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Seismic stratigraphy, sedimentary architecture and palaeo-glaciology of the Mackenzie Trough: evidence for two Quaternary ice advances and limited fan development on the western Canadian Beaufort Sea margin

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ABSTRACT

A comprehensive grid of high-resolution 2-D seismic reflection data from the western Canadian Beaufort Sea margin is used to reconstruct past ice-stream dynamics within the Mackenzie Trough. Eight seismic facies and five sequences, divided into two megasequences, are identified from the Mackenzie Trough stratigraphy. Evidence for two Quaternary ice advances to the shelf break is provided by two sequences of acoustically chaotic to semi-transparent facies, interpreted as subglacial till. Buried landforms interpreted as lateral moraines and a grounding-zone wedge record the positions of still-stands or re-advances in the ice margin. The continental slope beyond the trough is characterised by canyons separated by inter-canyon ridges and thin glacigenic debris flows. Correlation with the onshore record suggests that the older of the two ice advances, which excavated the Mackenzie Trough, probably occurred during the Illinoian or Early Wisconsinan glaciations. The younger ice-stream advance is interpreted to have occurred during the last, Late Wisconsinan glaciation. The onset of cross-shelf glaciation on the western Canadian Beaufort Sea margin is inferred to have been initiated significantly later than on the eastern Beaufort Sea and eastern Canadian Arctic margins, which have a longer history of ice advance and were less peripheral to the ice-sheet centre. The architecture of the slope beyond the Mackenzie Trough reflects this comparatively short history of ice advance and lacks the progradational architecture and major glacial-sedimentary depocentre or trough-mouth fan that is characteristic of slopes seaward of cross-shelf troughs on formerly-glaciated margins.

1. Introduction

Palaeo-ice sheets, including the Laurentide Ice Sheet (Fig. 1A) which developed over North America a number of times during the Quaternary, were partitioned into fast flowing ice streams separated by slower flowing inter-ice stream regions. Ice streams exert a major influence on ice sheet behaviour and have the potential to force abrupt climate change through the rapid drainage of ice and delivery of sediment to the ice sheet margin (Overpeck et al., 1989; Bond et al., 1992; Stokes et al., 2005). Assemblages of glacigenic landforms, including mega-scale glacial lineations (MSGL), drumlins, grounding-zone wedges, moraines and iceberg keel ploughmarks, have been used previously to reconstruct former ice stream configurations and dynamics (Clark, 1993; Stokes and Clark, 1999).

Submarine sediments and landforms preserved on the sea floor of formerly glaciated continental shelves can provide a comprehensive record of past ice activity (e.g. Ottesen et al., 2005; Mosola and Anderson, 2006; Ottesen and Dowdeswell, 2009). Where they advanced across the continental shelf, ice streams formed deep cross-shelf troughs, typically with associated major sedimentary depocentres, termed trough-mouth fans, on the adjacent continental slope (Vorren et al., 1998; Dowdeswell and Siegert, 1999; Rise et al., 2005). Whereas bathymetry and shallow acoustic data can be used to identify glacigenic landforms on the sea floor, these methods typically provide information concerning only the most recent ice advance and retreat. The use of seismic reflection data enables the identification of buried glacier-derived sediments and landforms, providing information about older ice advances across the continental shelf (Dowdeswell et al., 2007).

The Canadian Beaufort Sea margin is characterised by three major bathymetric depressions; the Mackenzie, Amundsen Gulf and M'Clure Strait troughs (Fig. 1B). These three cross-shelf troughs represent the former locations of ice streams which drained the

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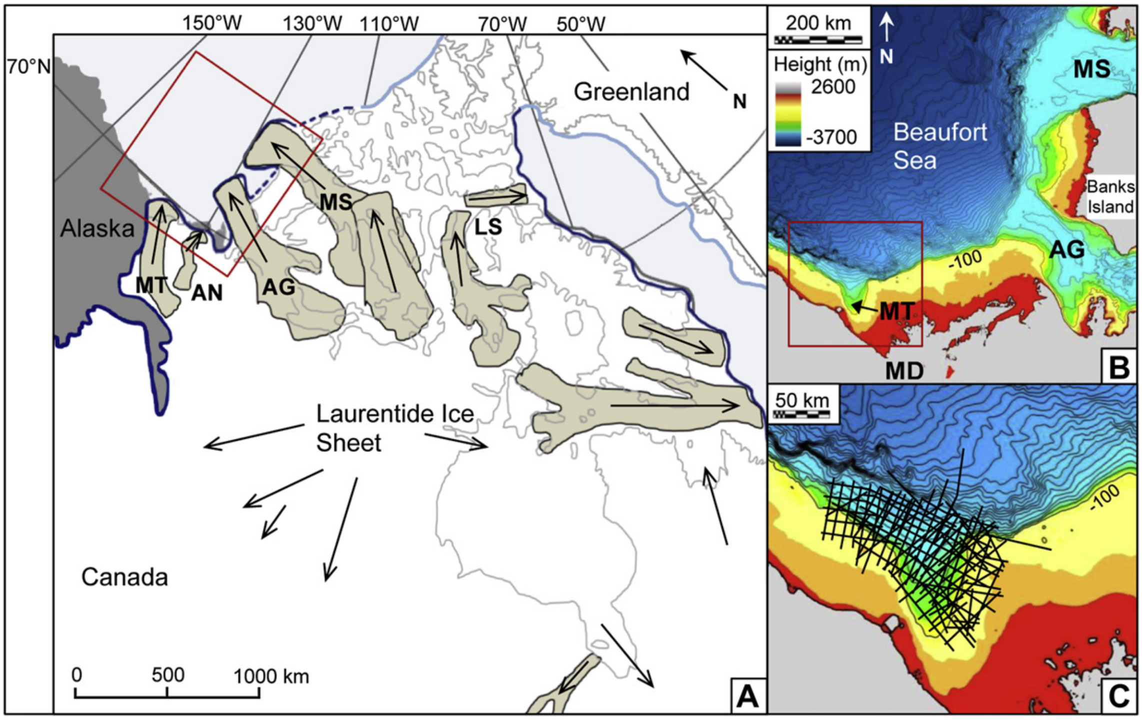


Fig. 1. A: Map of northern Laurentide Ice Sheet extent during Last Glacial Maximum about 20,000 years ago. Locations of ice streams, including the Mackenzie Trough (MT), Anderson (AN), Amundsen Gulf (AG), M'Clure Strait (MS), and Lancaster Sound (LS) ice streams are shown in grey (adapted from Winsborrow et al., 2004; updated to include Banks Island as ice-covered after England et al., 2009). B: IBCAO bathymetry of Canadian Beaufort Sea margin (100 m contours), showing locations of MT, AG, MS and the Mackenzie Delta (MD) (Jakobsson et al., 2012b). C: IBCAO bathymetry of the MT (100 m contours) showing distribution of analysed seismic lines.

north-west margin of the Laurentide Ice Sheet during Quaternary glaciations and served to transfer ice and debris from the ice-sheet into the Beaufort Sea (Sharpe, 1988; Blasco et al., 1990; Stokes et al., 2006, 2009). The Mackenzie Trough on the western Canadian Beaufort Sea margin is a 150 km-long, partially-infilled linear depression, which extends in a NNW direction from the modern Mackenzie River Delta to the continental shelf break at around 800 m below present sea level (Fig. 1B and C).

In this paper, we describe and interpret the seismic sequences, facies and architectural features present within the Mackenzie Trough with a view to furthering our understanding of Quaternary ice advances across the Beaufort Sea shelf. Particular emphasis is placed upon the identification of buried diagnostic glacigenic landforms and sediments within the seismic record. We discuss the implications of these data in relation to ice dynamics at the extreme north-west limit of the Laurentide Ice Sheet (Fig. 1A) and the glacial history of the Beaufort Sea margin of the Arctic Ocean.

2. Data acquisition and methods

The present study uses newly available, high-resolution 2-D seismic reflection data to examine the seismic stratigraphy and sedimentary architecture of the Mackenzie Trough and adjacent continental slope. The seismic reflection data were collected by ION Geophysical between 2006 and 2010 as part of the BeaufortSPAN East survey (http://www.iongeo.com/Data_Library/Arctic/BeaufortSPAN_East), and are supplemented by older seismic data. No well data was made available through the seismic sections in the Beaufort Sea.

The BeaufortSPAN East survey used airgun arrays to image down to the base crust. Acquisition parameters included a streamer length of 9000 m with 360 channels (720 channels per streamer in Phase 2 of acquisition), 18.4 s record intervals and a sample rate of around 2 m per second. Interpretations were made on two-way time seismic profiles in SeisWorks® Interpretation Software and then depth converted using a 3-D velocity model built from Pre-Stack Time Migration (PSTM) imaging velocities. These stacking velocities provide a reasonable time-depth conversion, especially over the interval of interest. Due to restrictions on the use of industrial data, further details of data processing and time-depth conversion models are not included. Structure and isopach maps were gridded in Z-MAP Plus™ Petroleum Mapping Software and imaged in ArcMap. A grid of data covering approximately 30,000 km^2 is analysed from the study area, with spacing of 5–15 km between seismic lines (Fig. 1C).

3. Background

3.1. Quaternary glacial history

The Laurentide Ice Sheet advanced across the western Canadian Beaufort Sea margin during at least one Quaternary glaciation, including the Toker Point Stade (Rampton, 1988; Blasco et al., 1990; Murton et al., 1997). The maximum ice limit during the Toker Point Stade has been partially mapped onshore and has been previously variably assigned to the Early Wisconsinan (Mackey and Mathews, 1983; Rampton, 1988; Vincent, 1989) and Middle Wisconsinan glaciations (Fig. 2A; Lemmen et al., 1994; Dallimore et al., 1997). However, recent evidence, including radiocarbon and luminescence dates from pre-glacial sands in the Tuktoyaktuk Coastlands, suggests that the Toker Point limit was reached during the Late Wisconsinan (Murton et al., 1997; Dyke et al., 2002; Duk-Rodkin et al., 2004; Bateman and Murton, 2006), no earlier than 22 ka ago (Murton et al., 2007). Extensive glaciation of the Beaufort Sea margin during the last, Late Wisconsinan, glaciation is supported by analyses of terrestrial and marine landform assemblages in the western Canadian Arctic Archipelago (Blasco et al., 2005; Stokes et al., 2005, 2006, 2009; MacLean et al., 2012), through numerical modelling (Stokes

Period	Epoch	Age (Ma)	North American Stage	Interpretation 1	Interpretation 2
Quaternary	Holocene	0 - 0.012	Present interglacial		
	Pleistocene	0.012 – 0.03	Late Wisconsinan Glaciation	Seq. 3 till	Seq. 3 till
		0.030 – 0.065	Middle Wisconsinan		
		0.065 – 0.08	Early Wisconsinan Glaciation	Seq. 1 till	
		0.080 – 0.13	Sangamonian Interglacial		
		0.130 – 0.3	Illinoian Glaciation		Seq. 1 till
		0.3 – 2.6	Pre-Illinoian (encompasses numerous distinct glacial stages including Banks Island Glaciation)		
Neogene	Pliocene	2.6 – 5.3	A		B

Fig. 2. A: Stratigraphic table showing the North American glacial and interglacial stages of the Pleistocene and Pliocene. B: Contrasting interpretations of the timing of the two ice advances through the Mackenzie Trough based on results in this study.

and Tarasov, 2010), and by recent geological evidence and radiocarbon dates from Banks and Victoria Islands (England et al., 2009).

The extent and timing of pre-Wisconsinan ice advances on the Beaufort Sea margin is presently uncertain. The subsurface stratigraphy of Banks Island, about 550 km east of the Mackenzie Trough (Fig. 1B), has been suggested previously to provide evidence of between four and seven pre-Late Wisconsinan Quaternary glaciations, including the earliest and most extensive Banks Glaciation between 1.77 and 1.07 Ma ago (Vincent, 1983; Barendregt et al., 1998). However, this interpretation has been challenged recently by England et al.'s (2009) revision to the Banks Island stratigraphy, in which all pre-Late Wisconsinan surficial tills are assigned to the Late Wisconsinan glaciation.

The most southerly extent of the Laurentide Ice Sheet was attained during the penultimate, Illinoian glaciation, between 130 and 300 ka ago (Fig. 2A). It has been suggested that an extensive ice shelf complex developed around the margins of the Arctic Ocean, including over the Beaufort Sea, during this glaciation, fed by ice streams emanating from the Mackenzie, Amundsen Gulf and M'Clure Strait troughs (Jakobsson et al., 2010). This ice shelf is inferred to have been particularly well-developed over the Canadian Arctic Ocean and has been dated based on the grounding of ice-shelf keels on bathymetric highs, such as the Chukchi Borderlands, in the Arctic Ocean (Jakobsson et al., 2008, 2010).

3.2. Generalised stratigraphy

The Mackenzie Trough is incised into fine-grained, fluvio-deltaic sediments of the Iperk Sequence of Plio-Pleistocene age (Grantz et al., 1990). The majority of Iperk Sequence sediment was provided to the Beaufort Sea margin by the palaeo-Porcupine River, a highly-competent river system which existed prior to the diversion and establishment of the Mackenzie River during the Late Wisconsinan (Grantz et al., 1990; Duk-Rodkin and Hughes, 1994). The overlying Shallow Bay Sequence is composed of Holocene fine-grained marine sediments deposited during the last, post-Late Wisconsinan, transgression. The base of the Iperk Sequence corresponds with the Late Miocene Unconformity of about 5 Ma ago, which was formed by a combination of eustatic, tectonic and climatic events, and represents a shift in depositional regime on the continental shelf (Dixon and Dietrich, 1990; McNeil et al., 2001). A substantial increase in margin progradation and in rates of sediment erosion and deposition are observed at this boundary and have been interpreted to be associated with the first expansion of ice sheets in the northern hemisphere (McNeil et al., 2001).

3.3. Previous work

It has been suggested previously that the Mackenzie Trough was excavated by an ice stream (Shearer, 1971; O'Connor, 1989), probably during a pre-Late Wisconsinan ice advance across the continental shelf (Blasco et al., 1990). Blasco et al. (1990) identified five seismo-stratigraphic units within the trough, including a basal unit of acoustically chaotic sediment (MT5), interpreted as subglacial till, overlain by an acoustically massive to poorly stratified sand (MT4), inferred to have been deposited during ice retreat. A second ice advance through the trough is suggested to have occurred during the Middle to Late Wisconsinan, overriding and only partially eroding the underlying units (Blasco et al., 1990). The existence of an ice stream in the Mackenzie Valley to the south of the Mackenzie Trough during the Late Wisconsinan has been suggested from terrestrial landform assemblages including eskers and MSGL (Beget, 1987; Winsborrow et al., 2004; Stokes et al., 2006; Brown et al., 2011). The ice stream is inferred to have extended beyond the present coastline through the Mackenzie Trough sometime between 22 and 16 ka ago (Murton, 2009).

4. Results: seismic facies and sequences

The base of the Mackenzie Trough is identified on seismic records as a high amplitude unconformity that truncates underlying reflections on the continental shelf (Fig. 3A–D). The trough is

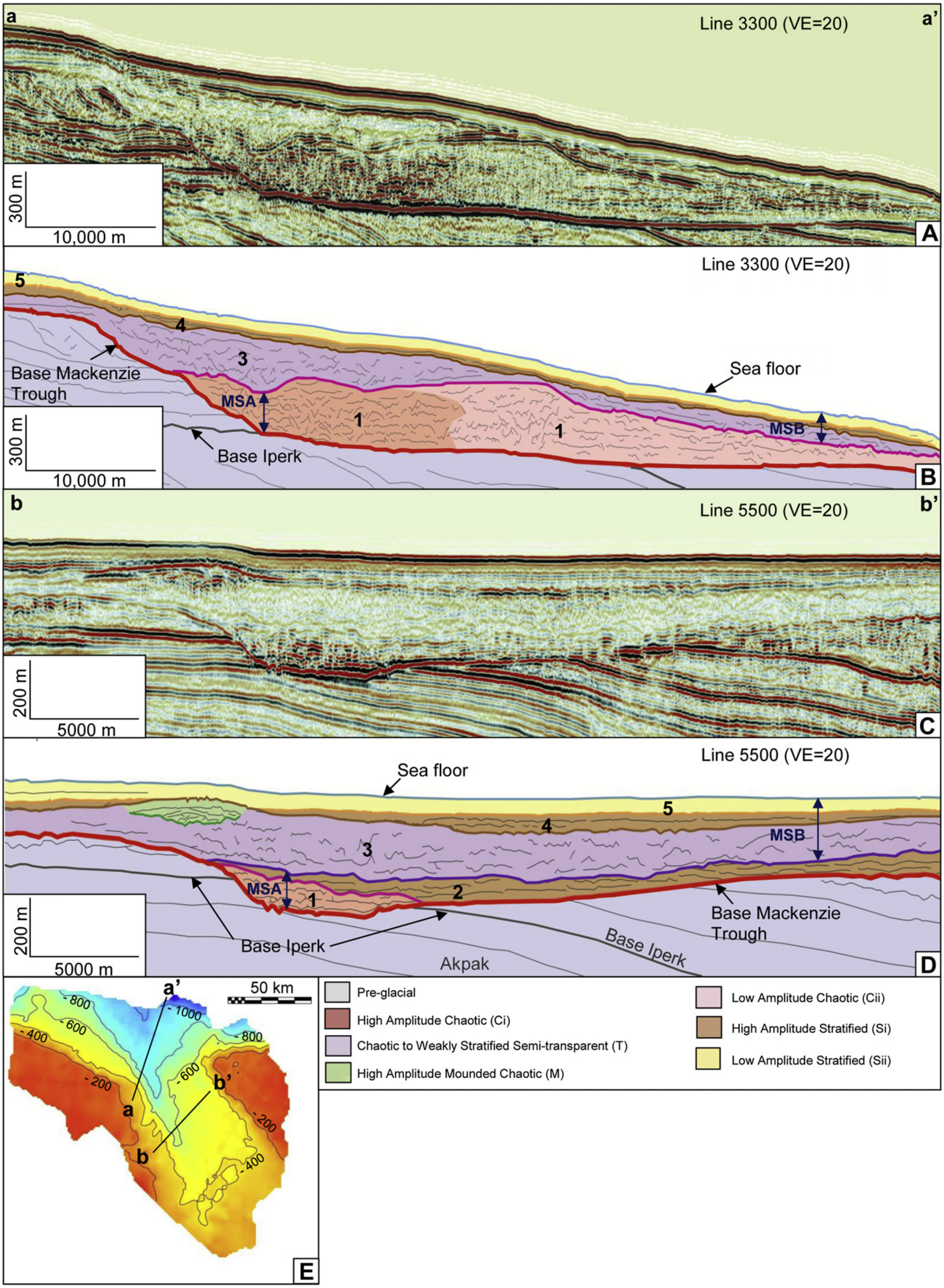


Fig. 3. Reflection seismic data from the Mackenzie Trough, western Canadian Beaufort Sea (Fig. 1). A: Seismic profile of a dip line through the Mackenzie Trough. B: Schematic line drawing illustrating distribution of seismic sequences 1–5, megasequences A and B, and facies. C: Seismic profile of a strike line across the Mackenzie Trough. D: Schematic line drawing illustrating distribution of seismic sequences 1–5, megasequences A and B, and facies. E: Map of the base of the Mackenzie Trough (m below sea level). Acoustic facies are shown in detail in Fig. 5.

partially infilled by up to 500 m of sediment (Fig. 4A). This sediment was divided into five genetic sequences, 1–5, bounded by unconformities and their correlative conformities. Two megasequences, A and B, have been identified from the fill of the Mackenzie Trough and were defined by the position of prominent erosional unconformities within the trough stratigraphy. Megasequence A contains two sequences, and Megasequence B contains three sequences (Fig. 3). Eight unique seismic facies, differentiated by the configuration and amplitude of their internal reflections, and several seismic features are described and form the building blocks for seismic sequences (Fig. 5).

4.1. Megasequence A – Sequence 1

4.1.1. Description

Sequence 1 is confined to the trough's central axis and reaches a maximum thickness of 270 m (Fig. 4B). Sequence 1 is composed predominantly of two chaotic seismic facies, Facies Ci and Cii (Fig. 3B). A gradual seaward transition from high amplitude (Facies Ci) to low amplitude (Facies Cii) chaotic facies occurs on the outer-shelf in association with a substantial increase in the width of Sequence 1 sediments (Fig. 6A).

Several U-shaped indentations with widths of up to 800 m and depths of 20 m (Fig. 5) are present on the basal unconformity below Facies Ci on the inner-shelf yet are not identified below Facies Cii on the outer-shelf. A number of hyperbolic reflections are also present on the trough's basal reflector below Facies Ci (Fig. 5).

A wedge of acoustically stratified sediment, Facies Siii, is identified overlying the chaotic facies in the middle- to outer-shelf region of the trough (Fig. 6). This feature has a length of 14 km, an across-trough width of 25 km and a maximum thickness of 100 m. The wedge of Facies Siii exhibits an asymmetric shape in long-profile with a steeper land-distal side (Fig. 6B).

4.1.2. Interpretation

The Mackenzie Trough is interpreted to have been excavated by an ice stream that traversed the continental shelf sometime during the Quaternary (Shearer, 1971; O'Connor, 1989; Blasco et al., 1990). The Plio-Pleistocene Iperk Sequence has been completely removed from the trough's deep central axis (Fig. 3), in which the basal unconformity is incised into sediment of the underlying Akpak or Mackenzie Bay Sequences (Dixon and Dietrich, 1990).

The stratigraphic position of Sequence 1 above a prominent erosion surface, together with its chaotic seismic character (Fig. 3), suggests that this sequence represents subglacial till. Subglacial till has been described previously to exhibit an internally structureless to chaotic texture on seismic records, reflecting a lack of sediment sorting beneath the ice sheet (Alley et al., 1989; King, 1993; Shipp et al., 1999). The distribution of Sequence 1 demonstrates that the initial ice advance that excavated the trough extended to the continental shelf break (Fig. 4B). Sequence 1 corresponds with Unit 5 of Blasco et al. (1990), in which it was interpreted as a 70 m-thick deposit of subglacial till confined to a narrow v-shaped valley.

The U-shaped indentations on the trough's basal unconformity (Fig. 5) may provide evidence for subglacial meltwater incision and the existence of a channelised meltwater network beneath at least some parts of the ice stream. On the outer-shelf, where U-shaped indentations are absent, subglacial meltwater may have been routed through smaller channels which are not resolved on the seismic data, or may have become incorporated into underlying sediment. Hyperbolic reflections are artefacts produced by the radial scattering of acoustic energy from a point source, such as irregular

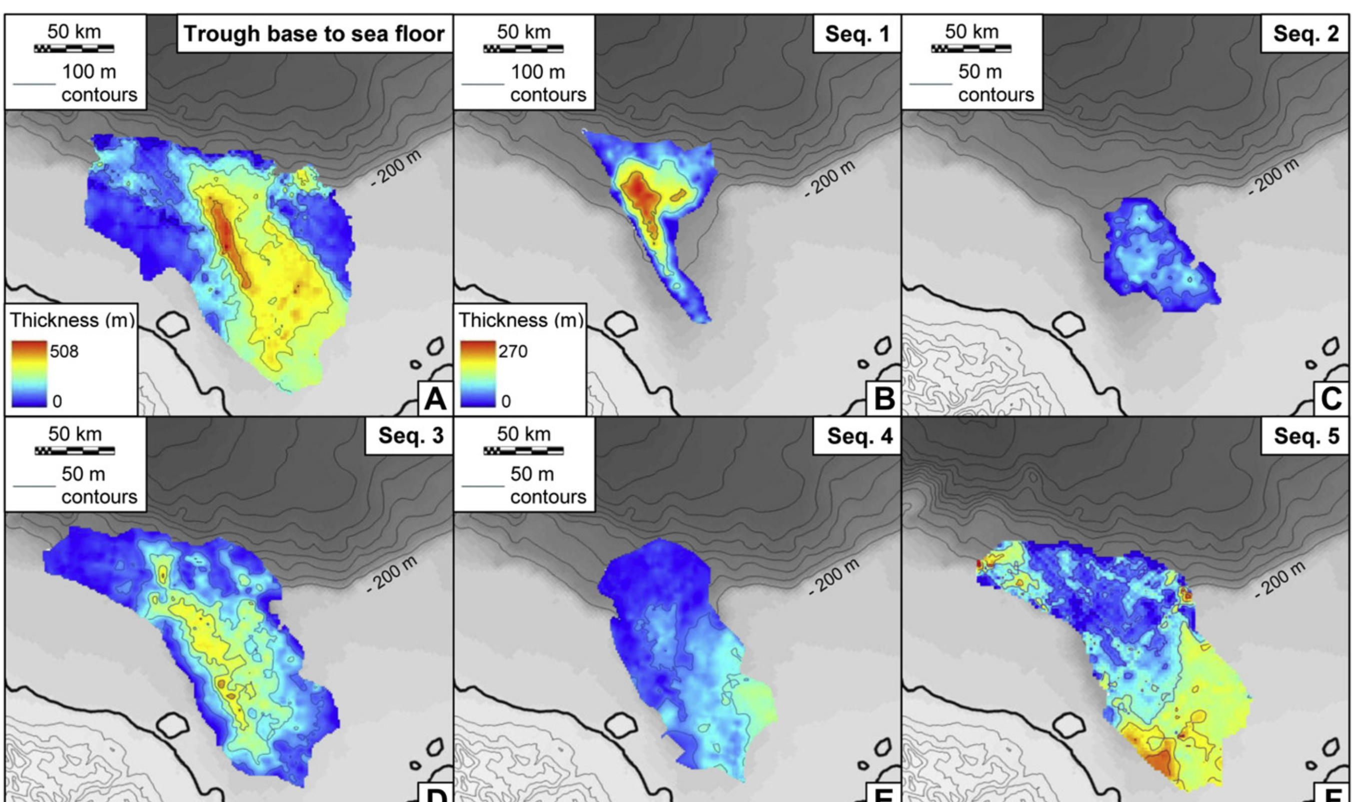
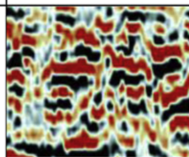
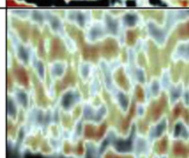
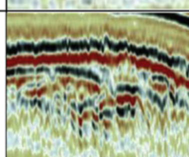
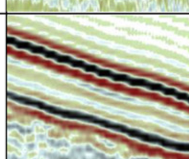
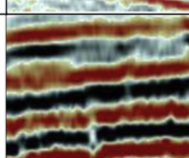
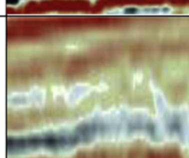
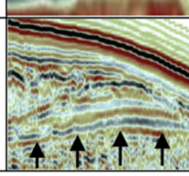


Fig. 4. A: Contoured isopach map of the trough base to sea floor, showing the composite thickness of sediment within the Mackenzie Trough. B–F: Contoured isopach maps of Sequences 1–5, respectively, overlying present-day IBCAO sea-floor bathymetry (200 m contours) (Jakobsson et al., 2012b). Maps B–F have the same scale bar as shown on B.

Seismic Facies	Example	Description
Ci		Chaotic seismic character, high amplitude reflections
Cii		Chaotic seismic character, low amplitude reflections
T		Semi-transparent seismic character, very low amplitude chaotic reflections
M		Chaotic seismic character, high amplitude reflections, mounded geometry
L		Semi-transparent to weakly stratified seismic character, on continental slope
Si		Stratified seismic character with high amplitude reflections
Sii		Stratified seismic character with low amplitude reflections
Siii		Stratified seismic character, occurs as discrete asymmetric wedge (base arrowed)

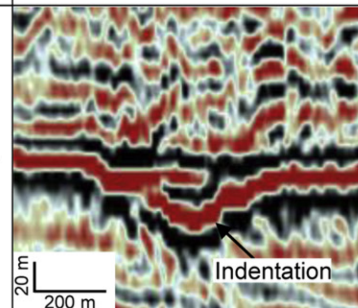
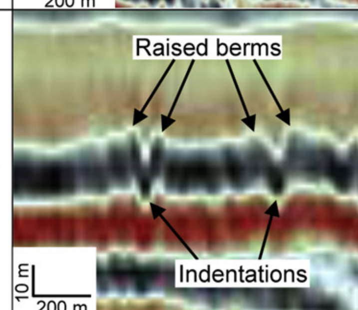
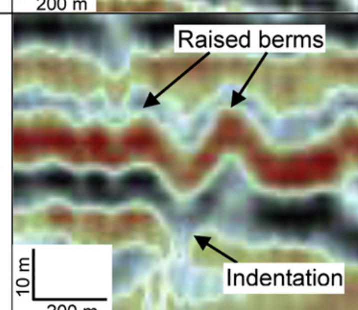
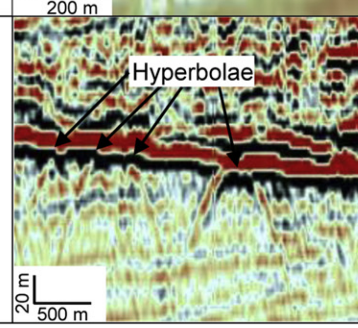
Seismic Feature	Example	Description
U-shaped indentations		U-shaped indentations on trough's basal reflector. Widths of up to 800 m, depths of up to 20 m.
Small V-shaped indentations		Small V-shaped indentations on upper reflectors of Sequences 3 and 4. Widths of up to 100 m, depths of a few metres. Berms either side of central depression
Large V-shaped indentations		Large V-shaped indentations on upper reflector of Sequence 3. Widths of up to 300 m, depths of up to 10 m. Berms either side of central depression
Hyperbolae		Hyperbolic reflections with apexes located on the trough's basal reflector

Fig. 5. Table illustrating the different seismic facies and seismic features identified from 2-D seismic profiling of the Mackenzie Trough.

topography or large clasts (Damuth, 1978). The presence of hyperbolic reflections below Facies Ci (Fig. 5) suggests that the trough's basal reflector is less smooth on the inner-shelf compared to the outer-shelf, possibly as a result of channel incision in this area.

The seaward transition from high to low amplitude chaotic facies within Sequence 1 (Fig. 6A) does not result from attenuation of the seismic signal, as both facies are overlain by sediments of a similar thickness and seismic character; it is probably caused by differences in the sedimentological properties of the tills. The reduced acoustic impedance contrasts within Facies Cii suggest that the outer-shelf till has a more homogeneous texture than till on the inner-shelf. It is possible that the inner-shelf till (Facies Ci) retains some original structures, such as internal bedding, or is less deformed than the outer-shelf till (Facies Cii).

The geometry and dimensions of Facies Siii (Fig. 6) suggest that this feature is a grounding-zone wedge produced by the supply of till to the ice margin during a still-stand in retreat (Dowdeswell and Fugelli, 2012). The wedge of Facies Siii occurs in association with a topographic high, which may have provided a pinning point for ice stabilisation (Dowdeswell and Siegert, 1999; Venteris, 1999; Dowdeswell and Fugelli, 2012). Grounding-zone wedges exhibit a characteristically asymmetric shape in the direction of ice-flow, with steeper ice-distal sides. The geometry of Facies Siii is therefore consistent with ice flowing in a NNW direction through the Mackenzie Trough towards the shelf break. The lengths and thicknesses of grounding-zone wedges on the continental margins of Greenland, Norway and Antarctica have been observed to scale approximately linearly (Fig. 6C). With an observed length of 14 km and a thickness of 100 m, the grounding-zone wedge identified within the Mackenzie Trough possesses similar dimensions to those documented off Antarctica, West Greenland and the Norwegian-Svalbard margin (Howat and Domack, 2003; Ottesen

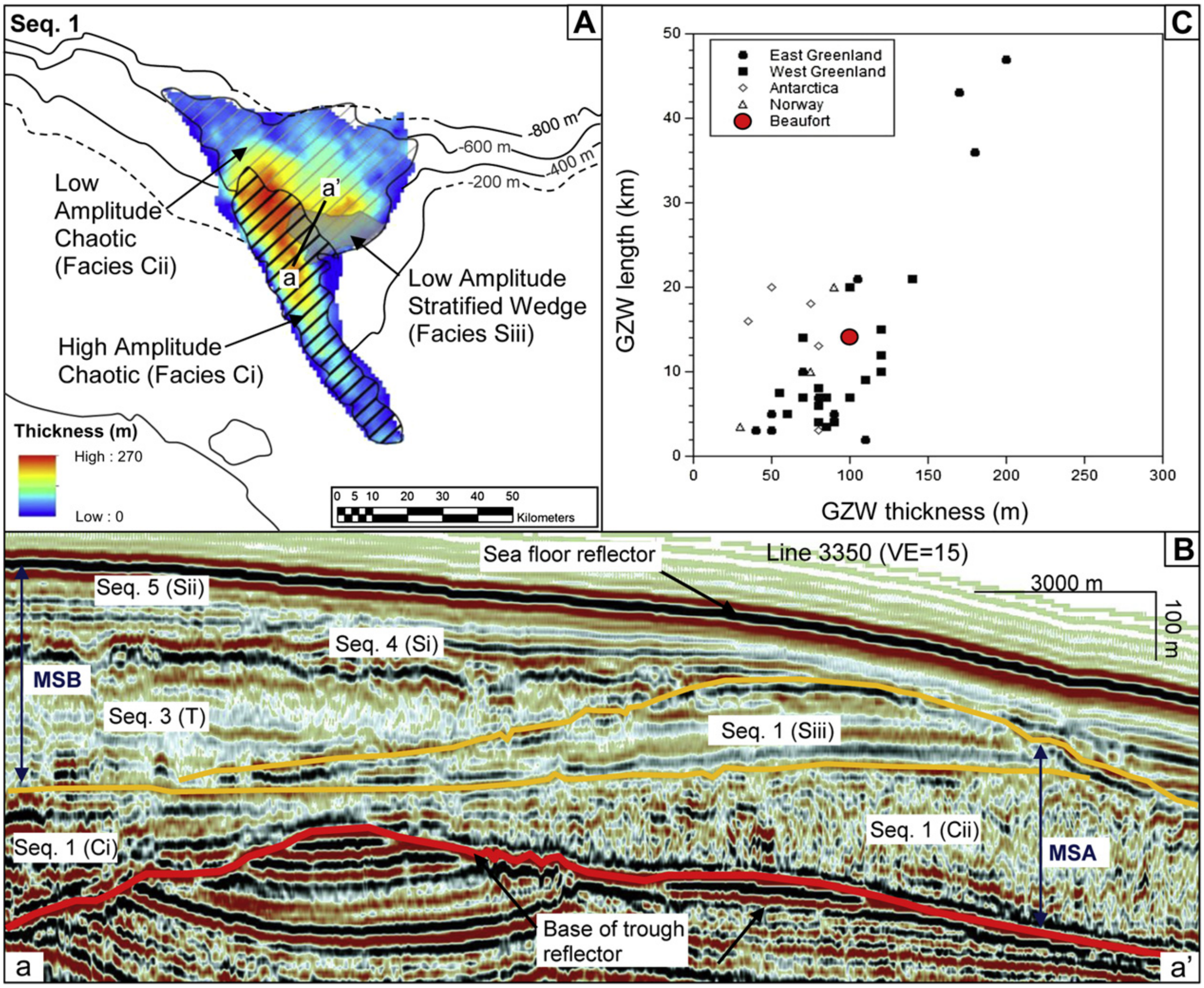


Fig. 6. A: Map showing the plan-form distribution of Facies Ci, Cii and Siii within Sequence 1. Dashed line indicates shelf break. B: Seismic profile of a dip line through the Mackenzie Trough grounding-zone wedge (Siii). C: Scatter-plot of length against thickness for grounding-zone wedges on high-latitude continental margins (Dowdeswell and Fugelli, 2012). Red circle marks the dimensions of the Mackenzie Trough grounding-zone wedge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2007; Dowdeswell and Fugelli, 2012; Jakobsson et al., 2012a). The Mackenzie Trough grounding-zone wedge is, however, smaller than several large, possibly composite, grounding-zone wedges identified off East Greenland (Fig. 6C) and to the north of the Amundsen Gulf Trough, which possess lengths of more than 30 km and are more than 150 m thick (Dowdeswell and Fugelli, 2012; Batchelor et al., 2013).

4.2. Megasequence A – Sequence 2

4.2.1. Description

Sequence 2 is composed of Facies Si, which has conformable geometry and a stratified seismic character (Figs. 3 and 5). Sequence 2 reaches a maximum thickness of 110 m and has a limited distribution within the Mackenzie Trough, covering an area roughly half the size of Sequence 1 and occurring only at the southeast side of the trough (Fig. 4C). Internal reflections within Sequence 2 are truncated by the basal reflector of Sequence 3.

4.2.2. Interpretation

The stratified seismic character and stratigraphic position of Sequence 2 suggest that this sequence represents glacimarine sediment deposited predominantly during deglaciation. Megasequence A (Fig. 3) is therefore interpreted to record a deglacial succession from subglacial till (Sequence 1) to ice-proximal glacimarine sediment (Sequence 2). The acoustic impedance contrasts within Facies Si are probably produced by layers of coarse material, such as sand, within fine-grained material (Taylor et al., 2000; Barrie and Conway, 2002). The truncation of the reflections within Sequence 2, combined with its limited spatial distribution (Fig. 4C) suggests that the unit was subjected to post-depositional erosion, possibly by a subsequent ice advance.

4.3. Megasequence B – Sequence 3

4.3.1. Description

Sequence 3 is composed predominantly of Facies T, an acoustically semi-transparent facies with very low amplitude, chaotic internal reflections (Figs. 3 and 5). The distribution of Sequence 3 is confined to the Mackenzie Trough, where it reaches a maximum thickness of 240 m towards the trough's central axis (Fig. 4D).

The upper reflector of Facies T is characterised by irregular topography and a number of v-shaped indentations (Fig. 5). Two types of v-shaped indentation are identified; smaller indentations with widths of 50–100 m and depths of a few metres, and larger indentations with widths of up to 300 m and depths of 10 m (Fig. 5).

Both types of indentation possess berms a few metres high either side of a central depression.

Two trough-parallel, positive relief ridges of Facies M (Fig. 5) are identified overlying Facies T in the landward region of the trough (Fig. 7). Each ridge is approximately 5 km wide and 50 km long, producing elongation ratios of 10:1. Both ridges have a maximum thickness of 90 m and decrease in height in a seaward direction.

4.3.2. Interpretation

Sequence 3 corresponds with Unit 4 of Blasco et al. (1990), which was interpreted as sand deposited during ice-stream retreat. The thickness of this sequence (240 m), its shelf geometry, which is limited to the Mackenzie Trough (Fig. 4D), and its transparent to chaotic seismic character are, however, suggestive of subglacial till. Subglacial till has been observed to exhibit a structureless to chaotic signature on seismic records (e.g. Alley et al., 1989; King, 1993; Shipp et al., 1999; Li et al., 2011) as a result of its homogeneous texture, which reflects a lack of sediment sorting and the destruction of pre-existing sediment structures. Sequence 3 is therefore interpreted as subglacial till deposited during a second ice stream advance through the Mackenzie Trough to the shelf break. The semi-transparent seismic character of the Sequence 3 till suggests that it contains fewer acoustic impedance contrasts than the Sequence 1 till, which possesses higher amplitude reflections (Figs. 3 and 5). This variation could be due to comparatively reduced internal bedding or increased sediment deformation within the Sequence 3 till.

The v-shaped indentations identified on the upper reflector of Sequence 3 (Fig. 5) are interpreted as ploughmarks formed by the action of iceberg keels grounding on the sea floor. The dimensions and geometry of these indentations, which include distinctive raised berms (Fig. 5), are consistent with an origin as ploughmarks and preclude their interpretation as meltwater channels. Iceberg keel ploughmarks can exhibit widths of up to 1 km and depths of over 15 m and are characterised by v-shaped cross-sections, often with raised berms at either side of a central depression (Woodworth-Lynas et al., 1985; Dowdeswell et al., 1993; Dowdeswell and Bamber, 2007). Iceberg keel ploughmarks are widespread on high latitude continental shelves and have also been identified from palaeo-surfaces on seismic records (Dowdeswell et al., 2007).

The stratigraphic position of the v-shaped indentations, above an acoustically semi-transparent sequence interpreted as subglacial till, suggests that these features record grounding events from icebergs produced during deglaciation of the Mackenzie Trough ice stream and the surrounding region. The larger v-shaped indentations, which possess widths of up to 300 m (Fig. 5), may have been formed by grounding events from larger, possibly tabular icebergs (Dowdeswell and Bamber, 2007).

Trough-parallel landforms can be formed by a wide range of processes within glacial and glaciofluvial environments, and include subglacially produced MSGL and drumlins, ice-marginal lateral moraines, and meltwater-derived tunnel valleys, channels and eskers (Ó Cofaigh, 1996; Ottesen et al., 2008; Ottesen and Dowdeswell, 2009). With lengths of over 50 km and widths of about 5 km, however, the dimensions of the two buried trough-parallel ridges of Facies M (Fig. 7) are remarkable and preclude their interpretation as MSGL, drumlins or eskers. The positive-relief geometry of these features precludes their interpretation as meltwater channels. In addition, the ridges do not possess the characteristic width to depth ratios of tunnel valleys (Ghienne and Deynoux, 1998). The trough-parallel ridges of Facies M are probably lateral moraines produced during a still-stand of the ice margin during retreat. The dimensions of the trough-parallel ridges in the Mackenzie Trough are comparable with those of lateral moraines identified from other high-latitude continental margins (Ottesen et al., 2005, 2007). This interpretation is also consistent with the stratigraphic position of the buried ridges, which overlie acoustically semi-transparent sediment (Facies T) that has been interpreted as subglacial till (Fig. 7B).

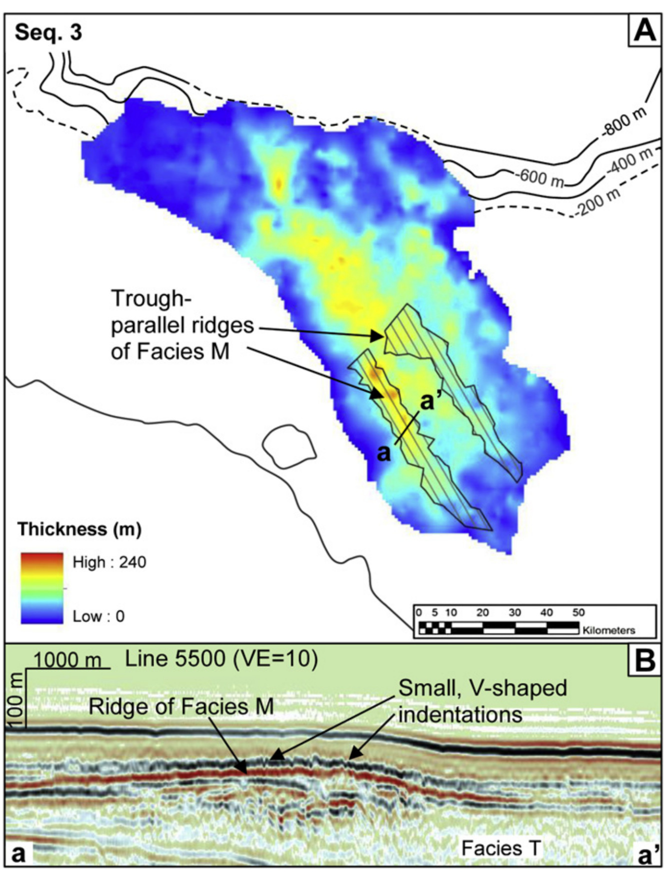


Fig. 7. A: Map showing the plan-form distribution of Facies M (hatched lines) within Sequence 3. The thickness of Sequence 3 is shown. Dashed line indicates shelf break. B: Seismic profile of a strike line across the western ridge of Facies M. Location of line shown in Part A.

4.4. Megasequence B – Sequence 4

4.4.1. Description

Sequence 4 is composed of a single facies, Facies Si (Figs. 3 and 5), and reaches a maximum thickness of about 130 m in the landward region of the trough (Fig. 4E). The sequence decreases in thickness in a seaward direction and internal reflections are observed to down-lap onto the upper reflector of Sequence 3.

The upper surface of Sequence 4 is defined by a high amplitude, continuous, undulating reflector containing a number of v-shaped indentations (Fig. 5). With maximum widths of about 100 m and depths of up to 5 m, these indentations possess similar dimensions to the small v-shaped indentations observed on the upper reflector of Sequence 3.

4.4.2. Interpretation

Facies Si, observed within Sequence 2, has been interpreted as ice-proximal glacimarine sediment deposited during ice-stream retreat. The stratigraphic position of Facies Si within Sequence 4, overlying a semi-transparent facies interpreted as subglacial till (Facies T), is consistent with this interpretation, suggesting that Sequence 4 was deposited during retreat of the second ice stream to occupy the trough. In contrast with Sequence 2, which has a limited spatial distribution, Sequence 4 sediments are preserved within the trough (Fig. 4) and have not been subjected to significant post-depositional erosion.

Similarly to the indentations identified above Sequence 3, the small v-shaped indentations on the upper reflector of Sequence 4 (Fig. 5) were probably formed by the ploughing action of iceberg keels on the sea floor during regional deglaciation (Dowdeswell et al., 2007; Ottesen and Dowdeswell, 2009).

4.5. Megasequence B – Sequence 5

4.5.1. Description

Sequence 5 is composed of a single facies, Facies Sii (Figs. 3 and 5). The boundary between Sequences 4 and 5 is characterised by a change in the nature of the internal reflections, from high amplitude, discontinuous reflections within Sequence 4, to low amplitude, continuous reflections within Sequence 5. The surface of the sea floor is defined by the high amplitude upper reflector of Sequence 5.

Sequence 5 is present as a thin (<50 m) sediment drape over most of the study area yet reaches a maximum thickness of about 200 m in the landward region of the trough (Fig. 4F). Where it occurs at the sides of the trough, Sequence 5 exhibits gently-dipping progradational–aggradational clinoforms.

4.5.2. Interpretation

The draping geometry of Facies Sii, combined with its low amplitude, parallel internal reflections and position at the top of the Mackenzie Trough stratigraphy, suggests that Sequence 5 was deposited in an ice-distal to open-marine environment dominated by the vertical accretion of suspended sediments (Elverhøi et al., 1980; Dowdeswell et al., 1997; Shipp et al., 1999; Kleiber et al., 2000). The gently dipping clinoforms observed within the thickest deposits of Sequence 5 probably reflect progradation of sediment within the Holocene Mackenzie River delta, which has been observed to preferentially infill the trough towards the east (Hill et al., 1991; Hill, 1996).

Holocene sediments have been calculated previously to reach thicknesses of between 30 and 50 m within the Mackenzie Trough (Hill et al., 1991). With a maximum thickness of about 200 m (Fig. 4F), Sequence 5 therefore probably contains a large component of relatively ice-distal deglacial sediment in addition to Holocene material.

The succession identified within Megasequence B (Fig. 3) is interpreted to record a typical deglaciation sequence in which subglacial till (Sequence 3) is overlain by heavily reworked glacimarine sediment (Sequence 4), beneath ice-distal to open-marine deposits (Sequence 5). Similar deglacial signals have been identified on seismic records and in sediment cores from a number of other high-latitude continental margins (e.g. Polyak and Solheim, 1994; Svendsen et al., 1996; Shipp et al., 1999; Kleiber et al., 2000).

4.6. Continental slope

4.6.1. Description

Bathymetric data demonstrate that the continental slope beyond the Mackenzie Trough is incised by a series of sub-parallel topographic depressions, separated by ridges (Fig. 8A and B). Some of these depressions indent the shelf break and can be traced for distances of several kilometres across the outer-shelf (Fig. 8A). A seismic line across one of these features on the outer-shelf shows that it has a width of more than 4 km and a depth of around 200 m (Fig. 8C). The seismic character and geometry of several of the depressions and ridges on the continental slope is shown in Fig. 8D. The ridges are imaged in cross-section as distinct blocks of sediment that rise 200–300 m above the surrounding sea floor. These ridges possess largely undisturbed internal seismic character and exhibit irregular upper reflectors (Fig. 8D).

Less disturbed areas of the continental slope are capped by a 30 to 60 m-thick accumulation of acoustically semi-transparent to weakly stratified sediment, Facies L (Figs. 5 and 8E). This deposit thins in a seaward direction and can be traced for a horizontal distance of at least 40 km beyond the shelf break. The base of Facies L is defined by a high amplitude, smooth and continuous reflector on the upper continental slope, which transitions into a more irregular surface on the middle to lower slope (Fig. 8E).

4.6.2. Interpretation

The topographic depressions identified on the sea floor bathymetry and seismic profiles seaward of the Mackenzie Trough (Fig. 8A–D) are interpreted as submarine canyons incised into slope sediments, separated by inter-canyon ridges. The undisturbed internal character of the ridges is consistent with this interpretation, as is their highly-irregular upper reflector, which probably records incision by smaller, superimposed canyons (Fig. 8D). It is possible that the inter-canyon ridges contain preserved glacigenic debris flow deposits produced by the supply of deformable till to the slope from the Mackenzie Trough ice stream. The lack of overlying sediment within the canyons (Fig. 8B–D) suggests that the most recent episode of canyon incision post-dates any full-glacial delivery of debris to the continental slope. The canyons were produced by one or more of the following processes: the delivery of turbid meltwater to the margin during deglaciation; active delivery of deforming sediments at the ice-sheet margin to the shelf break; debris flows on the upper slope; or brine-rejection and dense-water formation during sea ice production under interglacial conditions (Dowdeswell et al., 2008). Submarine canyons provide pathways for the transfer of sediment from the continental margin to the deep sea; they have been identified seaward of cross-shelf troughs on a number of high-latitude margins, including the Laurentian, North East, and Hopedale Saddle Fans on the eastern Canadian margin (Stow, 1981; Hesse, 1995; Piper et al., 2012).

The basal reflector of Facies L, which is present on less disturbed areas of the slope, is interpreted to be synonymous with the base of the Mackenzie Trough (Fig. 8E), suggesting roughly contemporaneous formation. The transparent seismic character, lobate geometry and stratigraphic position of Facies L suggest that it represents glacigenic debris flow deposits. Although post-glacial drapes of hemipelagic sediment can exhibit a transparent acoustic signature on seismic records (Damuth, 1978; Dowdeswell et al., 1997; Shipp et al., 1999), the thickness of Facies L (60 m) and its location on the continental slope preclude this interpretation.

5. Discussion

5.1. Timing of ice advances

The extensive grid of seismic data from the western Canadian Beaufort Sea margin (Fig. 1C) provides evidence for two ice advances to the shelf break through the Mackenzie Trough. Although it is possible that evidence of older ice advances have been removed by subsequent glaciations, leaving only the two youngest till sheets preserved, our interpretation of only two ice advances through the trough is supported by the lack of a major trough-mouth fan on the adjacent slope. The precise timing of the two ice-stream advances is uncertain, due to the absence of long drill cores from the western Canadian Beaufort Sea. However, although the timing of each glacial event cannot be constrained without direct dating techniques, the terrestrial record suggests that glaciation of the Mackenzie Delta region became progressively more extensive through the Quaternary (Murton et al., 1997; Dyke et al., 2002). Comparison with

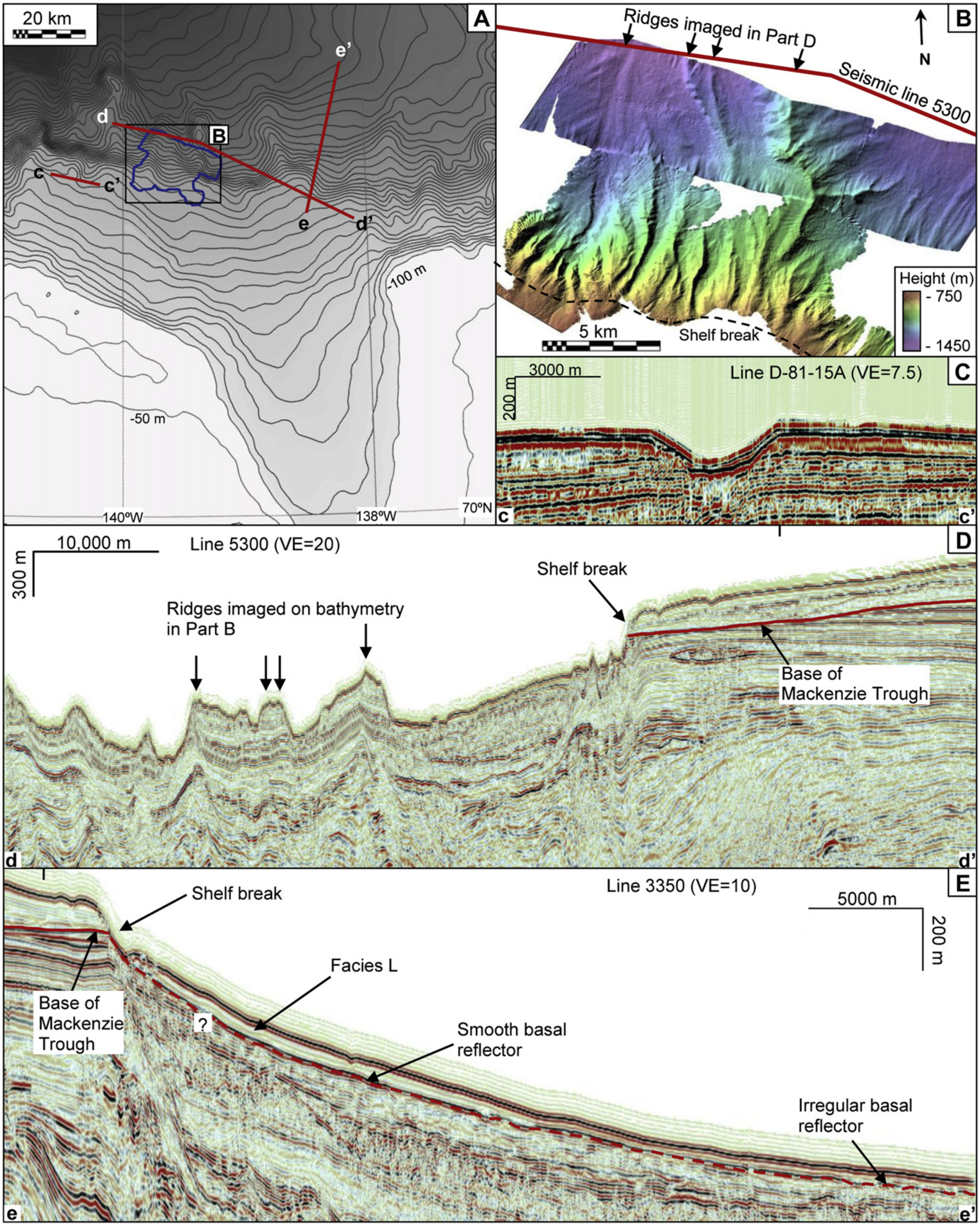


Fig. 8. A: IBCAO bathymetry of Mackenzie Trough and adjacent slope (50 m contours) showing locations of Parts B–E (Jakobsson et al., 2012b). B: High-resolution bathymetry of canyons on the upper slope beyond Mackenzie Trough. From University of New Brunswick's online ArcticNet 15′ × 30′ Basemap Series, 2003–2011. The location of the seismic line presented in Part D is shown in red. C: Seismic profile of a strike line across a large depression on the outer-shelf. D: Seismic profile of a strike line across the Mackenzie Trough and adjacent slope, showing the location of the inter-canyon ridges imaged in Part B. E: Seismic profile of a dip line through the Mackenzie Trough and an undisturbed area of the adjacent slope. The base of the trough may correspond with the high amplitude basal reflector of Facies L (dashed red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

onshore data implies that the younger of the two ice-stream advances through the Mackenzie Trough, illustrated by Sequence 3 till (Fig. 3), probably occurred during the last, Late Wisconsinan, glacial period (Fig. 2B; Blasco et al., 1990), which has been inferred to be synonymous with the Toker Point Stade (Murton et al., 1997; Dyke et al., 2002; Duk-Rodkin et al., 2004; Bateman and Murton, 2006).

The earlier ice-stream advance through the Mackenzie Trough, which is represented by the subglacial till of Sequence 1 (Fig. 3), probably occurred sometime during either the Early Wisconsinan or Illinoian glaciations (Fig. 2B). The Eurasian Ice Sheet and much of the Laurentide have been inferred to have been particularly widespread during the penultimate, Illinoian (Saalian) glaciation (Svendsen et al., 2004).

Our interpretation of grounded ice extending to the shelf break beyond the Mackenzie Trough during the Late Wisconsinan and either the Early Wisconsinan or Illinoian glaciations is in broad agreement with a number of ice-sheet reconstructions which provide marine evidence of large ice volumes and extensive ice shelves on the Beaufort Sea margin during the Late Quaternary (e.g. Stokes et al., 2005; Engels et al., 2008; Jakobsson et al., 2010). An extensive ice shelf, fed by ice streams emanating from the northwest Laurentide Ice Sheet, has been hypothesised to have developed around the margin of the Arctic Ocean, including over the Beaufort Sea, during the Illinoian glaciation (Fig. 2A), as a result of astronomical forcing combined with reduced influx of warm Atlantic water (Jakobsson et al., 2010). Margin-parallel sea floor lineations, interpreted to have been formed by occasional grounding of ice-shelf keels sometime between the Early Wisconsinan glaciation and a cold stage within the Sangamonian interglacial (Fig. 2A), also provide evidence for ice-shelf flow along the Alaskan Beaufort Sea margin to the west of the Mackenzie Trough (Engels et al., 2008). Sediment cores from the Alaskan margin show that the Late Wisconsinan glaciation is characterised by a unique IRD signature, consisting of sedimentary clasts and coals with provenance from the Mackenzie Trough region (Polyak et al., 2009). The IRD is interpreted to have been eroded and transported by the Laurentide Ice Sheet to the marine margin at low sea levels during the last, Late Wisconsinan, glacial period.

The Quaternary glacial history of the western Canadian Beaufort Sea shelf contrasts greatly with the inferred history of ice advance across the margins of the eastern Beaufort Sea and eastern Canadian Arctic margin. Whereas evidence for only two, probably Late Quaternary, ice advances to the shelf break is recorded in the seismic stratigraphy of the Mackenzie Trough (Fig. 3), the Amundsen Gulf and M'Clure Strait troughs, which are located 400 km and 750 km east of the Mackenzie, respectively (Fig. 1B), have been inferred previously to have been occupied by ice streams during a number of earlier Quaternary glaciations (Batchelor et al., 2013). Further to the east, the initiation of the Lancaster Sound ice stream of the eastern Canadian Arctic Archipelago (Fig. 1A) has been interpreted to have occurred during the Pre-Illinoian Stage of the Early Pleistocene, about 1.6 Ma (Fig. 2A), in association with the first appearance of glacigenic debris flows on the Lancaster Sound trough-mouth fan (Li et al., 2011). The western Canadian Beaufort Sea margin is suggested, therefore, to have remained free of Laurentide ice for most of the Quaternary, with the onset of cross-shelf glaciation being initiated significantly later in this region compared with those locations a few hundred kilometres to the east that were less peripheral to the ice-sheet centre and drained significantly larger interior drainage basins (Fig. 1A).

5.2. Geomorphological ice-stream signature

We suggest that this comparatively short history of Quaternary ice advance across the western Canadian Beaufort Sea shelf resulted in the formation of a relatively young glacially-excavated cross-shelf trough, which contains subglacial till from only two glacial events and lacks a major glacial-sedimentary progradational depocentre or fan on the adjacent slope (Fig. 9). The slope beyond the Mackenzie Trough is incised by canyons (Fig. 8), indicating sediment bypassing of the upper slope and erosion of the margin. In contrast, the more developed cross-shelf systems to the east have been interpreted previously to record evidence of many Quaternary ice advances to the shelf break, in the form of several stacked till sheets, which transition into major glacigenic depocentres composed of numerous glacigenic debris flows on the continental slope (Fig. 9; Niessen et al., 2010; Li et al., 2011; Batchelor et al., 2013). The Amundsen Gulf and M'Clure Strait continental margins possess the convex plan-form shape and progradational architecture that is characteristic of glacier-influenced trough-mouth fans (Fig. 1B; Vorren et al., 1998).

Although the flux of glacigenic sediment was insufficient to build a major trough-mouth fan on the slope beyond the Mackenzie Trough, the western Canadian Beaufort Sea margin is not a sediment-starved environment and has intermittently experienced high rates of fluvial sedimentation through the Quaternary. We argue that the Quaternary sedimentary history of the western Canadian Beaufort Sea margin was, in fact, characterised largely by fluvial activity. Prior to the initiation of the first Mackenzie Trough ice stream, large quantities of fluvio-deltaic sediment were provided to the Beaufort Sea shelf by the palaeo-Porcupine River, which was initiated in the Tertiary and persisted until its diversion by the Laurentide Ice Sheet in the Late Quaternary (Duk-Rodkin and Hughes, 1994). Subsequent to the retreat of Late Quaternary ice, the margin has again become dominated by fluvial sedimentation provided by the modern Mackenzie River system, which has a drainage basin of about 1.8 million km^2. In contrast, the Alaskan Beaufort Sea margin to the west, which remained outside the maximum limit of the Laurentide Ice Sheet (Fig. 1A), experienced limited sediment delivery to the shelf by alpine rivers and represents a more sediment-starved margin (O'Grady and Syvitski, 2002).

The Mackenzie Trough lacks many characteristic geomorphological features of an ice stream (Ottesen et al., 2005; Ottesen and Dowdeswell, 2009). Whereas formerly-glaciated cross-shelf troughs in both the Arctic and Antarctic typically display a seaward transition from crystalline bedrock to sedimentary sea-floor substrate (Shipp et al., 1999; Ó Cofaigh et al., 2002; Ottesen et al., 2005, 2008; Livingstone et al., 2012), the Mackenzie Trough is underlain entirely by fluvio-deltaic sedimentary strata (Figs. 3 and 9). Streamlined glacigenic landforms that are typically identified within cross-shelf troughs have been buried by post-glacial sediment and are lacking from the sea-floor reflector of the Mackenzie Trough. In contrast, the more developed cross-shelf systems of the Amundsen Gulf and the M'Clure Strait troughs to the east (Fig. 1B) have been suggested previously to possess a more characteristic signature of an ice stream and adjacent trough-mouth fan (Fig. 9) and record a minimal fluvial influence (Batchelor et al., 2013). These troughs contain a seaward transition from bedrock to sedimentary substrate (Niessen et al., 2010; MacLean et al., 2012; Batchelor et al., 2013), show evidence of a prograding shelf and associated fan, and have experienced low rates of post-glacial hemipelagic sedimentation, which has led to the preservation of streamlined landforms, including drumlins and MSGL, on the sea floor (Blasco et al., 2005; Stokes et al., 2006).

5.3. Diagnostic glacigenic landforms and sediments

Although the sea floor of the Mackenzie Trough lacks a characteristic ice stream signature, our seismic investigations have

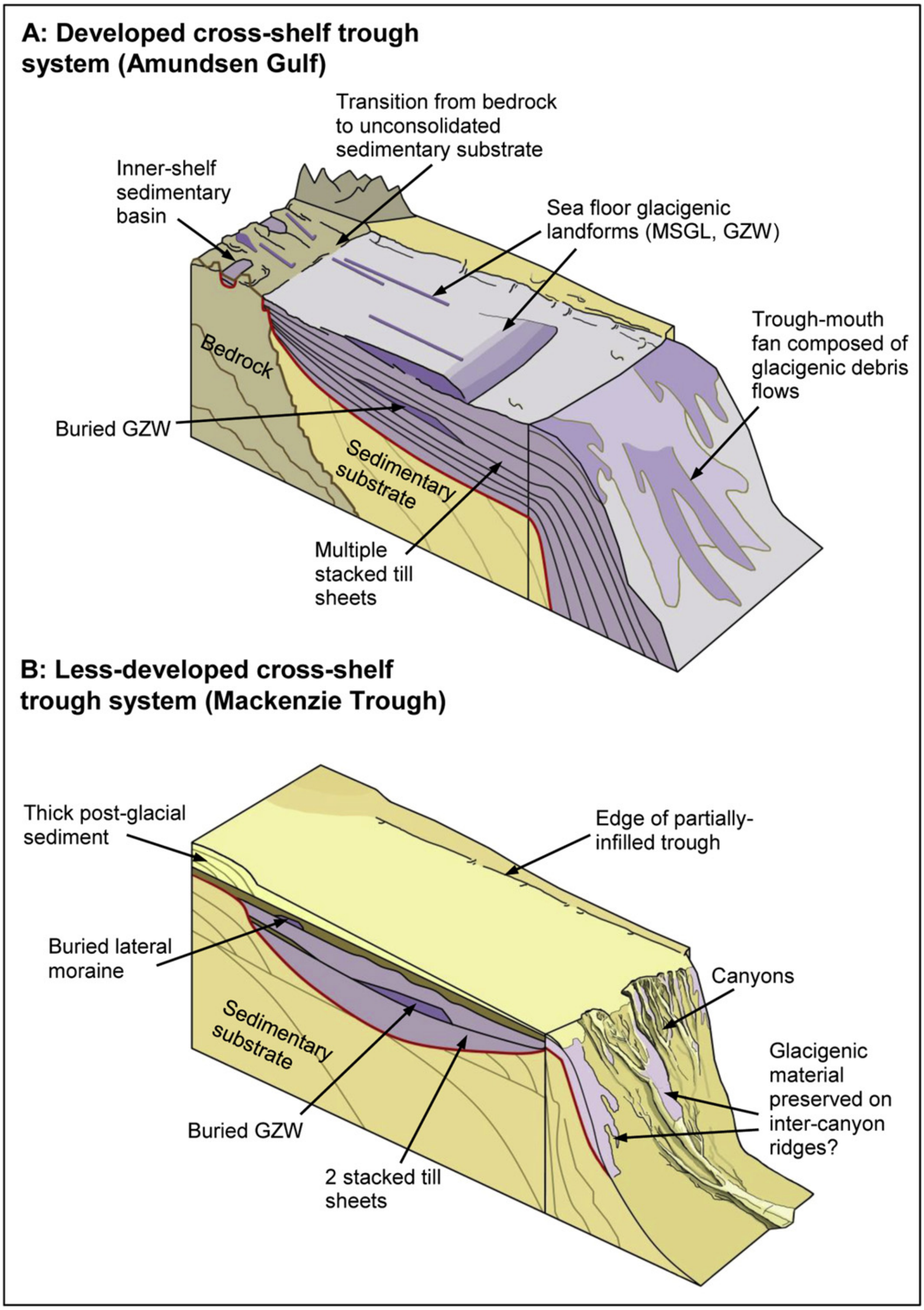


Fig. 9. 3-D schematic models of contrasting shelf and slope architectures, landforms and sediments produced by Quaternary ice-stream advances through the Mackenzie and Amundsen Gulf troughs, derived from 2-D seismic reflection data from the Canadian Beaufort Sea. A: A developed cross-shelf trough system, such as represented by the Amundsen Gulf Trough on the eastern Canadian Beaufort Sea margin (Batchelor et al., 2013). The red line marks the base of the trough. Multiple, stacked till sheets (purple) on the shelf transition into a trough-mouth fan composed of glacigenic debris flows on the slope. Low rates of post-glacial sedimentation enable the identification of glacigenic landforms on the sea floor. B: A less-developed cross-shelf trough system, such as represented by the Mackenzie Trough on the western Canadian Beaufort Sea margin. Two till sheets (purple) are present on the shelf and the adjacent slope is incised by canyons. High rates of deglacial (brown) and post-glacial sedimentation (yellow) have partially-infilled the trough. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

identified a number of buried glacigenic landforms and sediments (Fig. 5) which provide information about past ice dynamics. U-shaped indentations at the base of the trough (Fig. 5) are suggested to represent subglacial meltwater channels, suggesting that channelised drainage of meltwater occurred beneath the inner-shelf region of the ice stream. V-shaped indentations on the upper reflectors of Sequences 3 and 4 (Fig. 5) are interpreted as iceberg keel ploughmarks that record iceberg grounding events during regional deglaciation. An asymmetric wedge of sediment with a volume of approximately 13 km^3 (Fig. 6) is interpreted as a grounding-zone wedge, produced by a still-stand of the margin during retreat of the Early Wisconsinan or Illinoian ice stream (Fig. 2). The trough-parallel ridges of Facies M (Fig. 7) are probably lateral moraines formed during a still-stand or readvance of the ice margin during retreat of the last, Late Wisconsinan, Mackenzie Trough ice stream.

Two sequences of chaotic to semi-transparent facies are interpreted as subglacial till within the Mackenzie Trough. Although these facies possess a chaotic to semi-transparent seismic signature, differences are apparent in the amplitude of their internal reflections, suggesting variations in internal acoustic impedance between the deposits.

The seaward transition from Facies Ci to Facies Cii within Sequence 1 (Figs. 3B and 6A) is not produced by sedimentological differences in source materials due to the contemporaneous formation of the two facies, as demonstrated by the continuous upper and lower reflectors of Sequence 1. The transition does not result from differences in the nature of underlying sediments as no significant changes in substrate occur across the shelf. We suggest that the high amplitude acoustic impedance contrasts identified within Facies Ci (Figs. 3 and 5) are indicative of a relatively inhomogeneous till which has retained some internal bedding or original sediment structures. In contrast, Facies Cii, which is characterised by lower amplitude acoustic impedance contrasts (Fig. 5), may represent a more homogeneous and, possibly, more deformed till. The reason for this seaward variation in till homogeneity is presently uncertain. The transition may be associated with increased sediment deformation and/or ice stream velocity across the shelf or with the length of time during which sediment was transported beneath the ice stream. The seaward transition could also be related to the onset of fast, streaming ice flow in the outer-shelf region of the trough or to the way in which meltwater was distributed within the sediment at the base of the ice stream.

Facies T within Sequence 3 is characterised by a semi-transparent seismic signature (Figs. 3 and 5) and is suggested to represent a massive till which is largely devoid of significant bedding or internal structures. The identification of streamlined glacigenic landforms, including MSGL, of inferred Late Wisconsinan age, in the Mackenzie Valley to the south of the trough (Beget, 1987; Winsborrow et al., 2004; Stokes et al., 2006; Brown et al., 2011), provides evidence of fast ice-stream flow during this glaciation (Clark, 1993; Stokes and Clark, 1999). It is possible that the onset zone of ice steaming occurred further inland during this younger ice advance through the Mackenzie Trough compared with the earlier ice advance that deposited Sequence 1, resulting in the formation of a massive and pervasively deformed Sequence 3 till on the shelf.

6. Conclusions

High-resolution 2-D seismic reflection data (Fig. 1C) has enabled the identification and interpretation of five seismic sequences, divided into two megasequences, and eight seismic facies from the Mackenzie Trough and adjacent slope (Figs. 3 and 5). Two sequences of acoustically chaotic to semi-transparent facies (Sequences 1 and 3, Fig. 3) are interpreted as subglacial till, representing excavation of the trough by two Quaternary ice advances to the shelf break. The continental slope beyond the trough is incised by canyons, separated by inter-canyon ridges (Fig. 8A–D). A 60 m-thick accumulation of acoustically transparent to weakly stratified sediment is present on less disturbed areas of the upper continental slope (Fig. 8E) and is interpreted as glacigenic debris-flow deposits produced by the supply of deformable till to the margin. Whilst landforms diagnostic of former ice stream activity are absent from the sea floor of the Mackenzie Trough, a number of buried glacigenic landforms are identified from the seismic reflection data, including a grounding-zone wedge with a volume of approximately 13 km^3 (Fig. 6), and two trough-parallel ridges that are interpreted as lateral moraines (Fig. 7). Both types of landform were probably formed during still-stands in ice-stream retreat.

The western Canadian Beaufort Sea shelf is inferred to have remained free of Laurentide ice for most of the Quaternary. Correlation with the terrestrial record suggests that the Mackenzie Trough was excavated by an ice stream during either the Early Wisconsinan or the penultimate, Illinoian glaciation (Fig. 2B). The second ice advance through the trough probably occurred during the last, Late Wisconsinan, glaciation (Murton et al., 1997; Dyke et al., 2002; Duk-Rodkin et al., 2004; Bateman and Murton, 2006).

The Mackenzie Trough, therefore, represents a relatively recent, Late Quaternary, glacially-excavated cross-shelf system, which records evidence for only two ice advances to the shelf break and lacks a major glacigenic depocentre or trough-mouth fan on the slope beyond (Fig. 9B). The Quaternary glacial history of the western Canadian Beaufort Sea shelf contrasts greatly with the inferred longer history of ice advance recorded for the eastern Beaufort Sea and eastern Canadian Arctic Archipelago margins, which were closer to the ice sheet interior, drained larger ice interior basins, and produced major trough-mouth fans on the prograding shelf edge (Fig. 9A; Niessen et al., 2010; Li et al., 2011; Batchelor et al., 2013). The neighbouring Amundsen Gulf and M'Clure Strait troughs, a few hundred km to the east of the Mackenzie (Fig. 1B), represent more developed cross-shelf systems, which record numerous Quaternary ice advances across the shelf and are characterised by major trough-mouth fans on the slopes beyond (Stokes et al., 2005, 2006; Niessen et al., 2010; Batchelor et al., 2013).

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