chow and Bart, 2003)
	Chaotic reflections filling unconformity-bounded channel-like depressions	Subglacial channels

Fig. 11. Seismic facies classification used in this study.

subsidence resulted in continued deepening of the shelf, which maintained a seaward-dipping profile (De Santis *et al.* 1999). Chow & Bart (2003) and Bart (2003) conducted detailed seismic stratigraphic studies focusing on the Miocene section in the Ross Sea. They concluded that the WAIS advanced across the Ross Sea continental shelf on at least five occasions during the Middle Miocene. These results provide compelling evidence that the WAIS was at times larger than at the present day and may have been large enough during the Middle Miocene to experience shelf edge grounding events without overflow of the EAIS.

It was during the Middle to Late Miocene that the continental shelf began to be reshaped into the current landward-dipping profile and a new style of stratigraphic architecture began to evolve, one that was controlled by glacial processes rather than eustasy (Bartek *et al.* 1992; De Santis *et al.* 1999; Decesari *et al.* 2007). Higher resolution seismic data show broad, deep glacial unconformities with relief similar to modern troughs. These unconformities separate alternating acoustically massive units, interpreted as till, and layered seismic units, interpreted as proximal and distal glacio-marine and marine sediments (Anderson & Bartek 1992; De Santis *et al.* 1995; Anderson 1999; Bart 2003) (Figs 3 & 11). DSDP Sites 272 and 273 both sampled Middle Miocene strata containing diamictons. Even more compelling evidence for grounded ice on the continental shelf exists as wedges of strata, previously interpreted as till deltas or till tongues (Anderson & Bartek 1992), which are now interpreted as GZWs based on their similarity in size to larger post-LGM GZWs, the occurrence of foreset bedding and their deposition directly on glacial unconformities (Fig. 13). These combined results point to a series of expansions of the WAIS onto the continental shelf during the Middle–Late Miocene. One of the most interesting outcomes of the Chow & Bart

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

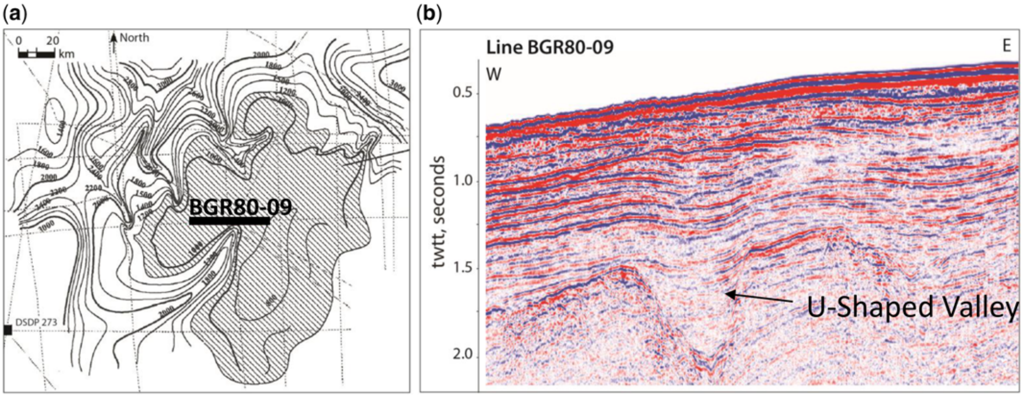


Fig. 12. (**a**) Time structure contour map of bedrock surface near the Central High showing valleys incised into banks and interpreted as having been cut by glaciers flowing off the banks during the late Oligocene. (**b**) Portion of seismic line BGR80-09 showing U-shaped valley (modified from De Santis *et al.* 1995). See Figure 2 for location.

(2003) study stems from their analysis of Middle Miocene strata thickness patterns. Their results showed considerable seafloor relief, with banks and troughs similar to those on the modern seafloor. They also used foreset strata to map progradation directions. Their results showed highly variable sediment progradation directions, indicating a strong influence of shelf bathymetry, with sediment shed from banks and transported within palaeotroughs (Fig. 14). If these progradation directions are taken as indicators of ice sheet palaeodrainage, then they reflect complex flow behaviour, similar to that observed for the post-LGM palaeodrainage reconstruction (Fig. 8; Halberstadt *et al.* 2016).

The spatial distribution and geometry of seismic facies, as well as correlation with the Northern Basin seismic sequences, document the expansion of an ice sheet seawards of North Victoria Land after 18 Ma and possibly in the early Pliocene. There is also evidence for expansion of the EAIS outlet glaciers, which cut glacial valleys near the Victoria Land coast as they advanced onto the shelf (Sauli *et al.* 2014). The larger of these valleys are >1 km deep and 1–2 km wide, occur along the seawards extension of the Tinker, Aviator, Fitzgerald and Icebreaker glaciers, and converge into the major David Glacier/Drygalski ice stream system that flowed through the Drygalski Trough (Fig. 2).

Plio-Pleistocene

The Plio-Pleistocene section lies above the RSU2 shelf-wide unconformity and is characterized by a change in stratigraphic architecture from progradational to relatively thin aggradational sequences (Fig. 10). Alonso *et al.* (1992) mapped seven widespread unconformity-bounded Plio-Pleistocene sequences recording episodes of widespread WAIS expansion onto the outer continental shelf in the eastern Ross Sea. Glacial/interglacial cycles are

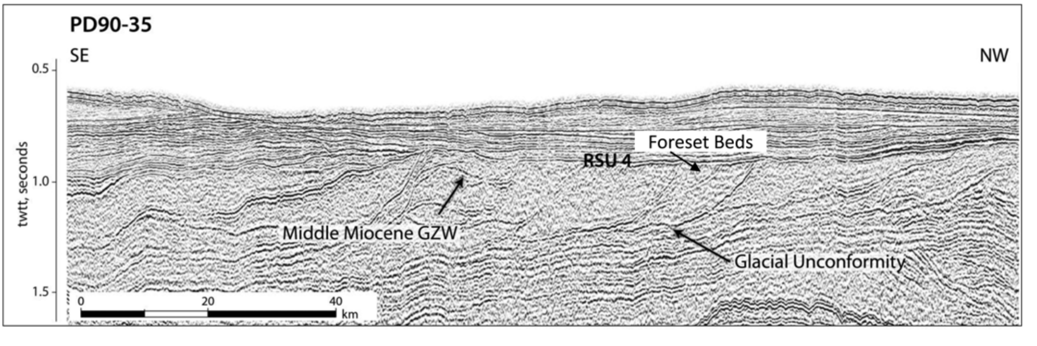


Fig. 13. Seismic profile PD90-35 illustrating prograded units with chaotic reflections, interpreted as stacked grounding zone wedges of Middle Miocene age. GZW, grounding zone wedge.

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

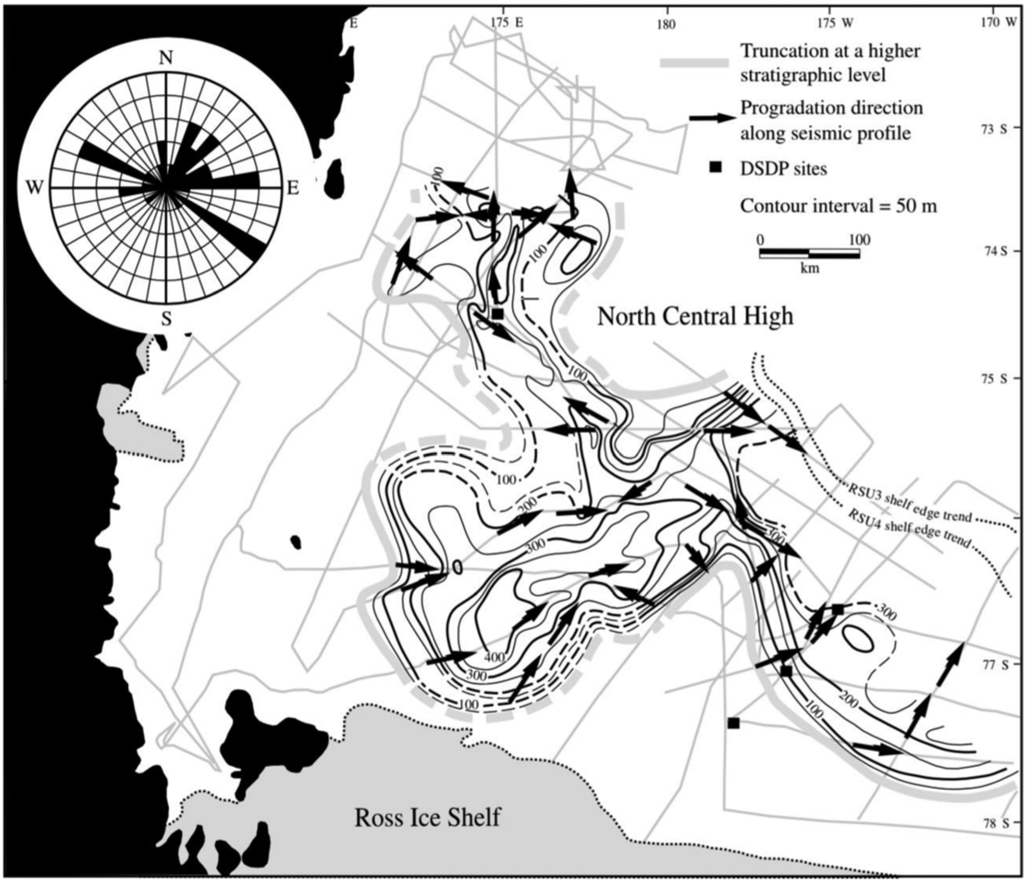


Fig. 14. Time structure contour map of the RSU3 (Middle Miocene) surface illustrating topographic relief on the western Ross Sea continental shelf and complex ice drainage around highs (arrows) derived from foreset progradation directions (from Chow & Bart 2003).

manifest as couplets of massive and acoustically layered deposits; the former are interpreted as till and proximal glacio-marine deposits and the latter as ice-distal glacio-marine deposits (Fig. 11). In east–west-oriented seismic lines, bounding unconformities exhibit large-scale relief mimicking modern troughs on the eastern shelf. They extend to the continental shelf edge, so these glacial advances were similar in extent to the LGM advance (Alonso *et al.* 1992). Thus these sequences record extensive WAIS grounding events and their thickness and available age control indicate an increase in the frequency of glacial–interglacial cycles relative to the Miocene. Detailed work by Bart (2003) showed that these glacial–interglacial cycles were associated with major changes in palaeodrainage, with the WAIS experiencing episodes of both northwards and west-directed flow across the eastern Ross Sea continental shelf. Seismic profiles also provide direct evidence of subglacial channels beneath the ice sheet (Fig. 11), further indicating the existence of a thick, polythermal WAIS during glacial expansions.

The Northern Basin of the Ross Sea (Fig. 2) is the only portion of the surveyed outer continental shelf that has experienced sufficient subsidence to have accumulated and preserved a relatively thick stratigraphic record of EAIS advance and retreat during the Plio-Pleistocene. Bart *et al.* (2000) recognized a total of ten Plio-Pleistocene glacial–interglacial cycles in the Northern Basin. At least one glacial unconformity is located within the lower Pliocene section.

The ANDRILL drill site in South McMurdo Sound shows that many cycles of grounded ice advance and retreat occurred at this inner shelf sector of the western Ross Sea during the past 5 myr (McKay *et al.* 2012*a*). Drilling results from the McMurdo Ice Shelf Project Site AND-1B focused

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

on the 3–5 Ma sedimentary record and sampled multiple glacial cycles (Scherer *et al.* 2007; Fielding *et al.* 2011).

Controls on ice sheet evolution

Both the EAIS and the WAIS advanced across the Ross Sea continental shelf during the LGM. The palaeodrainage for both ice sheets during and following the LGM is now relatively well constrained and shows ice flow patterns dominated by the shelf bathymetry, especially in the western Ross Sea where the EAIS occupied the continental shelf (Halberstadt *et al.* 2016) (Fig. 5a).

The principal controlling factors in regional retreat behaviour were the ice sheet configuration (i.e. thickness and surface profile), the shelf bathymetry and, to a lesser extent, the nature of the subglacial bed (Halberstadt *et al.* 2016). Ice was pinned on the high-relief banks in the western Ross Sea, whereas the lack of comparable features in the eastern Ross Sea indicates that the WAIS was not stabilized by pinning points. Large areas of the WAIS flowed across unconsolidated Plio-Pleistocene strata, which promoted bed deformation and more rapid flow and discharge, recorded by extensive fields of MSGLs and large GZWs. These landforms show that the grounding line retreated in a stepwise fashion, with episodes of stability followed by ice stream decoupling and landward retreat of tens of kilometres, consistent with a low profile ice sheet retreating across a landward-sloping continental shelf with minimal pinning points. Individual ice streams experienced independent behaviour as they retreated from the continental shelf (Mosola & Anderson 2006; Bart *et al.* 2017), which indicates variability in the sensitivity of these ice streams to external processes, such as climate warming and sea-level change.

During the LGM, the EAIS was a relatively thick ice sheet with three major ice streams, which also experienced independent retreat histories. The westernmost ice stream occupied Drygalski Trough, the deepest trough in the Ross Sea. It experienced stepwise retreat, similar to that of the WAIS, which culminated in the retreat of outlet glaciers back into their valleys within the Transantarctic Mountains (Anderson *et al.* 2014; Halberstadt *et al.* 2016; Lee *et al.* 2017). The grounding lines of the other two EAIS ice streams in the JOIDES and Pennell troughs formed continuous trails of recessional moraines and GZWs throughout their retreat from the continental shelf (Fig. 6). Rates of regional grounding line retreat varied and were controlled mainly by the seafloor topography, with the geology of the subglacial bed being a secondary influence (Halberstadt *et al.* 2016). MSGLs are isolated on the western shelf, being mostly confined to the topsets of GZWs. These combined observations indicate a thick, steep-profiled ice sheet (Halberstadt *et al.* 2016). Subglacial meltwater may have contributed to grounding line instability by influencing the dispersal of subglacial meltwater and sediment delivery to the grounding line (Simkins *et al.* 2017).

The record of pre-LGM glaciation in the Ross Sea is based on a robust collection of seismic data, but the timing of glacial events remains poorly constrained due to a paucity of drill core needed for chronostratigraphic analysis. There is good agreement with the seismic stratigraphic record of early Ross Sea glaciation, indicating that glaciation of the continental shelf extends back to at least the Late Oligocene and initially involved restricted ice caps on isolated banks. Both the eastern and western Ross Sea experienced widespread ice sheet expansion during the Early and Middle Miocene, growth that was undoubtedly facilitated by the fact that the foredeepened bathymetry of the continental shelf was not established until the Late Miocene (De Santis *et al.* 1999; Bart *et al.* 2016). Hence these ice sheet expansions do not necessarily call for thick, LGM-type marine-based ice.

The early ice streams were confined to troughs, the locations of which were generally controlled by roughly north–south-oriented rift basins separated by graben and half-graben (Cooper *et al.* 1991). This tectonic setting has been the dominant control on ice sheet palaeodrainage far back in time. Isolated banks that existed in the eastern Ross Sea during the onset of glaciation in the Late Oligocene were gradually buried in sediment, with the exception of the Central High, and a more regional south–north ice sheet palaeodrainage evolved in the Late Miocene–Early Pliocene. In the western Ross Sea, banks also served as nucleation centres for the early EAIS, but these banks have been persistent features since glaciation began in the Oligocene and continued to exert a strong influence on the EAIS by controlling ice stream flow patterns, by providing pinning points for the ice sheet and by supporting remnant semi-independent ice rises during deglaciation.

Both ice sheets have experienced multiple expansions across the continental shelf since the Middle Miocene. With each advance of the ice sheet, the inner shelf was deeply eroded and the products of this erosion were deposited on the outer shelf, leading to an overdeepened, landward-sloping profile by Late Miocene time. Despite this change in shelf bathymetry, both the EAIS and the WAIS have continued to grow and expand onto the continental shelf.

Results from Alonso *et al.* (1992) and Bart & Anderson (2000) clearly show a shift to higher frequency ice sheet advance and retreat in the Ross Sea during the Plio-Pleistocene, which involved both the EAIS and the WAIS. Both ice sheets

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

extended to the outer continental shelf during glacial advances. At least one of these advances occurred during the Early Pliocene, which is significant because it indicates that the Antarctic ice sheets advanced despite the generally warmer climates of the Early Pliocene (Bart *et al.* 2000). Numerical modelling supports the view that grounded ice advanced to the Ross Sea outer shelf during the Pliocene and especially the Late Pleistocene, inferred from large-amplitude δ^{18}O oscillations (Pollard & DeConto 2009). A similar shift to higher frequency glacial advance and retreat has been observed in the Antarctic Peninsula (Bart & Anderson 1995, 1996; Rebesco *et al.* 2006; Smith & Anderson 2010; Bart & Iwai 2012), although there the number of glacial–interglacial cycles is even higher and more consistent with the oxygen isotopic records (Smith & Anderson 2010).

Bart *et al.* (2011) used diatom assemblage data from piston cores to make regional-scale correlations from Northern Basin to ANDRILL data on the inner shelf. The correlations suggested that the Pleistocene ice sheet dynamics indeed involved grounding line translations >600 km. However, the data also suggested that only two major advances of grounded ice have occurred since *c.* 0.71 Ma. This further indicates that the seven glacial advance and retreat cycles recorded at the AND-1B site during the past 0.780 Ma (McKay *et al.* 2012*b*) record regionally restricted events. Based on LGM reconstructions, these cycles record EAIS and not WAIS advance and retreat. The similar number of preserved unconformities in the eastern and western Ross Sea could reflect similarities in the overall forcing of EAIS and WAIS behaviour. Thus seismic results from the shelf do not support the conventional view that the land-based EAIS was relatively stable and that the marine-based WAIS was relatively dynamic.

Rebesco *et al.* (2006) argued that the shift to higher frequency glacial cycles occurred at *c.* 3.0 Ma and reflects the transition of the ice sheet from polythermal to the present polar conditions. However, the record of glaciation around Antarctica suggests diachronous ice sheet development (Anderson 1999), even within the Antarctic Peninsula region (Smith & Anderson 2010; Anderson *et al.* 2011; Davies *et al.* 2012). Thus we consider it unlikely that all sectors of the Antarctic Ice Sheet experienced simultaneous transitions from polythermal to polar conditions. Bartek *et al.* (1992) argue that the change to higher frequency cycles is a global phenomenon and most likely results from larger magnitude glacial eustatic fluctuations that would have regulated marine ice sheet stability. Overdeepening of the continental shelf undoubtedly contributed to ice sheet sensitivity to eustatic fluctuations, as well as greater exposure to warm, deep water incursion onto the continental shelf.

Although climate and eustasy appear to have been the dominant control on ice sheet evolution, shelf bathymetry, which is ultimately controlled by tectonics and basin evolution, has been the dominant control on regional ice sheet palaeodrainage, as is clearly shown in the Ross Sea. The western Ross Sea has maintained greater relief, with banks providing pinning points for the ice sheet and locations of ice rises during late stages of retreat. During ice sheet expansions, ice streams were routed around banks through deep troughs, resulting in a complex palaeodrainage regime showing similar patterns in the Early and Middle Miocene to the palaeodrainage that occurred during the LGM (Figs 8 & 14).

Conclusions

The stratigraphic record of marine glaciation in the Ross Sea extends back to at least the Late Oligocene and shows that both the EAIS and WAIS have existed since that time. Bathymetric highs provided nucleation points for early ice sheet growth and expansion onto the continental shelf. High sediment accumulation during the Early Miocene led to more subdued relief in the eastern Ross Sea, while the western Ross Sea maintained high relief. Widespread expansions of the both the EAIS and the WAIS across the continental shelf occurred during the Middle Miocene, with palaeodrainage in western Ross Sea strongly influenced by bathymetry. The inner continental shelf was deeply eroded with each advance of the ice sheets and the products of this erosion were deposited on the outer shelf, leading to an overdeepened, landward-sloping profile by Late Miocene time. Continued glacial sculpturing of the continental shelf accentuated the relief, especially in the western Ross Sea, enhancing the influence of bathymetry of ice sheet behaviour. By Pliocene time, the palaeodrainage of the WAIS began to take on a style that was more similar to the previous glacial cycle, with large ice streams advancing and retreating across mostly unconsolidated strata within a series of roughly north–south-oriented troughs. By contrast, the western Ross Sea maintained its high relief and more complex palaeodrainage. The frequency of WAIS and EAIS advance and retreat across the Ross Sea increased in the Plio-Pleistocene. This shift to higher frequency glacial–interglacial cycles appears to have been more in response to changes in shelf bathymetry and associated changes in eustatic and oceanic forcing than a direct response to climate variability.

The physiographic control on ice sheet drainage and behaviour is well expressed in the LGM and post-LGM time by geomorphic features. Broad ice streams of the WAIS were loosely guided by the south to north cross-shelf troughs, in contrast with

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

the EAIS palaeodrainage, where ice streams were funnelled through troughs that merged and converged around banks. Retreating ice streams of the EAIS were also influenced by subglacial meltwater drainage at palaeogrounding lines by altering grounding line sedimentation and restricting the growth of GZWs. This may have also been a process that influenced the grounding lines of the Plio-Pleistocene ice sheet. While the WAIS retreated from north to south in a stepwise fashion, the EAIS experienced more continuous and complex retreat guided by the pronounced shelf bathymetry.

Acknowledgements We thank the Bundesanstalt für Geowissenchaften und Rohstoffe, Germany for providing multichannel seismic data through the University of Trieste Antarctic Seismic Data Library System (http://sdls.ogs.trieste.it/).

Funding Support for cruise NBP1502 came from the National Science Foundation (NSF-PLR 1246353 to JBA) and the Swedish Research Council (D0567301 to SLG).

References

Accaino, F., Böhm, G. & Brancolini, G. 2005. Analysis of Antarctic glaciations by seismic reflection and refraction tomography. *Marine Geology*, **216**, 145–154.

Alonso, B., Anderson, J.B., Diaz, J.T. & 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*. American Geophysical Union, Antarctic Research Series, **57**, 93–103.

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

Anderson, J.B. & Bartek, L.R. 1992. Cenozoic glacial history of the Ross Sea revealed by intermediate resolution seismic reflection data combined with drill site information. *In*: Kennett, J.P. (ed.) *The Antarctic Paleoenvironment: A Perspective on Global Change: Part One*. American Geophysical Union, Antarctic Research Series, **56**, 231–263.

Anderson, J.B., Brake, C.F. & Myers, N.C. 1984. Sedimentation on the Ross Sea continental shelf, Antarctica. *Marine Geology*, **57**(1–4), 295–333.

Anderson, J.B., Warny, S., Askin, R., Wellner, J., Bohaty, S. & Smith, T. 2011. Cenozoic cryosphere expansion and the demise of Antarctica's Last Refugium. *Proceedings of the National Academy of Sciences of the USA*, **108**, 11299–11726.

Anderson, J.B., Conway, H. *et al.* 2014. Ross sea paleo-ice sheet drainage and deglacial history during and since the LGM. *Quaternary Science Reviews*, **100**, 31–54.

Banfield, L.A. & Anderson, J.B. 1995. Seismic facies investigation of late Quaternary glacial history of Bransfield Basin, Antarctica. *In*: Cooper, A.K., Barker, P.F. & Brancolini, G. (eds) *Geology and Seismic Stratigraphy of the Antarctic Margin*. American Geophysical Union, Antarctic Research Series, **68**, 123–140.

Barrett, P.J. 1975. Textural characteristics of Cenozoic preglacial and glacial sediments at Site 270, Ross Sea, Antarctica. *In*: Hayes, D.E., Frakes, L.A. *et al.* (eds) *Initial Reports of the Deep Sea Drilling Project*, **28**. US Government Printing Office, Washington, DC, 757–767.

Bart, P.J. 2003. Were West Antarctic ice sheet grounding events in Ross Sea a consequence of East Antarctic ice sheet expansion during the middle Miocene? *Earth and Planetary Science Letters*, **216**, 93–107.

Bart, P.J. & Anderson, J.B. 1995. Sequence record of glacial events affecting the Pacific margin of the northwestern Antarctic Peninsula. *In*: Cooper, A.K., Barker, P.F. & Brancolini, G. (eds) *Geology and Seismic Stratigraphy of the Antarctic Margin*. American Geophysical Union, Antarctic Research Series, **68**, 75–96.

Bart, P.J. & Anderson, J.B. 1996. Seismic expression of depositional sequence associated with expansion and contraction of ice sheets on the northwestern Antarctic Peninsula continental shelf. *In*: De Batist, M. & Jacobs, P. (eds) *Geology of Siliciclastic Shelf Seas*. Geological Society, London, Special Publications, **117**, 171–186, https://doi.org/10.1144/GSL.SP.1996.117.01.1

Bart, P.J. & Anderson, J.B. 2000. Relative stability of the Antarctic ice sheets during the Plio-Pleistocene from the perspective of the continental shelf. *Earth and Planetary Science Letters*, **182**, 259–272.

Bart, P.J. & Cone, A.N. 2012. Early stall of West Antarctic Ice Sheet advance on the eastern Ross Sea middle shelf followed by retreat at 27 500 ^{14}C yr BP. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **335–336**, 52–60.

Bart, P.J. & Iwai, M. 2012. The overdeepening hypothesis: how erosional modification of the marine-scape during the early Pliocene altered glacial dynamics on the Antarctic Peninsula's Pacific margin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **335–336**, 42–51.

Bart, P.J. & Owolana, B. 2012. On the duration of West Antarctic Ice Sheet grounding events in Ross Sea during the Quaternary. *Quaternary Science Reviews*, **47**, 101–115.

Bart, P.J., Anderson, J.B., Trincardi, F. & Shipp, S.S. 2000. Seismic data from the Northern basin, Ross Sea, record extreme expansions of the East Antarctic Ice Sheet during the late Neogene. *Marine Geology*, **166**(1–4), 31–50.

Bart, P.J., Sjunneskog, C. & Chow, J. 2011. Piston-core based biostratigraphic constraints on Pleistocene oscillations of the West Antarctic Ice Sheet in western Ross Sea between North Basin and AND-1B drill site. *Marine Geology*, **289**, 86–99.

Bart, P.J., Mullally, D. & Golledge, N. 2016. The influence of continental shelf bathymetry on Antarctic Ice Sheet response to climate forcing. *Global and Planetary Change*, **142**, 87–95.

Bart, P.J., Krogmeir, B.J., Bart, M.P. & Tulaczyk, S. 2017. The paradox of a long grounding during West Antarctic Ice Sheet retreat in Ross Sea. *Scientific Reports*, **7**, 1–8.

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington
on October 7, 2021

Bartek, L.R., Vail, P.R., Anderson, J.B., Emmet, P.A. & Wu, S. 1992. The effect of Cenozoic Ice Sheet fluctuations on the stratigraphic signature of the Neogene. *Journal Geophysical Research*, **96**, 6753–6778.

Bartek, L.R., Henrys, S.A., Anderson, J.B. & Barrett, P.J. 1996. Seismic stratigraphy of McMurdo Sound, Antarctica: implications for glacially influenced early Cenozoic Eustatic Change? *Marine Geology*, **130**, 79–98.

Batchelor, C.L. & Dowdeswell, J.A. 2015. Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins. *Marine Geology*, **363**, 65–92.

Belknap, D.F. & Shipp, C.R. 1991. Seismic stratigraphy of glacial marine units, Maine inner shelf. *In*: Anderson, J.B. & Ashley, G.M. (eds) *Glacial Marine Sedimentation; Paleoclimatic Significance*. Geological Society of America. Special Papers, **261**, 137–158.

Böhm, G., Ocakoğlu, N., Picotti, S. & De Santis, L. 2009. West Antarctic Ice Sheet evolution: new insights from a seismic tomographic 3D depth model in the Eastern Ross Sea (Antarctica). *Marine Geology*, **266**, 109–128.

Brancolini, G., Cooper, A.K. & Coren, F. 1995. Seismic facies and glacial history in the Western Ross Sea, Antarctica. *In*: Cooper, A.K., Barker, P.F. & Brancolini, G. (eds) *Geology and Seismic Stratigraphy of the Antarctic Margin*. American Geophysical Union, Antarctic Research Series, **68**, 209–233.

Chow, J.M. & Bart, P.J. 2003. West Antarctic Ice Sheet grounding events on the Ross Sea outer continental shelf during the middle Miocene. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **198**, 169–186.

Clark, C.D. 1993. Mega-scale glacial lineations and cross-cutting ice-flow landforms. *Earth Surface Processes and Landforms*, **18**, 1–29.

Cooper, A.K., Barrett, P.J., Hinz, K., Traube, V., Leitchenkov, G. & Stagg, H.M.J. 1991. Cenozoic prograding sequences of the Antarctic continental margin: a record of glacio-eustatic and tectonic events. *Marine Geology*, **102**, 175–213.

Davies, B.J., Hambrey, M.J., Smellie, J.L., Carrivick, J.L. & Glassier, N.J. 2012. Antarctic Peninsula Ice Sheet evolution during the Cenozoic Era. *Quaternary Science Reviews*, **31**, 30–66.

Decesari, R.C., Wilson, D.S., Luyendyk, B.P. & Faulkner, M. 2007. Cretaceous and tertiary extension throughout the Ross Sea, Antarctica.

De Santis, L., Anderson, J.B., Brancolini, G. & Zayatz, I. 1995. Seismic record of Late Oligocene through Miocene glaciation on the Central-Eastern Continental Shelf of Ross Sea. *In*: Cooper, A.K., Barker, P.F. & Brancolini, G. (eds) *Geology and Seismic Stratigraphy of the Antarctic Margin*. American Geophysical Union, Antarctic Research Series, **68**, 235–260.

De Santis, L., Prato, S., Brancolini, G., Lovo, M. & Torelli, L. 1999. The Eastern Ross Sea continental shelf during the Cenozoic: implications for the West Antarctic ice sheet development. *Global and Planetary Change*, **23**(1–4), 173–196.

Domack, E.W., Jacobson, E.A., Shipp, S. & Anderson, J.B. 1999. Sedimentologic and stratigraphic signature of the Late Pleistocene/Holocene fluctuations of the West Antarctic Ice Sheet in the Ross Sea: a new perspective: Part 2. *Geological Society of America*, **111**, 1516–1536.

Dowdeswell, J.A. & Fugelli, E.M.G. 2012. The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets. *Geological Society of America Bulletin*, **124**, 1750–1761.

Farmer, G.L. & Licht, K.J. 2016. Generation and fate of glacial sediments in the central Transantarctic Mountains based on radiogenic isotopes and implications for reconstructing past ice dynamics. *Quaternary Science Reviews*, **150**, 98–109.

Farmer, G.L., Licht, K., Swope, R.J. & Andrews, J.T. 2006. Isotopic constraints on the provenance of fine-grained sediment in LGM tills from the Ross Embayment, Antarctica. *Earth and Planetary Science Letters*, **249**, 90–107.

Fielding, C.R., Browne, G.H. *et al.* 2011. Sequence stratigraphy of the ANDRILL AND-2A drillcore, Antarctica: a long-term, ice-proximal record of Early to Mid-Miocene climate, sea-level and glacial dynamism. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **305**, 337–351.

Golledge, N.R., Levy, R.H. *et al.* 2013. Glaciology and geological signature of the Last Glacial Maximum Antarctic ice sheet. *Quaternary Science Reviews*, **78**, 225–247.

Greenwood, S.L., Gyllencreutz, R., Jakobsson, M. & Anderson, J.B. 2012. Ice flow switching and East/West Antarctic ice sheet roles in glaciation of the western Ross Sea. *Geological Society of America Bulletin*, **124**, 1736–1749, https://doi.org/10.1130/B30643.1

Halberstadt, A.R., Simkins, L.M., Greenwood, S.L. & Anderson, J.B. 2016. Past ice sheet behavior: retreat scenarios and changing controls in the Ross Sea, Antarctica. *The Cryosphere*, **10**, 1003–1020.

Hayes, D.E. & Frakes, L.A. 1975. General synthesis: Deep Sea Drilling Project 28. *In*: Hayes, D.E., Frakes, L.A. *et al.* (eds) *Initial Reports of the Deep Sea Drilling Project*. US Government Printing Office, Washington, DC, **28**, 919–942.

Heroy, D. & Anderson, J.B. 2005. Ice sheet extent on the Antarctic Peninsula during the last glacial maximum (LGM) – insights from glacial geomorphology. *Geological Society of America Bulletin*, **117**, 1497–1512.

Hinz, K. & Block, M. 1984. Results of geophysical investigations in the Weddell Sea and in the Ross Sea, Antarctica. *In*: *Proceedings of the 11th World Petroleum Congress*. Wiley, New York, 279–291.

Jakobsson, M., Anderson, J.B. *et al.* 2012. Ice sheet retreat dynamics inferred from glacial morphology of the Central Pine Island Bay Trough, West Antarctica. *Quaternary Science Reviews*, **38**, 1–10.

Jones, R.S., Mackintosh, A.N. *et al.* 2015. Rapid Holocene thinning of an East Antarctic outlet glacier driven by marine ice sheet instability. *Nature Communications*, **6**, 8910.

King, E.C., Hindmarsh, R.C. & Stokes, C.R. 2009. Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream. *Nature Geoscience*, **2**, 585–588.

Larter, R.D., Graham, A.G.C. *et al.* 2009. Subglacial bedforms reveal complex basal regime in a zone of paleo-ice stream convergence, Amundsen Sea Embayment, West Antarctica. *Geology*, **37**, 411–414.

Lee, J., II, McKay, R.M., Golledge, N.R., Ho, Y., Kyu-Cheul, Y., Hyoung, J.K. & Hong, J.K. 2017. Widespread persistence of expanded East Antarctic glaciers in the southwest Ross Sea during the last deglaciation. *Geology*, **45**, 403–406.

Downloaded from http://sp.lyellcollection.org/ at Victoria University of Wellington on October 7, 2021

LICHT, K.J., LEDERER, J.R. & SWOPE, R.J. 2005. Provenance of LGM glacial till (sand fraction) across the Ross Embayment, Antarctica. *Quaternary Science Reviews*, **24**, 1499–1520.

LIVINGSTONE, S.J., Ó COFAIGH, C., STOKES, C.R., HILLENBRAND, C.-D., VIELI, A. & JAMIESON, S.S.R. 2012. Antarctic palaeo-ice streams. *Earth-Science Reviews*, **111**, 90–128.

MCKAY, R., NAISH, T. *ET AL.* 2012*a*. Antarctic and Southern Ocean influences on Late Pliocene global cooling. *Proceedings of the National Academy of Sciences of the USA*, **109**, 6423–6428.

MCKAY, R., NAISH, T. *ET AL.* 2012*b*. Pleistocene variability of Antarctic Ice Sheet extent in the Ross Embayment. *Quaternary Science Reviews*, **34**, 93–112.

MOSOLA, A.B. & ANDERSON, J.B. 2006. Expansion and rapid retreat of the West Antarctic Ice Sheet in Eastern Ross Sea: possible consequence of over-extended ice streams? *Quaternary Science Reviews*, **25**, 2177–2196.

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. *Geophysical Research Letters*, **29**, 41–44.

Ó COFAIGH, C., EVANS, J., DOWDESWELL, J.A. & LARTER, R.D. 2007. Till characteristics, genesis and transport beneath Antarctic paleo-ice streams. *Journal of Geophysical Research*, **112**, 1–16.

POLLARD, D. & DECONTO, R.M. 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature*, **458**, 329–332.

PROTHRO, L.O., SIMKINS, L.M., MAJEWSKI, W. & ANDERSON, J.B. 2018. Glacial retreat patterns and processes determined from integrated sedimentology and geomorphology records. *Marine Geology*, **395**, 104–119.

REBESCO, M., CAMERLENGHI, A., GELETTI, R. & CANALS, M. 2006. Margin architecture reveals the transition to the modern Antarctic ice sheet *c.* 3 Ma. *Geology*, **34**, 301–304.

SAULI, C., BUSETTI, M., DE SANTIS, L. & WARDELL, N. 2014. Late Neogene geomorphological and glacial reconstruction of the northern Victoria Land coast, western Ross Sea (Antarctica). *Marine Geology*, **355**, 297–309.

SCHERER, R., HANNAH, M. *ET AL.* 2007. Palaeontologic characterisation and analysis of the AND-1B Core, ANDRILL McMurdo Ice Shelf Project, Antarctica. *Terra Antarctica*, **14**, 223–254.

SHIPP, S., ANDERSON, J.B. & DOMACK, E.W. 1999. Seismic signature of the Late Pleistocene fluctuation of the West Antarctic Ice Sheet System in Ross Sea: a new perspective, Part I. *Geological Society America Bulletin*, **111**, 1486–1516.

SIMKINS, L.M., ANDERSON, J.B. *ET AL.* 2017. Anatomy of a meltwater drainage system beneath the ancestral East Antarctic ice sheet. *Nature Geoscience*, **10**(9), 691.

SMITH, T.R. & ANDERSON, J.B. 2010. Ice sheet evolution in James Ross Basin, Weddell Sea margin of the Antarctic Peninsula: the seismic stratigraphic record. *Geological Society of America Bulletin*, **122**, 830–842.

SOLHEIM, A., FORSBERG, C.F. *ET AL.* 1991. Geotechnical properties of glacigenic shelf sediments from Prydz Bay, East Antarctica. *In*: BARRON, J., LARSEN, B. *ET AL.* (eds) *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, TX (Ocean Drilling Program), **119**, 143–167.

SORLIEN, C.C., LUYENDYK, B.P., WILSON, D.S., DECESARI, R.C., BARTEK, L.R. & DIEBOLD, J.B. 2007. Oligocene development of the West Antarctic Ice Sheet recorded in eastern Ross Sea strata. *Geology*, **35**, 467–470.

SPAGNOLO, M., CLARK, C.D. *ET AL.* 2014. Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset. *Earth Surface Processes and Landforms*, **39**, 1432–1448, https://doi.org/10.1002/esp.3532

STOKES, C.R. & CLARK, C.D. 2001. Palaeo-ice streams. *Quaternary Science Reviews*, **20**, 1437–1457.

VANNESTE, L.E. & LARTER, R.D. 1995. Deep-tow boomer survey on the Antarctic Peninsula Pacific margin: an investigation of the morphology and acoustic characteristics of late Quaternary sedimentary deposits on the outer continental shelf and upper slope. *In*: COOPER, A.K., BARKER, P.F. & BRANCOLINI, G. (eds) *Geology and Seismic Stratigraphy of the Antarctic Margin*. American Geophysical Union, Antarctic Research Series, **68**, 97–121.

WELLNER, J.S., LOWE, A.L., SHIPP, S.S. & ANDERSON, J.B. 2002. Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: implications for ice behavior. *Journal of Glaciology*, **47**, 397–411.

YOKOYAMA, Y., ANDERSON, J.B. *ET AL.* 2016. Widespread collapse of the Ross Ice Shelf during the late Holocene. *Proceedings of the National Academy of Sciences of the USA*, **113**, 2354–2359.