

REGIONAL STRATIGRAPHIC INTERPRETATION OF AN ANTARCTIC SHELF EDGE SEISMIC LINES

ABSTRACT:

A regional stratigraphic interpretation was carried out on the processed single-channel data. Four major sequence boundaries were interpreted; two are sub-horizontal erosional surfaces while the other two show permanent onlap. Four major high-amplitude and high-frequency sedimentary units were interpreted on the single-channel data within a time range of 730ms. Shelf break exists at a water depth of 640 ± 17 m on profile s27, 480 ± 16 m on s29. The profiles were interpreted to show sequences of glacially prograded sediments lying underneath the outer continental shelf. These sediments were deposited by grounded ice during times of glacial maximum which caused deposition in an overall progradational style and the grounded ice must have reached the continental shelf edge many times on most parts of the Bellingshausen Sea margin. The continental shelf across the area where these lines are located is relatively horizontal and the movement of ice front was across the whole area.

Keywords: Stratigraphic, Sequence, Sediments, Bellingshausen Sea and continental shelf.

INTRODUCTION

The identification and strata geometry of glacially deposited sediments on the Antarctic continental shelves provide significant clues for the reconstruction of the glacial history of West Antarctica (Nitsche et al., 1997). The sediment stratigraphy and the physiography of the sea floor reflect the history of the West Antarctic glaciation as well as the processes that eroded, transported and deposited sediments on the outer shelf, slope and rise of the continental margin (Scheuer et al., 2006). Multichannel seismic (MCS) reflection investigations of the Antarctic continental margin have revealed thick Cenozoic prograding sequences in several areas (Cooper et al., 1991).

In order to investigate further, the British Antarctic Survey (BAS) shot some seismic lines off the coast of Bellingshausen Sea with a single airgun and two hydrophones. This work was carried out with the aim to interpret the continental shelf front that sits under the area just off the coast of Bellingshausen Sea.

ANTARCTICA

Antarctica is the most southerly continent located about the southern point of the Earth's rotational axis (the Geographic South Pole). Out of the seven continents in the world, it is the fifth largest and it covers 10% of the earth's land area.

In the eighteenth century, Captain James Cook concluded that the southern polar continent must be "doomed by Nature . . . to lie for ever buried under everlasting snow and ice" (Beaglehole, 1961 as cited by Anderson, 1991). Cook's opinion was formed as a result of the large size and number of icebergs, and the turbulent and cold weather encountered during his Southern Ocean journeys. What Cook assessed during his eighteenth century voyage is what is now known as Antarctica. 2%

of the Antarctic land surface is exposed bedrock, while 98% is covered with ice. This 98% creates a difficult and challenging fieldwork environment, which is a large part of the attraction for the earth scientists from many nations who choose to pursue their profession at the end of the earth.

The Bellingshausen Sea

The Bellingshausen Sea (Figure 1) is located between Thurston Island on the West and the Antarctic Peninsula on the East. It is the inlet of the Southern Ocean along the coast of Antarctica. Bellingshausen Sea extends along the coast of Ellsworth Land from Alexander Island to Thurston Island. Its location is longitude 75° to 98° west and latitude 70° to 72° south. The continental shelf is a maximum of approximately 500 km wide from the margin of the ice sheet in the Ronne Entrance to the shelf break. The shelf break occurs in water depths of 500–700 m (Dowdeswell et al., 2008).

The sedimentary record of the Bellingshausen Sea area has been influenced by environmental changes in the history of the continental margin off West Antarctica. The significant changes in the sedimentary structure of the area are a result of the period of glacial/interglacial cycles.

Location

The single-channel seismic lines BAS923-s27, BAS923-s28 and BAS923-s29, to be interpreted are located within longitude 86°W to 89°W and latitude 69.8°S and 70.7°S which is in the Bellingshausen Sea in Antarctica as shown in Figure 2.



Figure 1. Location of Bellingshausen Sea, Antarctica. Inset shows the position of the study area within Antarctica. (Sources: Google Maps and Dowdeswell et al., 2008 respectively).

The Geology of Antarctica

The geology of Antarctica includes Eastern and Western Antarctica (Anderson 1991). Anderson (1991) defines the larger segment (East Antarctica) as the area, mostly in eastern longitudes, bounded on the seaward and the northern side by the South Atlantic and Indian Oceans and on the landward side by the Transantarctic Mountains, Pensacola Mountains, and eastern Filchner Ice Shelf. East Antarctica includes all known Antarctic exposures of Archaean rocks, and the great majority of outcrops of Proterozoic rocks. West Antarctica includes the Antarctic Peninsula, Marie Byrd Land, and other land areas not included in East Antarctica. Barker et al. (1991) explained the tectonic evolution of the Scotia Arc/Antarctic Peninsula region in a Mesozoic-Cenozoic plate tectonic framework. From their account, it is clear that the two areas consist almost entirely of Mesozoic and Cenozoic rocks. The British Antarctic Survey published the best available portrayal of the geology of the Antarctic Peninsula in 1979. This publication is the 1:500 000 scale regional geological maps published as BAS series 500G (Sheets 1-5). Volcanic and plutonic rocks dominate the outcrop, but sedimentary and metamorphic rocks are also present.

Physiography of the Antarctic Continental Shelf

The unusual features of the Antarctic continental shelf are its great depth, rugged topography, highly varied and commonly broad width, and its glacial setting. The continental shelf of Antarctica is the deepest in the world with an average depth of 500m, and in some places more than a kilometre deep. This shelf depth is approximately eight times the world average (Shepard 1973 via Anderson 1991). The shelf is broader on the average than other continental shelves, being for example more than 200 km wide in most areas of West Antarctica. Ice shelves or marine extensions of the ice sheet cover large portion of the shelf. The shelf is rugged (Figure 3) and commonly slopes towards the continent. These qualities are attributed to the combined effects of glacial isostasy, which partly explains the landward slope of the shelf and glacial erosion (Anderson, 1991). The Antarctic continental shelf is characterized by major differences in sediment thickness, basement type, and by large tectonic features such as rifts. Anderson (1991) cited that Høltedahl (1929, 1958) and Shepard (1931) first emphasized the unique morphological character of high-latitude continental shelves, mainly their great depth and rugged topography, which they attributed to glacial erosion. He further argued that it is now quite apparent that glacial erosion has significantly contributed to the great depth of the Antarctic continental shelf.

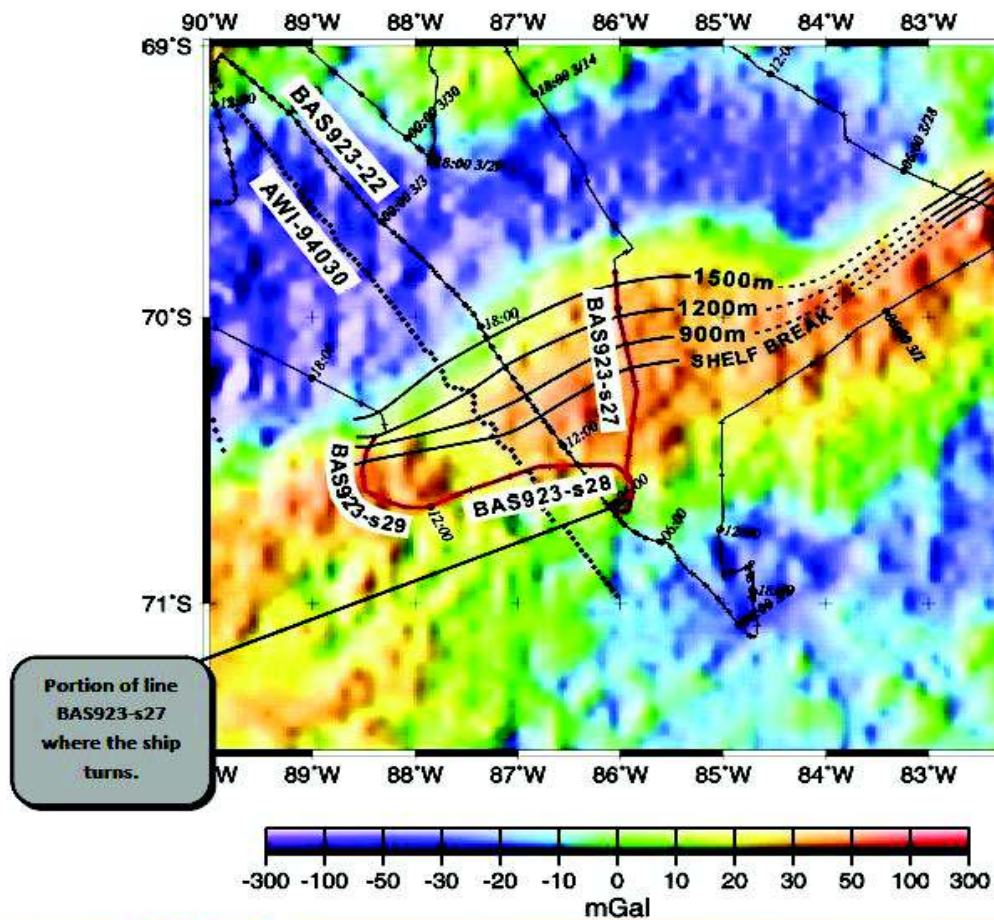


Figure 2. Bellingshausen Sea Free-Air Gravity and Ship Tracks showing the lines of investigation highlighted in red.

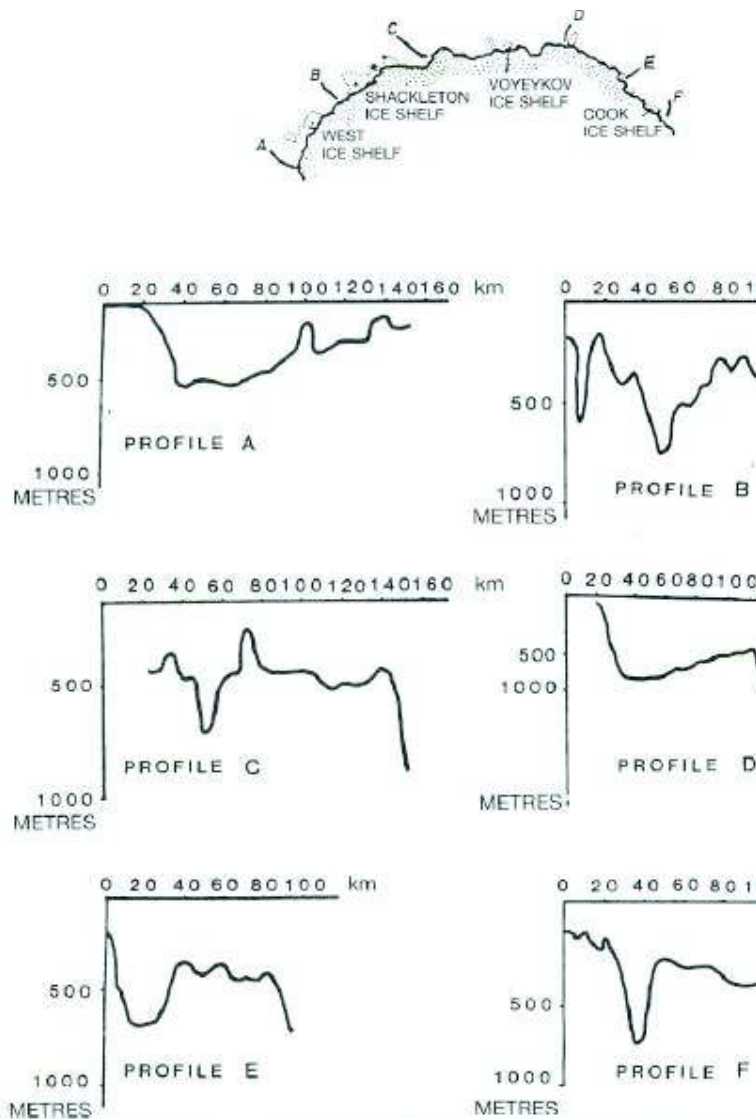


Figure 3. Depth Profile across the East Antarctic continental shelf showing typical rugged topography (from Anderson, 1991). Deep depression can be seen on the inner shelf in most areas. Landward slope is observed on profile A.

Seismic Reflection Data

Based on seismic reflection and bathymetric data, the continental slope of West Antarctica and the Antarctic Peninsula was formed by sediments released from broad line sources associated with ice grounded at the shelf break (Larter and Cunningham, 1993 via Noormets et al., 2008).

The multichannel seismic (MCS) data across many parts of the Antarctic continental shelf from the Weddell Sea eastward to Marie Byrd Land show features characteristic of passive margins, such as layered sedimentary and possible volcanic deposits filling deep fault-bounded rift structures, widespread intermediate-depth unconformities, and overlying prograding sedimentary sequences that are bounded by unconformities (Cooper et al., 1991 following Hinz and Krause, 1982; Hinz and

Block, 1984; Wannesson et al., 1985; Cooper, 1989a; Wannesson, 1990; Cooper et al., 1991a). These deposits are principally Cenozoic glacial marine strata.

Cenozoic sedimentary sequences observed beneath at least five segments of the Antarctic continental margin were categorized by Cooper et al, (1991) using two general categories based on acoustic geometry largely near the present and palaeocontinental shelf edges. Type IA: Sequences that mostly, but not exclusively, prograde the palaeocontinental shelf, building it outward. Type IA sequences have complex geometries, and include some features that may occur only on polar margins with grounded ice sheets. Type IIA: Sequences that mostly, but not exclusively, aggrade the palaeocontinental shelf, building it upward. Type IIA sequences have less complicated geometries that are common on low-latitude, nonglaciaded margins. The Cenozoic sedimentary sections of the Antarctic margin are composed principally of type IA sequences.

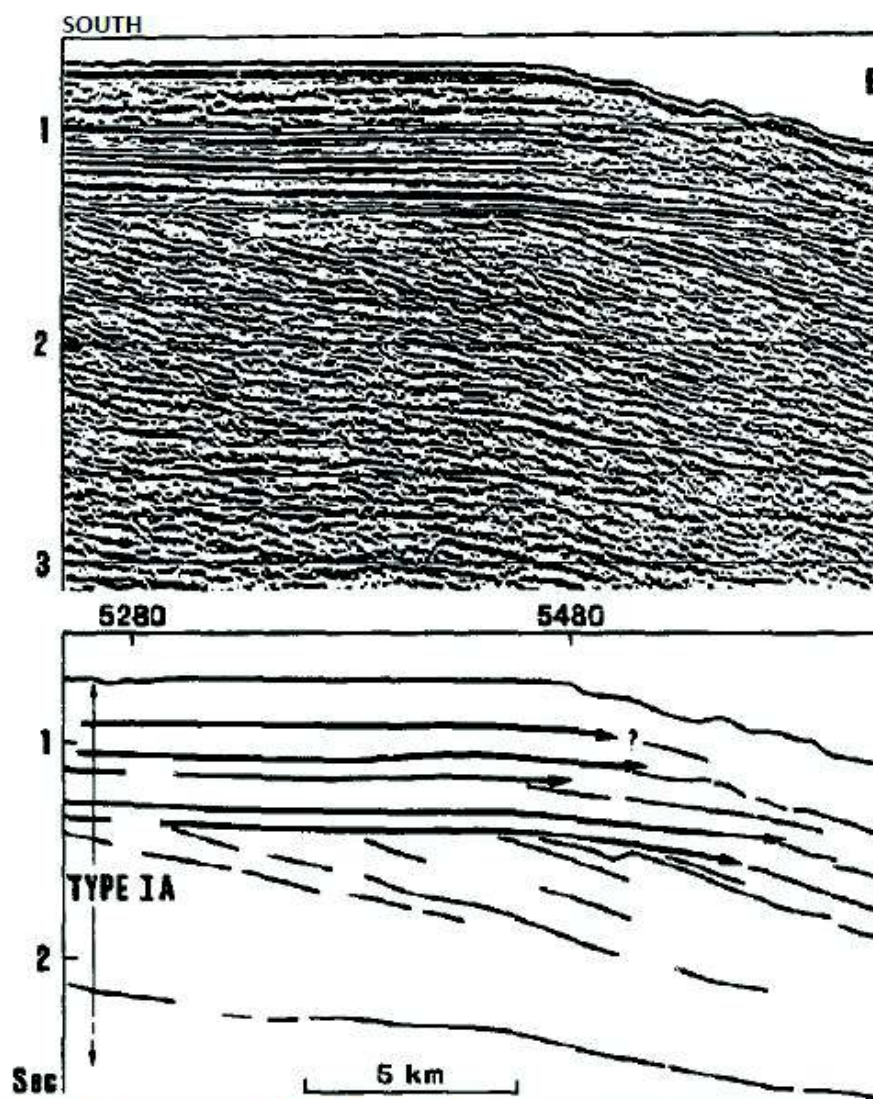
Cooper et al (1991) further explained that Antarctic type IA sequences are most commonly characterized by strongly prograding strata that have relatively thin topset beds and steeply dipping (4-15 °) foreset beds, particularly on the palaeoupper continental slope near the palaeo-shelf edges. Reflections within the sequences have strong and variable amplitudes that are often disrupted locally, but can sometimes be traced over tens of kilometres in the topset and foreset beds (Figures 4 and 5). The dips of foreset beds may differ between adjacent sequences, and foreset reflections downlap seaward onto underlying type IA and IIA sequences (Figure 5). Type IA sequences are believed to be deposited principally by grounded ice sheets on over-deepened continental shelves.

As further concluded by Cooper et al, 1991, type IIA acoustic sequences (Figure 6) are relatively uncommon in Antarctic sedimentary sections of possible Cenozoic age beneath the outer continental shelf, but their geometry is relatively simple. They identified the type IIA sequences by;

- i. Relatively gently dipping and continuous reflections that principally aggrade the buried palaeo-shelf edges,
- ii. The absence of abrupt angular unconformities and terminated topset reflections near the palaeo-shelf edges such as those found in type IA sequences,
- iii. The downlap of overlying type IA strata onto these sequences, and
- iv. The truncation of the type IIA sequences by overlying type IA sequences.

These sequences are difficult to identify at great depths because of the severe multiple noises (as identified in Figure 7) that are common in seismic profiles across the Antarctic continental margin. Type IIA sequences are suggested to be deposited possibly by non-glacial and open-marine glacial processes on normal depth shelves.

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167 **Figure 4. Seismic data and line drawings showing examples of type IA sequences beneath**
 168 **the outer shelf in the Ross Sea. (Modified from Cooper et al., 1991). Topset strata are**
 169 **uncommonly thick with many channel and mound features. High-amplitude topset**
 170 **reflections commonly terminate abruptly near inferred palaeo-shelf edges. Relative dips of**
 171 **foreset reflections are variable. Arrows denote inferred extent of former grounded ice sheets**
 172 **to palaeo-shelf edges. Water depths at the shelf edge are about 500 m.**

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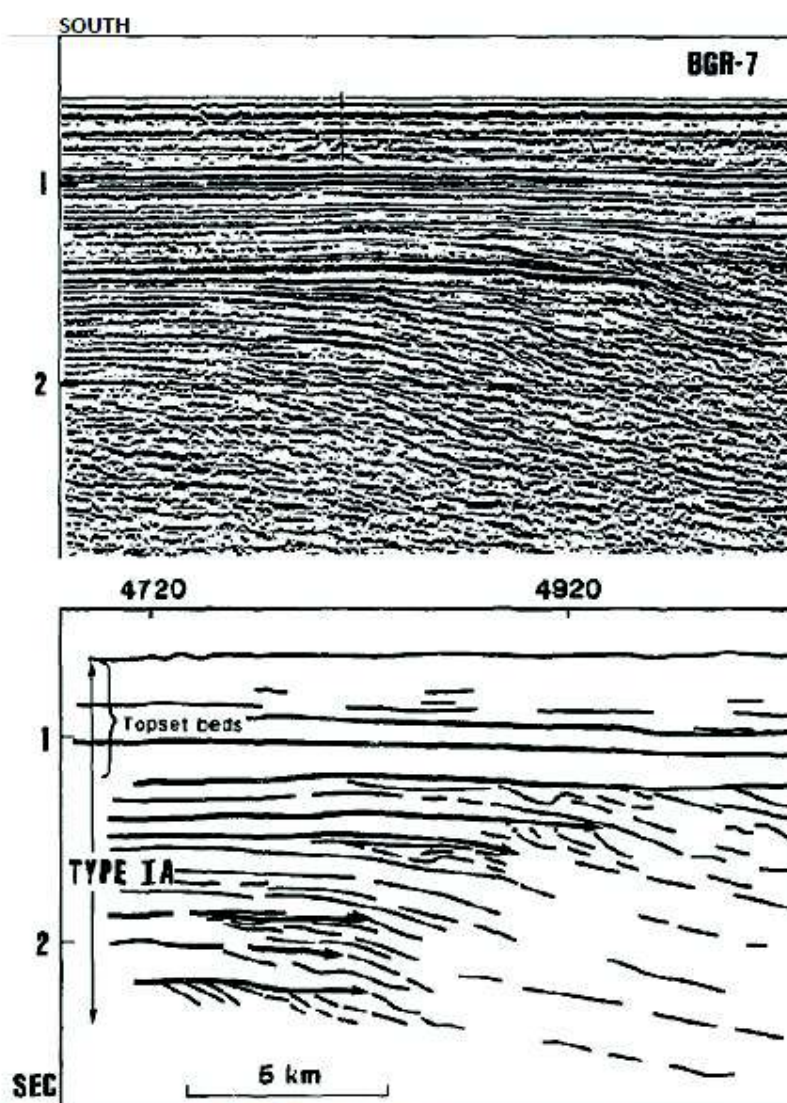
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180 Figure 5. Seismic data and line drawing showing examples of type 1A sequences beneath a
 181 mid-shelf area of the eastern Ross Sea (Cooper et al., 1991). Like the outer shelf, high-
 182 amplitude topset reflections commonly terminate near palaeo-shelf edges, where mounded
 183 and channel reflections also occur. The relatively large-scale aggradation of type 1A
 184 sequences here is uncommon elsewhere around Antarctica; extensive apparent prograding
 185 is most common. Arrows denote inferred extent of former grounded ice sheets to palaeo-
 186 shelf edges.

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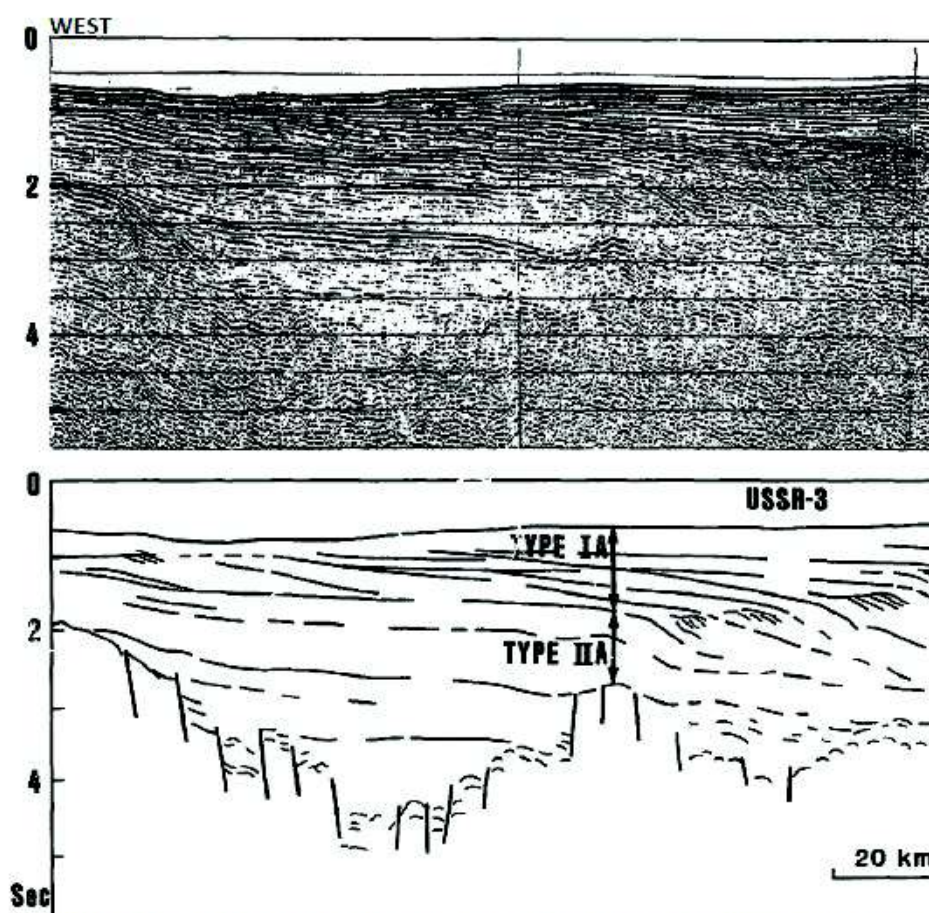
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195 **Figure 6. Seismic data and line drawing showing type IA and IIA sequences along line USSR-**
 196 **3 in the eastern Ross Sea (Modified from Cooper et al., 1991).**

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198 The pervasive occurrence of type IA sequences, particularly beneath the outer continental shelf,
 199 suggested to Cooper et al (1991) that grounded ice sheets have strongly controlled the location and
 200 depositional environments of the thick offshore prograding sedimentary sections since at least
 201 middle Cenozoic time. These grounded ice sheets probably extended to the continental shelf edge
 202 many times, as it is evident from the numerous unconformities within the type IA sequences and
 203 from the drilling evidence of numerous high-velocity near-seafloor layers and multiple over-
 204 compaction events (Cochrane and Cooper, 1991; Solheim et al., 1991 via Cooper et al., 1991).

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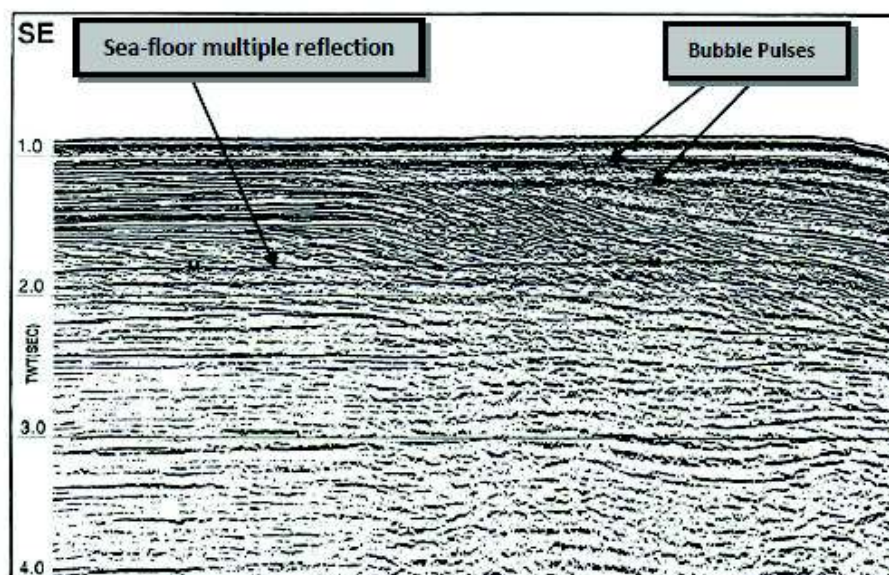


Figure 7. The continental shelf-edge region on MCS reflection profile BAS923-22 (Cunningham et al., 1994). Note that the first sea-floor multiple reflection has been labelled “M” for clarity.

Further Stratigraphic Studies on the continental margin of the Bellingshausen Sea

Almost all the previous studies on the continental margin of the Bellingshausen Sea made a common recommendation that further geophysical and geological investigations on this margin are required to verify their respective conclusions and improve the general knowledge of the area. This work is therefore targeted towards making a contribution to the accumulated geophysical and geological investigations on this margin.

An attempt was made to carry out a stratigraphic interpretation of three single channel lines BAS923-s27, BAS923-s28 and BAS923-s29. These lines are part of the data acquired at the Antarctic continental margin bordering the Bellingshausen Sea during the RRS James Clark Ross cruise JR04 (February and March, 1993).

SEQUENCE STRATIGRAPHIC ANALYSIS.

The SEG-Y processed data of the three single channel lines BAS923-s27, BAS923-s28 and BAS923-s29 were imported into the Kingdom Software (Copyright © 1993-2007 Seismic Micro-Technology, Inc.) for stratigraphic interpretation. This stratigraphic interpretation involves the definition of sequence boundaries and picking of reflection terminations.

Picking Parameters/Display

Prior to the processing, the polarity of the data was normal SEG polarity. This polarity standard is the convention adopted by the Society of Exploration Geophysicists (SEG) for the display of zero-phase data. The convention states that if the signal arises from a reflection that indicates an increase in acoustic impedance, the polarity is positive and is displayed as a peak and if the signal arises from a reflection that indicates a decrease in acoustic impedance, the polarity is negative and

is displayed as a trough. After processing of the seismic lines, every reflection was defined as a peak. So, the picking of events on the seismic section during interpretation focused on the peaks.

The seismic display used in the interpretation was an amplitude variable display with wiggle overlay; in most cases the wiggle overlay was removed. On subsequent display of seismic section, the blue colour is the peak while the brown is the trough as shown in Figure 8.

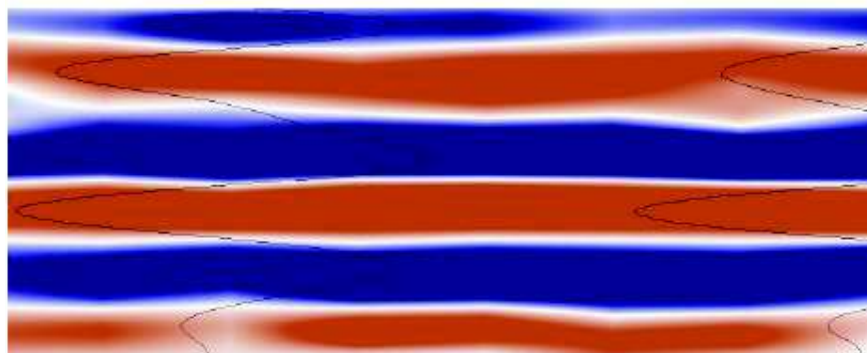


Figure 8. Seismic trace display for stratigraphic interpretation. Blue is the peak and brown is the trough.

Identification of Prominent Events and Sequence Boundaries

The first step in this stratigraphic interpretation was to identify the very visible and prominent events. The sea-bed reflection was identified at roughly 0.92s as the light-green marked event of Figure 9. The red-marked event of the same figure at roughly 1.83s is the sea-bed multiple which is caused by the sound waves bouncing twice between the sea-surface and sea-bed, and being recorded at a two way time twice that of the sea-bed. This reflection does not have any significance to this interpretation and it was subsequently ignored in the rest of the interpretation.

As a follow-up to the picking of the sea-bed and its multiple, the data was then divided into discrete natural stratigraphic packages that make up the section. In order to do this, reflection terminations were first identified and marked (shown in Figure 9). Based on the terminations of reflections in a consistent manner, four major surfaces were identified, resulting in the four sequence boundaries.

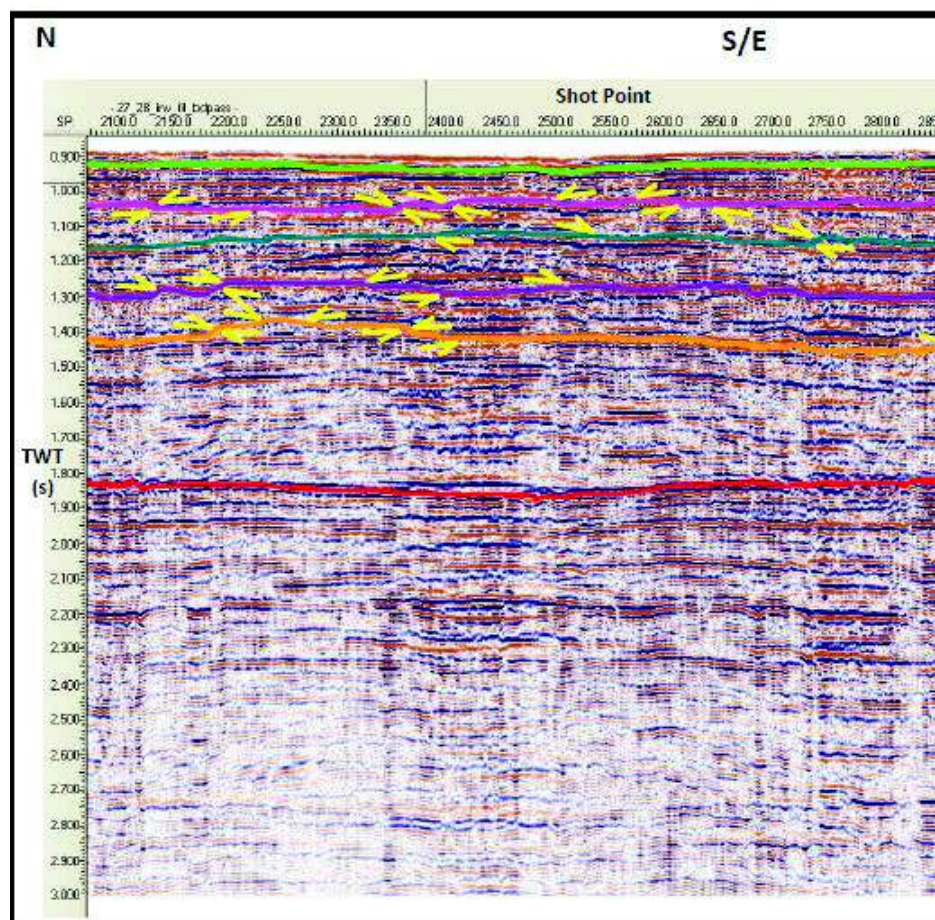


Figure 9. A section of line BAS923-s27 and BAS923-s28. Prominent events have been identified. SBR is the sea-bed reflection, SB1 to 4 are the sequence boundaries, and SBM is the sea-bed multiple. The yellow arrows are the reflection terminations.

Lap Geometries

Reflection terminations were categorized due to the geometric relationship between the reflection and the seismic surface against which it terminates. Geometries identified were toplap, downlap, and onlap. Toplap is the termination of inclined reflections against an overlying lower angle surface (Figure 10). Downlap occurs where reflections terminates against an underlying seismic surface. Onlap is recognised by the termination of low-angle reflections against a steeper seismic surface.

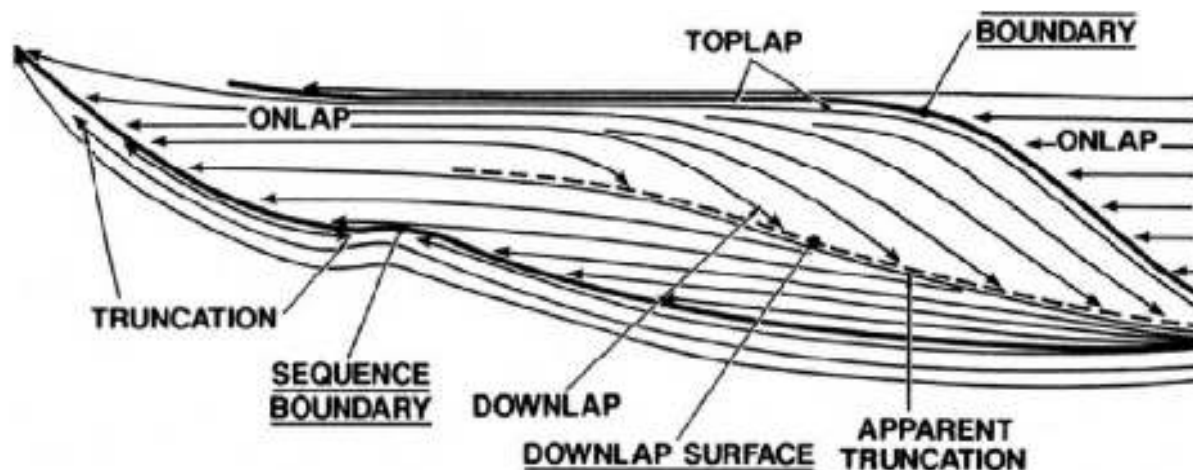


Figure 10. Diagrammatic representation of possible lap geometries and surfaces in stratigraphic interpretation (Vail et al, 1987).

Stratigraphic Surfaces

The major stratigraphic surfaces identified were sequence boundaries. These sequence boundaries were recognized on the seismic data by the presence of reflection terminations and downward shift in coastal onlap across the boundaries. Between the Sea-bed and its multiple, four major sequence boundaries were interpreted on lines BAS923-s27 and BAS923-s28, and they were named sequence boundary 1 to 4 from the bottom of the section. Line BAS923-s29 was acquired in a shallower part of the shelf; only sequence boundary 4 was clearly interpreted, all other possible sequence boundaries were masked by multiples. Sequence boundary 2 and 4 are sub-horizontal erosional surfaces, they show visible erosion and they have similar characteristics. The other two sequence boundaries show permanent onlap and they are similar as well.

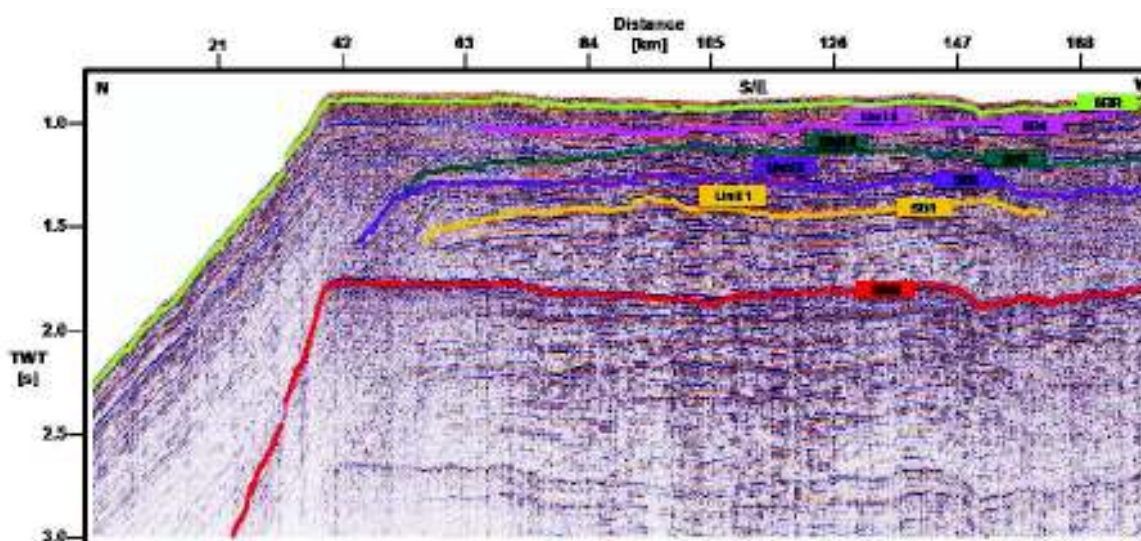


Figure 11. Sequence boundaries and Sediment units interpreted on dataset of profiles BAS923-s27 and BAS923-s28. SBR is the sea-bed reflection, SB1 to 4 are the sequence boundaries, and SBM is the sea-bed multiple.

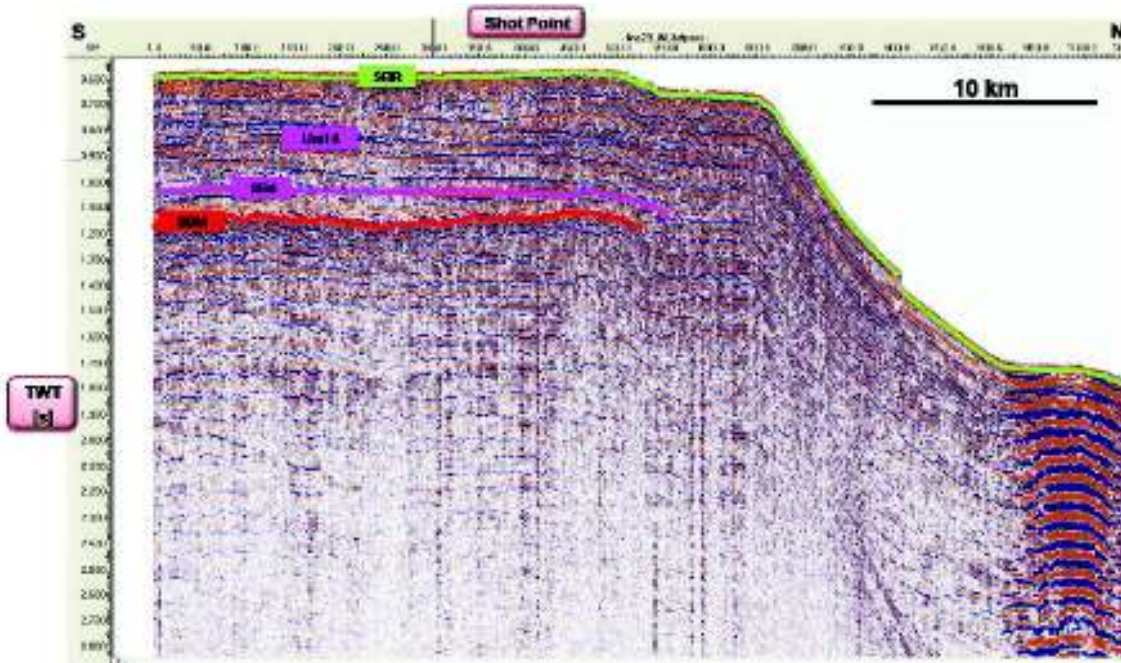


Figure 12. Sequence boundaries and Sediment units interpreted on dataset of profile BAS923-s29

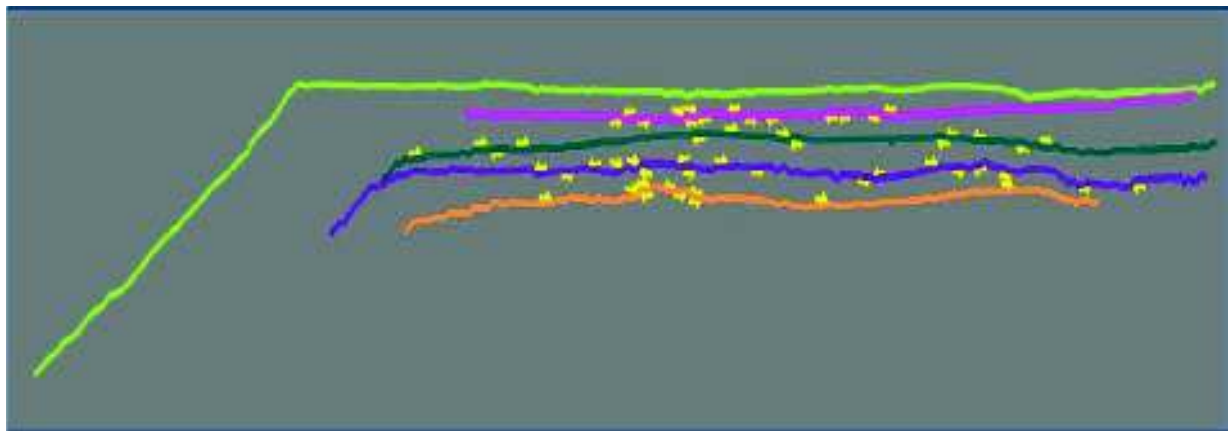
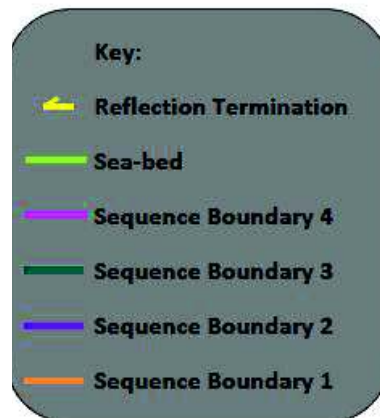


Figure 13. Cartoon depicting the stratigraphic interpretation of lines BAS923-s27 and BAS923-s28. Stratigraphic surfaces and reflection terminations are the major highlights of this cartoon. The key to this figure is shown below, and this key also serves Figure 14.



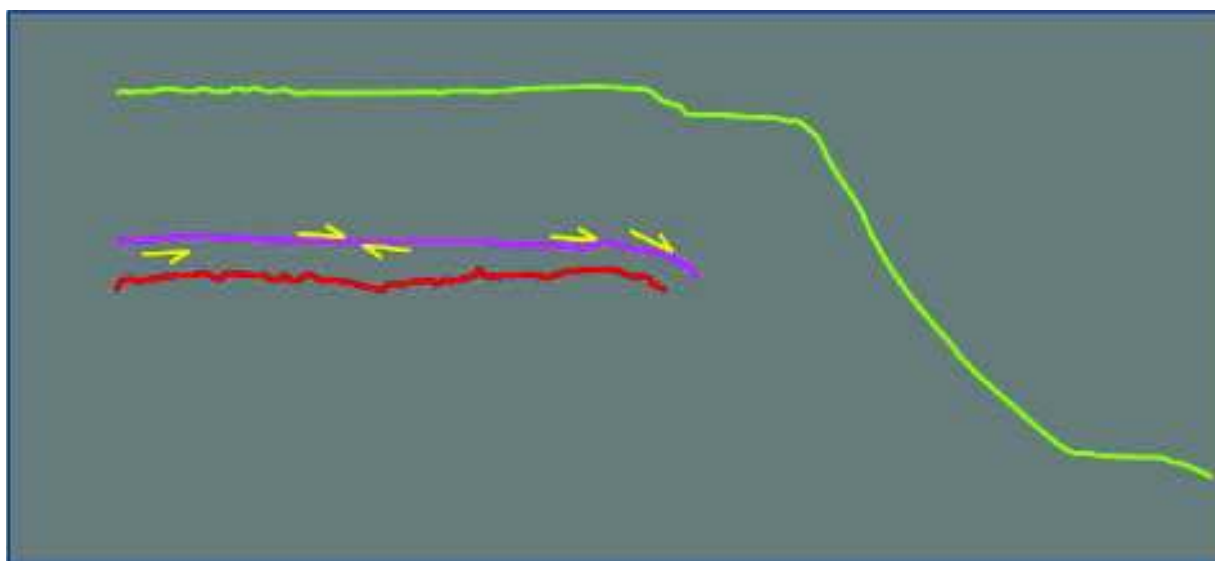


Figure 14. Cartoon depicting the stratigraphic interpretation of line BAS923-s29. Stratigraphic surfaces and reflection terminations are the major highlights of this cartoon.

Sediment Units

Profile BAS923-s27/BAS923-s28 (Figure 11) shows four sedimentary units that have been interpreted, Unit 1 to Unit 4. Unit 1 consists of parallel, relatively gently dipping and continuous reflections which appear to prograde the buried palaeo-shelf edges. The upper boundary of this unit is characterised by erosional truncation and toplaps and the lower boundary is characterised by downlaps. Internally, the reflections appear divergent in the northern side of the sequence, but they are generally evenly parallel except for the wavy parallel nature of the sequence towards the western side of line BAS923-s28. This unit also consist of high amplitude and relatively high frequency reflections. The thickness of Unit 1 varies between 0.1 s to 0.25 s. This unit closely resembles the Type IA sequence as defined by Cooper et al. (1991).

Unit 1 and Unit 2 are separated by an erosional surface. Unit 2 and Unit 3 shows prograding character on the outer shelf, building sediment wedge on the palaeo-slope. These units have relatively thin topset beds and they show strong prograding character on the upper palaeo-continental slope near the palaeo-shelf edges. The upper boundary of Unit 2 is characterised by toplaps and the lower boundary is characterised by downlaps. Internally, the reflections are generally evenly parallel with some fairly noticeable contortions towards the western side of line BAS923-s28. This unit also consist of moderate to high amplitude and relatively high frequency reflections.

The upper boundary of Unit 3 is characterised by both erosional truncation and toplaps and the lower boundary is characterised by downlaps. Internally, the reflections are generally evenly parallel. This unit also consist of high amplitude and relatively high frequency reflections. Both Units 2 and 3 clearly show the characteristics of Type IA sequence as defined by Cooper et al. (1991), which was interpreted to have been influenced by glacial erosion and transport processes. The thickness of Unit 2 varies between 0.05 s to 0.15 s while that of Unit 3 varies between 0.04 s to 0.18 s.

The uppermost part of the section is Unit 4. Unit 4 is fairly similar in character to Units 2 and 3 except that it progrades further down to the present-day continental slope. The thickness of Unit 4 varies between 0.03 s to 0.15 s. The upper boundary of this unit is the ocean floor which is quite smooth and no visible lap geometry was seen. The lower boundary is characterised by downlaps.

329 Internally, the reflections are generally parallel, and it consist of high amplitude and relatively high
330 frequency reflections.

331 **CONCLUSIONS**

332 The major question here is that "Is there any distinct feature in the depositional sequences that
333 shows that the prevailing processes at the time of deposition was as a result of glacial movement or
334 river action?". On the basis of the 2D lines for this work, the answer is "no". If there has been a 3D
335 seismic data, then the features can be differentiated. When a series of ice lobes are advancing
336 towards the shelf edge, then shallow and broad unconformities develop unlike a situation where a
337 series of rivers cuts through an exposed shelf resulting in mappable incised canyons. A very good
338 circumstantial evidence from the data of this work is that the same sequences and sequence
339 boundaries exist within profiles BAS923-s27 and BAS923-s28. It can therefore be assumed that the
340 movement of the ice front was across the whole area; this could be a confirmation that the action
341 was by ice. But the fact remains that this could also be as a result of sea level fall/rise, since sea
342 level fall/rise is relatively uniform across the affected area. It is thought that the movement of ice
343 creates boulders/ridges as it moves across the shelf, which may be represented as chaotic units on
344 the seismic. These units are obviously absent, what is seen are some rather well organised
345 progradational packages. It is quite possible that the ridges could have been reworked by marine
346 processes to produce normal shelf geometries.

347 The main conclusions of this interpretation are summarized below.

- 348 ▪ Identified on the profiles are sequences with steeply dipping prograded foresets, which are
349 truncated on their upper limit by erosional unconformities. These sediments were deposited
350 by grounded ice during times of glacial maximum which caused deposition in an overall
351 progradational style.
- 352 ▪ Although all the profiles (BAS923-s27, BAS923-s28 and BAS923-s29) shows similar
353 depositional sequences, some differences were observed in the steepness of the continental
354 slope, the depth of the shelf break, and the amount of progradation observed on individual
355 profiles. These differences could be due to the type of material been eroded, the path that
356 this erosion was taking, and different glacial drainage patterns.
- 357 ▪ Grounded ice must have reached the continental shelf edge many times on most parts of the
358 Bellingshausen Sea margin.
- 359 ▪ It was presumed that the sediments corresponding to all the units identified were possibly
360 transported at the base of an ice sheet and deposited where the ice was detached from the
361 sea floor. When the ice sheet was grounding near the shelf edge, the resulting glacial
362 sediments were deposited directly onto the upper slope, leading to the generation of foresets
363 and shelf-edge progradation observed on all profiles.

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