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Cenozoic basin evolution beneath the southern McMurdo Ice Shelf, Antarctica

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Abstract

Fifty-two kilometres of multi-channel seismic reflection data were acquired from the southern McMurdo Ice Shelf (SMIS) during potential drill site investigations for the Antarctic Drilling (ANDRILL) program. The survey was acquired atop 110 to 220 m of floating ice and extended across ablation and accumulation zones of the ice shelf. Seismic processing was tailored to the ice shelf environment, including: datum static corrections to account for changes in the thickness and average velocity of the near-surface firn layer, and changes in the surface elevation across the survey area; residual static corrections to account for near-surface ice shelf irregularities; and two-step predictive deconvolution to suppress ice and firn layer multiples. A model for the ice shelf thickness was also incorporated in the interval velocity model during depth conversion to ensure that the ice shelf structure did not impose non-static shifts on the seismic section.

The depth converted CMP stacked sections reveal several N to NE trending normal faults, that offset reflective horizons by up to 150 m within the lower part of the section and form a broad east-dipping, half-graben structure. The seafloor possesses trough and arch morphology in parallel with the half-graben structure. These features are interpreted as the southern extension of the Terror Rift. The rift succession comprises a dislocated (?)early-Miocene synrift package and a relatively undeformed (?)late-Miocene post-rift package separated by an erosional unconformity. The post-rift package infills and onlaps the rift topography, and drapes over the graben system, reaching a maximum thickness of 400 m. Throughout the post-rift phase, the basin was also influenced by Neogene volcanism, evidenced by three small volcanic features within the seismic profiles, and associated successions of inferred volcanic material. An angular unconformity within the post-rift succession is interpreted as a flexural horizon related to the load of Mount Discovery and/or Mount Morning. Up to 150 m of flexural moat fill occurs above this surface at ~20 km from the load centres. The post-rift succession also includes several glacio-geomorphic features, the orientation and morphology of which indicate an approximately SW to NE ice flow direction during a mid-Miocene grounding event and a SE to NW ice flow direction during Quaternary ice sheet grounding events.

The thickness and lower extent of the rift succession was not able to be determined because signal-to-noise ratio and vertical resolution were low at these depths. Strata from an earlier, Paleogene, rift episode may underlie the Terror Rift succession, or it may be directly underlain by acoustic basement. A Paleogene rift episode has previously been proposed based on the occurrence of Eocene fossiliferous erratics around the margin of the SMIS and the structural setting revealed by the SMIS seismic reflection profiles is consistent with this hypothesis.

Keywords: Southern McMurdo Ice Shelf; ANDRILL; seismic reflection survey; Terror Rift; Cenozoic; Antarctica; ice layer multiples

1. Introduction

Southern McMurdo Sound endured an era of intense tectonic, volcanic and climatic activity in the Cenozoic. The continental crust has been stretched, thinned, heated and

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dislocated during the evolution of the West Antarctic Rift (WAR; Van der Watteren and Cloetingh, 1999; Davey, 2001), and has been intruded by alkaline igneous intrusions and volcanoes which now define the limits of the Sound (Kyle, 1990). At the surface, there has been a broad climatic shift from a temperate environment in the Eocene to the present glacial environment (Barrett, 2001). Relatively little is known about the evolution and interplay of these major earth processes in this region, because fieldwork in this area is logistically challenging and most of the geological record has been eroded or concealed beneath the widespread ice cover. However, growing concern about future climate change and its impact on the human population has provided the impetus for further research into the Antarctic cryosphere, its development, and its role within the global climate system. Current research in this field is led by the Antarctic Drilling (ANDRILL) program, a stratigraphic drilling initiative that aims to recover core from the Antarctic margin to investigate the evolution of the Antarctic cryosphere over the past 50 Myr (Harwood et al., 2001). The project also provides an opportunity to develop an holistic understanding of the earth processes that have shaped this region during the Cenozoic. During potential drill site investigations, 52 km of reconnaissance multi-channel seismic data were acquired over three field seasons to develop an understanding of basin evolution beneath the southern McMurdo Ice Shelf.

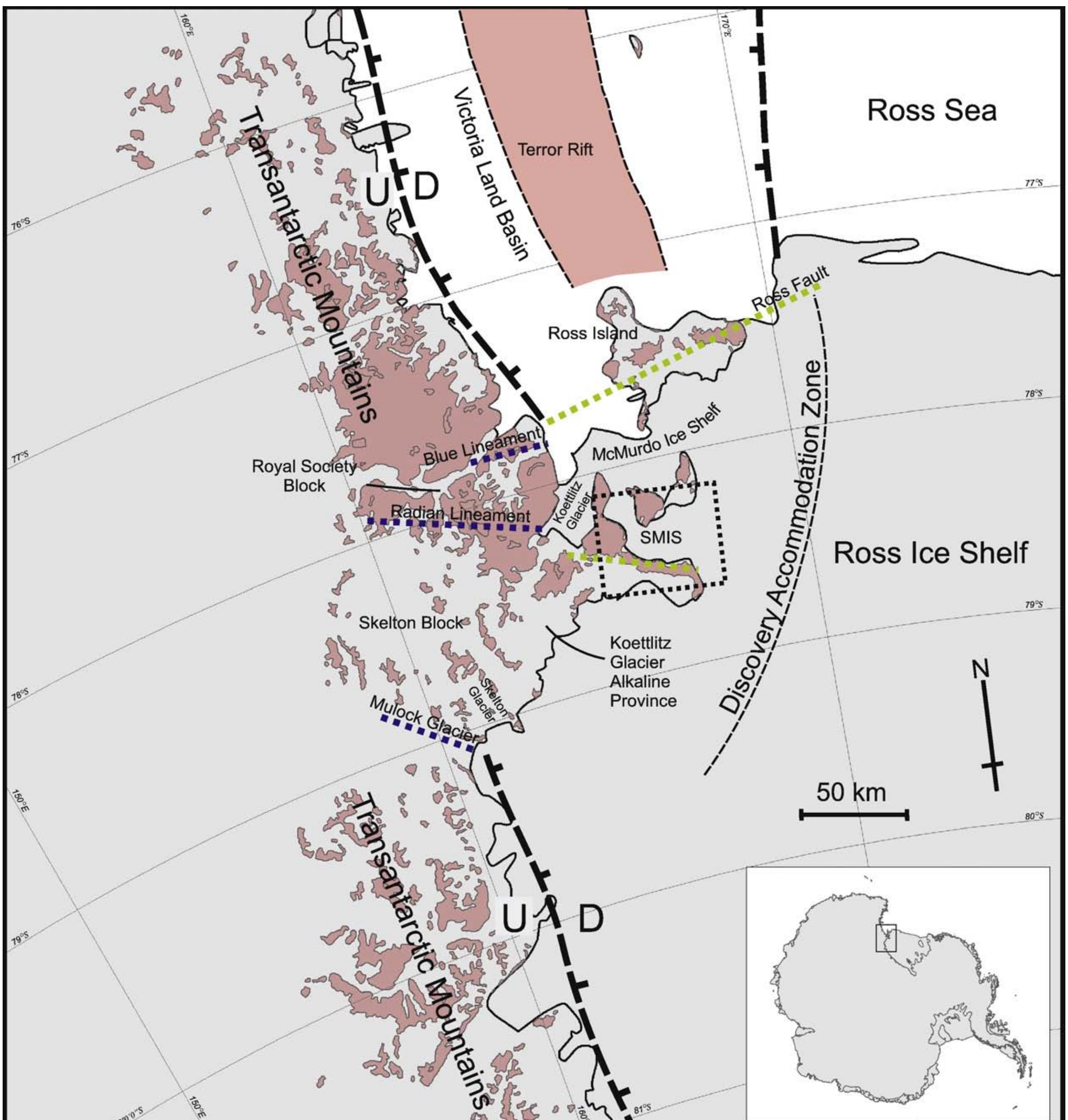

Fig. 1. Map showing the structural setting of McMurdo Sound / SW Ross Sea, after Cooper et al. (1987) and Wilson (1999). The area of the southern McMurdo Ice Shelf is indicated by the dashed rectangle. SMIS = southern McMurdo Ice Shelf. Ice-free terrain is indicated by darker shade of grey. U = up, D = down.

2. Setting

The focus of this study is a sedimentary basin underlying the southern McMurdo Ice Shelf (SMIS) within southern McMurdo Sound (Figs. 1 and 2). The basin is located within the West Antarctic Rift System, lying along the western margin of the Ross Embayment, immediately east of the Transantarctic Mountains.

Abundant marine seismic reflection data to the north of the sound, in the Ross Sea, reveal the Victoria Land Rift Basin (VLB) which trends approximately N–S to NNE–SSW, and has accommodated up to 14 km of sediment (Cooper et al., 1987; Fielding et al., 2006). Previous seismic data reveal two episodes of Cenozoic rifting recorded by strata of the Victoria Land Basin (Cooper et al., 1987; Fielding et al., in press). Recent integration of existing and new seismic data sets with drill core records (Fielding et al., in press) suggests that the first episode was predominantly Oligocene in age with early extension in the late Eocene and late phase passive subsidence persisting into the early Miocene. The second episode is more recent with renewed rifting associated with the Terror Rift beginning in the Miocene and continuing to the present. Cooper et al. (1987) speculated that the VLB and Terror Rift may extend south of Ross Island, beneath the ice shelf and into the present field area. However, several other authors have suggested that these structures may be terminated or offset at their southern end by an accommodation zone or transverse fault coinciding with Ross Island, approximately 70 km north of the field area (Kyle, 1990; Damaske et al., 1994; Wilson, 1999). Wilson et al. (1993) proposed the name Discovery Accommodation Zone, for the proposed late Cenozoic transverse zone, which coincides with a prominent offset of the rift flank adjacent to the SMIS, and is defined by several large-scale, rift-transverse (WNW–ESE) lineations (Fig. 1).

The SMIS is surrounded by a series of late Cenozoic alkaline volcanoes, which are part of the Erebus Volcanic Province, and may have been channelled along the intersection between rift-transverse and rift-parallel structures (Fig. 2: Kyle, 1990; Wilson, 1999). A mantle plume origin has been suggested for these volcanoes based on the ocean island basalt chemistry of

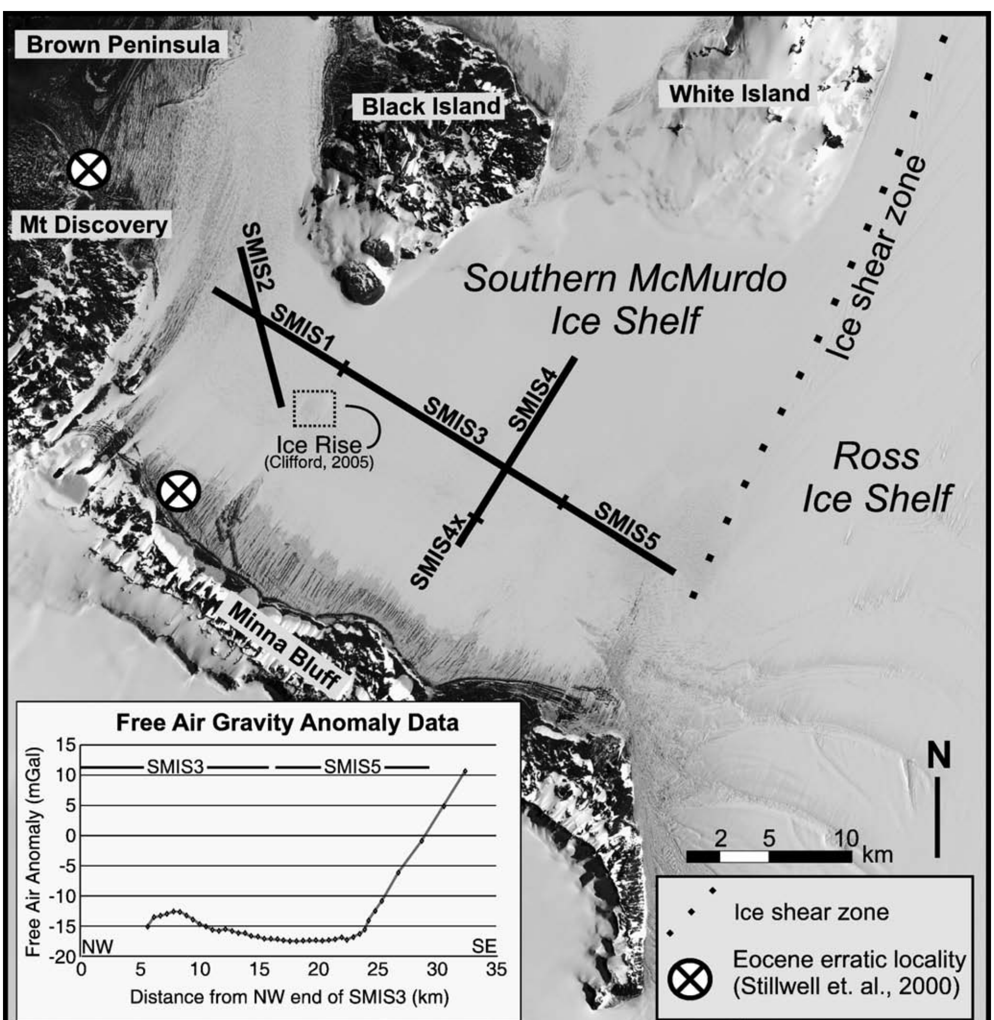

Fig. 2. LANDSAT7 image with SMIS seismic survey location overlain. Free Air gravity data acquired during the site survey are also shown in the bottom left corner. A sharp 25 mGal anomaly was recorded toward the SE end of the SMIS5 profile. The localities of Eocene fossiliferous-erratic deposits reported by Stilwell and Feldmann (2000), and the position of the ice shear zone between the southern McMurdo and Ross Ice Shelves are indicated.

the rocks (Rocholl et al., 1995), higher than average heatflow measurements in the area (up to 100 mW/m^2) (Berg, 1991; Vedova et al., 1992), and insufficient amounts of late Cenozoic crustal extension to produce the large volumes of igneous material by decompression melting (Lawver et al., 1991; Behrendt et al., 1992; Hole and Le Masurier, 1994). Emplacement ages for the Erebus Volcanic Province are summarised for volcanoes surrounding the SMIS in Table 1.

The Erebus Province volcanoes represent a substantial load on the lithosphere that can be expected to respond by flexing downward over a broad region, providing accommodation space for sedimentation in a circular moat basin (Watts, 2001). Flexural studies in the McMurdo Sound region indicate that loading of the Erebus Volcanic Province is compensated over a relatively narrow region due to the low strength (i.e., thin elastic thickness) of the lithosphere in this region, which may be caused by stretching, thinning, faulting and heating associated with development of the West Antarctic Rift and a possible mantle plume (Stern et al., 1991). A series of multi-channel seismic profiles acquired during ANDRILL site investigations on the McMurdo–Ross Ice Shelf, confirmed the existence of a sub-circular flexural moat basin around Ross Island, which accommodates up to 1200 m of sediment and is superimposed on the regional pattern of accommodation space created by rifting (Horgan et al., 2005b). The sedimentary package was shown to thicken toward Ross Island and displayed several angular unconformities which were interpreted as indicating progressive loading of the Ross Island volcanic complex (Horgan et al., 2005b). Horgan et al. (2005b) suggested that over-deepening of the moat basin may have protected the elusive Plio-Pleistocene sediments – a specific ANDRILL target – from erosion during ice sheet expansions. The seismic data acquired in the present study provide the first opportunity to test for a similar control around the more dispersed southern volcanoes of the Erebus Volcanic Province. However, previous glacial studies indicate that it is likely that the ice sheet grounded within southern McMurdo Sound during the Last Glacial Maximum (~20,000 BP), and possibly during other glacial maxima within the Quaternary, flowing along a W to NW path (Denton and Marchant, 2000; Wilson, 2000).

Glacial deposits around the SMIS contain middle to late Eocene fossiliferous erratics (Stilwell and Feldmann, 2000). In-situ middle Eocene strata have not yet been found to crop out in the Ross Embayment, nor have they been recovered by drilling.

Harwood and Levy (2000) proposed that the Eocene fossiliferous erratics may have been derived from a sub-glacial basin (Discovery Deep) south of Minna Bluff. However, Wilson (2001) suggested from their distribution that the erratics were derived from the uplifted footwall of a normal fault, near the SE end of the SMIS seismic survey area, implying that Eocene rift strata are contained within the sub-ice-shelf basin. Further evidence in support of this hypothesis was provided by Gamble et al. (2006) who used finite element modelling to show that ice flow across a shear zone between the southern McMurdo and Ross Ice Shelves (Fig. 2), may be restricted by a local grounding zone caused by a bathymetric rise. Gravity data also indicate a sharp rise in bathymetry or an increase in dense material leading into this boundary (Fig. 2; Horgan et al., 2005a).

Table 1
Summary of measured ages for Erebus Volcanic Province volcanoes surrounding the southern McMurdo Ice Shelf

Volcano	Age (Ma)	
Mt Morning	18.7–1.2	(Armstrong, 1978; Kyle and Muncy, 1983)
Minna Bluff	11–7.3	(Wright-Grassham, 1987)
Mt Discovery	5.4–1.9	(Armstrong, 1978; Wright-Grassham, 1987)
White Island	7–0.2	(Kyle, 1981; Cooper et al., 2007)
Black Island	11.2–2	(Armstrong, 1978; Timms, 2006)
Brown Peninsula	2.8–2.2	(Armstrong, 1978)

Several potential influences on basin evolution are implied by the regional setting of the field area and are summarised below:

(1) Tectonic
- The Victoria Land Rift Basin and Terror Rift may extend beneath the SMIS or may be truncated or offset to the west by the "Ross Fault" (Damaske et al., 1994), or Discovery Accommodation Zone north of the field area (Wilson, 1999).
- Late Cenozoic, transverse (WNW), steeply dipping faults associated with the proposed Discovery Accommodation Zone, may dissect the strata, and may have controlled glacial flow/erosion, and volcanic intrusions (Wilson, 1999).
- Rifting may have occurred in two main episodes.
- Paleogene rifting may have accommodated sediments, which were later exposed in the footwall of a normal fault beneath the SMIS-Ross Ice Shelf boundary and distributed around the SMIS during subsequent glacial events.

(2) Volcanic
- Progressive loading of the Erebus Volcanic Province on weak lithosphere may have formed a series of overlapping flexural moat basins, which may have accommodated Neogene to Pliocene sediment.

(3) Climatic
- During the Last Glacial Maximum (~20 000 yr BP), and possibly at other times during the Quaternary, a grounded ice sheet may have flowed along a W to NW path, eroding and distributing material from the seafloor beneath the present SMIS (Stuiver et al., 1981; Denton and Marchant, 2000; Wilson, 2000).
- Over-deepening of the flexural moat basin (from volcanic loading) may have protected the Plio-Pleistocene moat fill from erosion during ice sheet expansions.

3. Seismic methods

The SMIS seismic data (Fig. 2) were acquired over three field seasons in 2002/03, 2003/04 and 2005 in conjunction with other ANDRILL geophysical data sets, including GPR, GPS and aeromagnetic surveys (Aitken, 2003; Clifford, 2005; Horgan et al., 2005a; Henrys et al., 2006; Wilson et al.,

Table 2

Seismic Acquisition Parameters	
Source Type	3.2 kg Anzomex PPP primers (2002,2003) 3.2 kg Pentex (2005)
Seismic Detonators	Electric 30 m red-cord detonation cord
Receiver Type	Mark Products 40 Hz single geophones
Low-cut Acquisition Filter	10 Hz
High-cut Acquisition Filter	None
Sample Rate	1 ms
Number of Live Channels	48
Survey Geometry	Split spread (24:24)
Shot Spacing	96 m
Shot Depth	18 m
Shot-Receiver Near Offset	24 m
Shot-Receiver Far Offset	1128 m
Receiver Spacing	48 m
Seismic Acquisition System	Geometrics Stratavisor (2002, 2003) Seistronix RAS-24 (2005)

2007). Seismic acquisition parameters are displayed in Table 2. The data were processed using GLOBE Claritas™ seismic processing software (Ravens, 2001).

The seismic survey extended across ablation and accumulation zones of the ice shelf and consequently, near-surface conditions were variable (Clifford, 2005). Within ablation zones, the near-surface consists of hard ice with internal void spaces and surface irregularities. Collapse of the void spaces during shot detonation contaminated the primary data, the hard ice impaired geophone coupling, and surface irregularities caused short wavelength static shifts within the data. Within the accumulation zones, the near-surface consisted of a low-velocity firn layer. This layer possesses a positive vertical P-wave velocity gradient, which acts as a dispersive wave guide, resulting in an amplified, ringy and complex wave train (Beaudoin et al., 1992). The firn layer also absorbs seismic energy and consequently reduces energy penetration.

Static shifts were imposed on the data by lateral changes in elevation, and by the thickness and velocity structure of the firn layer (analogous to weathered layers and drift in conventional land seismic methods). Static shifts were quantified and removed using field datum static corrections, computed within GLOBE Claritas™ (Ravens, 2001) and cross-checked against manually-calculated values using the time-depth method (Hawkins, 1961). Near-offset geophone spacing was too large to recover details of the velocity-depth structure within the firn, so it was treated as a single constant-velocity layer. This yielded small (<4 ms) travel time effects — lowest in the ablation zones and greatest in the accumulation zones, consistent with existing models for the physiography of the SMIS (Clifford, 2005). Elevation components of the static shifts were larger (up to 10 ms). Short-wavelength refinements to the field statics were computed using three passes of residual statics, giving distinct improvements in reflection continuity in areas of irregular near-surface conditions.

The most significant and unique aspect of a seismic reflection survey on an ice shelf is the consideration of the complex, high-amplitude multiples within the high velocity ice (with typical P-wave velocities of 3200 m/s) and the underlying low-velocity water layer (with typical velocities < 1500 m/s). Lateral changes in the periodicity of these multiples reflect changes in the ice shelf and water column thicknesses across the survey area. A profile of ice thickness was calculated by measuring differences between periodicities of the water column and the water column-ice shelf multiples, and the associated stacking velocities. Ice thickness was shown to vary from ~110 to ~220 m over a lateral distance of 20 km, decreasing into ablation zones and increasing into accumulation zones (Fig. 3). These long-wavelength changes in ice thickness imposed non-static shifts on the seismic section that were treated as velocity anomalies (in a similar fashion to a subsurface low velocity zone) by incorporating the ice shelf thickness model into the interval velocity model at the depth conversion stage. These corrections equate to intra-survey differences of up to 68 m within the depth-converted seismic section.

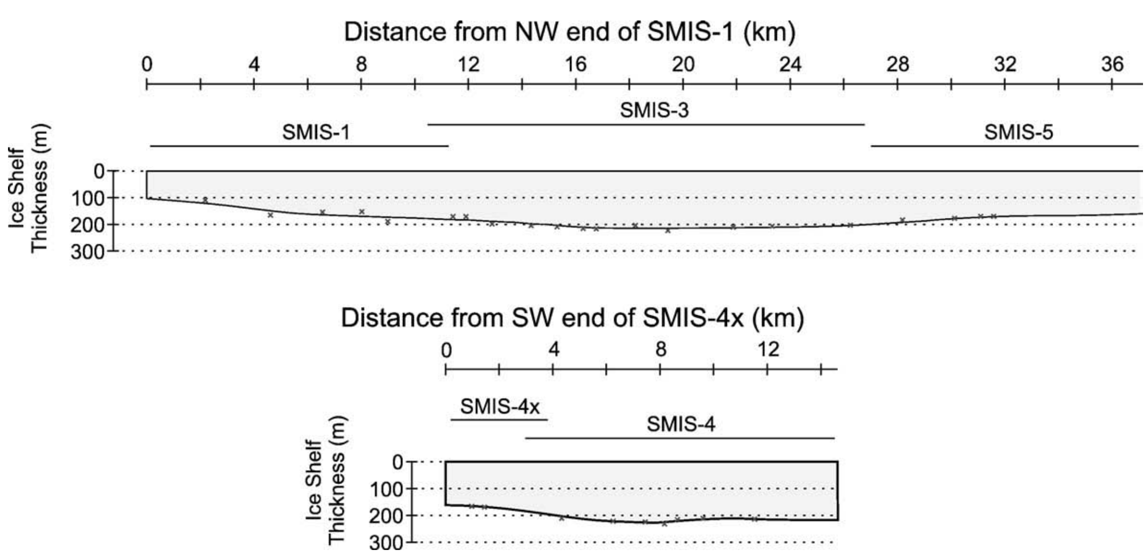

Fig. 3. Ice thickness profiles for the SMIS seismic lines. Ice thickness varies by approximately 110 m over a lateral distance of ~20 km, and was calculated using the arrival times and stacking velocities of long-path multiples. The thickness profile is consistent with a qualitative mass-balance model derived by Clifford (2005).

The rest of the seismic processing flow utilised a combination of conventional land and marine seismic processing techniques; refer to Johnston (2006) for a detailed description of the processing flow briefly described in order of application here. Initial trace editing removed occasional noisy traces. A spherical divergence amplitude scaling method was used to account for geometric spreading of the wavefront. FK filtering and top muting removed most of the shot-generated linear noise, which was more problematic in areas of shallow bathymetry. Band-pass filtering suppressed most of the remaining shot-generated linear noise, some of the water column multiple energy, and most of the high-frequency incoherent noise. Prestack predictive deconvolution partially collapsed the lengthy and complex seismic wavelet that resulted from the buried source and the firn-layer wave guide. Residual static calculations mentioned previously were applied at this point in the flow. Prestack processing was completed with a radon demultiple technique that suppressed water-column multiple energy. Velocity analysis was undertaken by evaluating a combination of semblance spectra, constant velocity stacks and constant velocity gathers. The application of the resulting normal move-out corrections and the subsequent CMP stack suppressed some of the water column and ice multiple energy, as well as incoherent noise. A post-stack application of predictive deconvolution further suppressed ice multiple energy and was tailored to account for across-survey differences in ice thickness. Finite-difference time migration – based on a finely-discretised interval-velocity model extracted from the stacking velocities – collapsed diffractions that were particularly pervasive in the lower portion of the seismic sections, and repositioned dipping reflections. Finally an F–X running mix filter (FX deconvolution) attenuated remaining random and dipping noise in the migrated sections. Final plots of the data (Fig. 4) were converted to depth using the same interval-velocity model used for the finite-difference migration. Plots were scaled with a horizontal trace balance and a linear two-way-time scalar; this boosted low-amplitudes in the lower part of the section that were not adequately scaled by the earlier application of a geometric spreading correction.

Despite the successful suppression of long-path multiple reflections (generated at the base of the ice shelf and at the sea bed — both of which obscured primary reflections from interfaces within the basin), the extended wave train caused by the firn layer was not collapsed completely. This compromised vertical resolution. Future ice shelf seismic studies would benefit from a focus on wavelet shaping, and improvement of spiking deconvolution techniques, processes that were unsuccessful on these data.

4. Interpretation

Time migrated, depth converted CMP sections are presented in Fig. 4 in their interpreted and uninterpreted form. Reflection terminations are indicated by red half-arrows and used to define unconformity surfaces, which are delimited by the coloured dashed horizons. Deeper within the section, unconformities were not able to be identified by reflection terminations, due to the loss in vertical resolution and consequent increase in interference. In these areas, prominent reflections are marked with blue dashed horizons to provide an indication of reflector geometry. Faults are interpreted from the planar truncation, offset and tilting of reflections and are indicated by the solid red lines. Igneous intrusions are inferred by the truncation of reflections and associated diffuse reflectivity beneath bathymetric rises and are delineated in the interpreted profiles by dashed burgundy lines. The first occurrence of the long-path water column multiple is indicated by the thick dashed cream line.

4.1. Bathymetry

The seafloor is associated with several glacio-geomorphic features. In the SMIS1-3-5 profile, two local bathymetric rises (A and B in Fig. 4), which are interpreted as volcanic features, have an asymmetric roche moutonnée morphology, suggesting erosion by an approximately SE to NW flowing ice sheet. Glacio-geomorphic features on the seafloor of the SMIS4-4× profile also indicate a NW flowing ice sheet. The bathymetry has a broad U-shaped profile, measuring approximately 6 km in width along the base. This feature is interpreted as a glacial trough. It is likely that the position of the trough was controlled by the Minna Bluff Peninsula, which coincides with the SW limb of the trough. A smaller scale channel occurs adjacent to the SW limb of the trough and is interpreted as a glacial channel or lineation. An irregular, hummocky feature adjacent to the channel is interpreted as a lateral moraine ridge. Plio-Pleistocene strata may have been removed during the erosional episodes that formed these features.

The seafloor in the SMIS1-3-5 profile also possesses a long-wavelength form, deepening from 400 m b.s.l. at the NW end of the line to 700 m b.s.l. at CMP 1100, and then shallowing more abruptly to 500 m b.s.l. at the SE end of the line. This bathymetric feature is similar in morphology, orientation and dimension to the Discovery Graben and Lee Arch in the Ross Sea to the north, which constitute the bathymetric expression of the Terror Rift (Cooper et al., 1987).

4.2. Seismic stratigraphy

The SMIS profiles image four primary units that are identified based on internal reflection characteristics, and genetic interpretations within the framework defined by Nøttvedt et al. (1995) for a typical rift sequence. These units are bounded by unconformity surfaces, but may also contain internal unconformity surfaces. The nomenclature used in this interpretation is not intended to correlate directly with that used in other seismic interpretations from the Ross Embayment.

4.2.1. Unit III: deeper than the green horizon

Unit III comprises low amplitude, irregular reflections dislocated by inferred normal faults. The lower extent of the unit is unknown due to the low vertical resolution and interference effects in the seismic data at this depth. Divergent reflection patterns are recorded between the blue horizons and

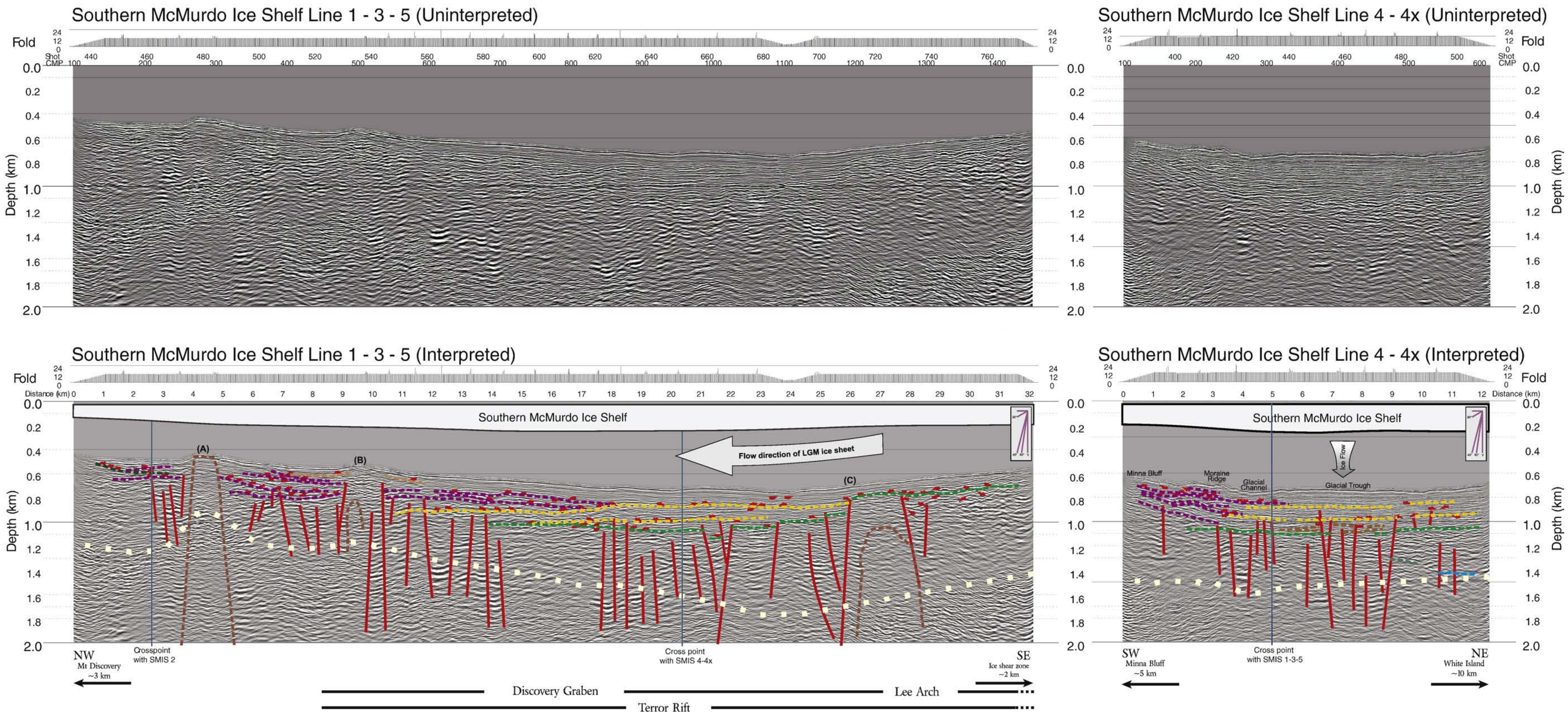

Fig. 4. SMIS 1-3-5 and 4-4× seismic sections (interpreted and uninterpreted). Location of the lines is shown on Fig. 2. Line positions in km, CMP location, and shot point location are annotated. See text for discussion and explanation of symbols and interpretation as well as processing sequence employed.

the overlying green unconformity, implying that deposition was synchronous with rifting and associated block rotation. Accordingly, unit III is interpreted as a "syn-rift sequence" (Nøttvedt et al., 1995). The generally very low reflectivity of this unit is disrupted by localised patches of very high amplitude, (apparent) negative polarity, low frequency reflections.

The unit is bounded at its upper surface by the green horizon, a high-amplitude erosional unconformity, which truncates underlying reflections, and is overlain by onlapping reflections. This unconformity is offset by several faults, most noticeably in the SE portion of the SMIS1-3-5 profile by several NW dipping faults. The largest of these displays 150 m of vertical offset (CMP 1200; Fig. 4). In the uplifted footwall of this fault, the green horizon has a very high amplitude and a rounded morphology, indicating that erosion has focused on the fault scarp.

The green unconformity marks a dramatic change in the interval velocity model, vertical resolution and seismic characteristics, implying that it may represent a significant hiatus in time, which may vary throughout the basin. It is interpreted as the "syn-rift unconformity" (Nøttvedt et al., 1995) marking the end of active rifting.

4.2.2. Unit IIa: green–orange–yellow horizons

For most of the SMIS4-4× profile and the SE part of the SMIS1-3-5 profile, unit IIa reflections are continuous, undeformed, sub-parallel, of moderate amplitude and occur with high frequency. In the NW portion of the SMIS1-3-5 profile, the reflections are higher in amplitude, are less continuous and have a more wavy form; the interval velocities are also higher. This shift in seismic characteristics implies either a change to coarser more chaotic material in the NW part of the SMIS1-3-5 profile, or preferential erosion in this area.

Unit IIa infills the relief created by the faulted green unconformity, with onlap directed away from the unconformity's deepest point (near CMP 1050; Fig. 4). The absence of significant faulting within unit IIa, and the manner in which it infills the pre-existing topography, suggests that it is an "early post-rift sequence" (Nøttvedt et al., 1995).

The unit contains an angular unconformity, marked as the orange horizon that dips gently toward the NW in the SMIS1-3-5 profile. Overlying reflections onlap toward the SE. In the SMIS4-4× profile, this horizon dips very gently toward the SW but no onlap is observed. This horizon is interpreted as a flexural unconformity associated with the loading of the Mount Morning and/or Discovery volcanoes. Assuming the horizon was originally deposited horizontally, a maximum accumulation of 150 m of flexural fill is recorded in the SMIS1-3-5 profile ~20 km from the loads.

Unit IIa is bounded at its upper surface by the yellow horizon, which has a moderate-to-high amplitude, is sub-horizontal, and has an irregular surface with local onlap around irregularities. A pronounced inflection point in its profile occurs near CMP 880 on the SMIS1-3-5 profile (Fig. 4), where the surface drops by approximately 70 m, before continuing toward the NW with a sub-horizontal trend. The irregular morphology of the yellow unconformity suggests that it is an erosional horizon. The pronounced drop may represent a glacial trough from a north flowing ice sheet prior to the emplacement of Minna Bluff (>11 Ma; Wright-Grassham, 1987).

4.2.3. Unit IIb: purple horizons

Reflections within unit IIb are irregular, and hummocky in form and have very low to very high amplitudes. The unit occurs in association with bathymetric highs (A and B in Fig. 4) with reflections generally dipping away from these features, and onlap directed towards them. The bathymetric rise at CMP 500 on the SMIS1-3-5 profile (Fig. 4) occurs 1 km north of a volcanic seamount imaged protruding into the base of the ice shelf in ANDRILL GPR profiles acquired by Clifford (2005). The bathymetric rise at the SW end of the SMIS4-4× profile coincides with the Minna Bluff Peninsula. Reflectivity beneath the bathymetric highs is diffuse. Consequently, they are interpreted as volcanic features, and unit IIb is interpreted to comprise igneous intrusions and volcanic debris and lavas flows, possibly interbedded with glaciomarine strata.

4.2.4. Unit I: yellow/purple horizons — seafloor

Unit I reflections are continuous, sub-parallel and low amplitude. The unit has an approximately tabular form, although stratal thickness increases slightly toward CMP 1050 and thins in the uplifted footwall of the fault at CMP 1200 in the SMIS1-3-5 profile (Fig. 4). The unit is interpreted as the "late post-rift succession" (Nøttvedt et al., 1995).

4.2.5. Structural Overview

Normal faults are mostly clearly imaged in the SMIS1-3-5 profile, where vertical offsets of up to 150 m are interpreted. The majority of these faults are steeply dipping and planar, with some antithetic listric faulting in the hanging wall of the major faults. In the NW part of the SMIS1-3-5 profile, the faults mostly dip toward the SE and in the SE part of the profile they mostly dip toward the NW. The overall form appears to be that of an east-dipping half-graben or asymmetric graben.

Offsets across faults are ambiguous within the SMIS4-4× profile but pervasive diffraction hyperbolae beneath the green unconformity (in the unmigrated section) and abrupt reflection truncations indicate the presence of several steeply dipping faults. A NE dipping fault at CMP 380 and a SW dipping fault at CMP 490 may define the outer limits of a negative flower structure, indicating some strike-slip movement.

The normal faults imaged within the SMIS profiles appear to be oriented at a high angle to the SMIS1-3-5 profile, approximate parallel with the N to NNE trending rift fabric. A strike-slip component is also implied by the interpreted flower structure in SMIS4-4× and may be associated with the proposed Discovery Accommodation Zone. However, the interpretation of this structure remains somewhat uncertain due to low resolution in this area and ambiguous offsets across the faults.

5. Discussion

Interpretation of the depth converted seismic sections (Fig. 4) provides several insights into the interplay between tectonic, volcanic and climatic processes within this region. The temporal aspects of these processes are not well constrained, since the SMIS survey was a reconnaissance survey with no proximal well ties. However, a broad chronological framework was developed by:

- correlation with well-tied northern rift basins
- interfingering and flexural relationships with local volcanoes
- relationship to major regional glacial events.

There are several drawbacks to this approach, in that, rift development typically varies structurally and temporally along the length of a rift system, volcano emplacement in this area spans several million years, and erosional surfaces cannot be associated definitively with specific glacial events without further chronological information. Nonetheless, models for the evolution of the sedimentary basin, and its structural setting were developed and are presented in Figs. 5 and 6. The primary controls on basin development are discussed below in terms of tectonic, volcanic and climatic controls.

5.1. Tectonic controls

The primary tectonic control on the basin beneath the SMIS appears to have been rifting. The succession is consistent with the idealised model for stratigraphic expression of rift basins, defined by Nøttvedt et al. (1995), comprising the following components:

- Syn-rift sequence (Unit III): displays complex divergent reflection patterns and is dislocated by steeply dipping faults.
- Syn-rift erosional unconformity (Green unconformity): manifested as a high amplitude reflection that develops on the uplifted footwalls of fault blocks, and weakens or feathers in the hanging walls.
- Early post-rift sequence (Unit IIa): reflections onlap and infill the remanent basin topography created by rifting.
- Late post-rift sequence (Unit I): a broad tabular or saucer shaped sedimentary package that drapes over the entire graben system.

The rift succession is interpreted to represent the southern extension of the Terror Rift, which is imaged in the Ross Sea to

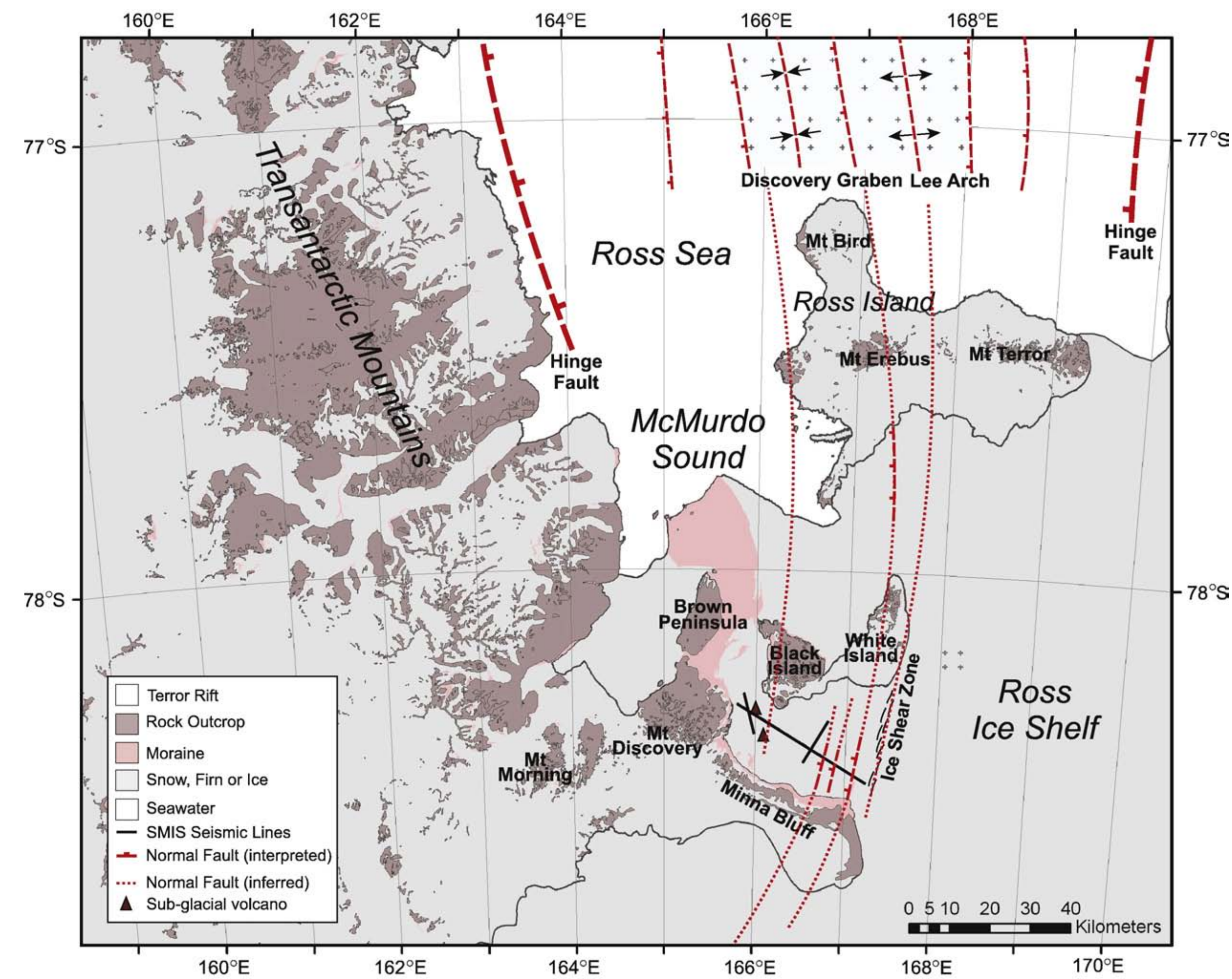

Fig. 5. Map showing the structural interpretation from the SMIS seismic profiles in relation to the regional structural setting. Structure to the north of the SMIS is after Cooper et al. (1987) and Fielding et al. (2006, in press).

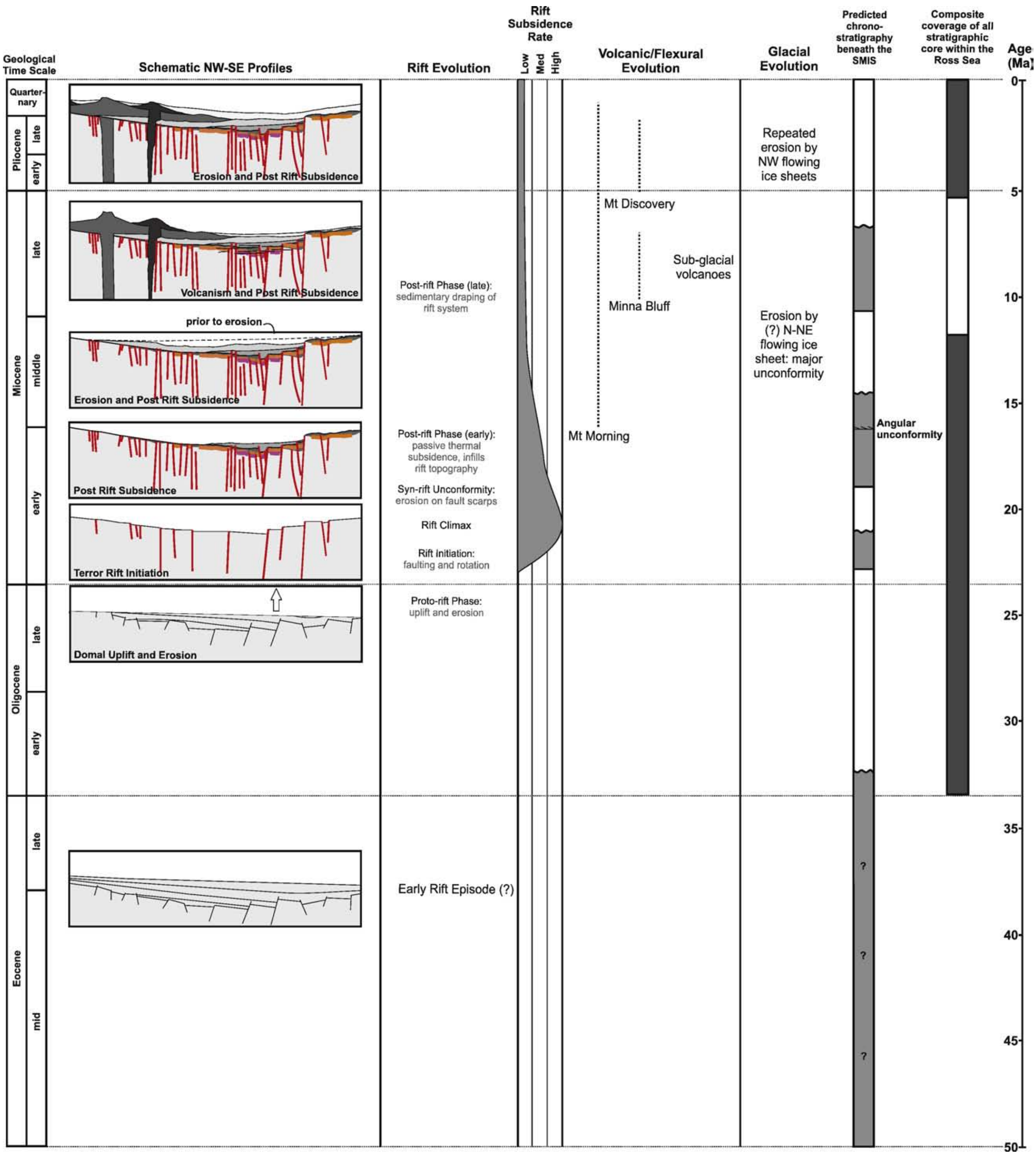

Fig. 6. Model for basin evolution beneath the SMIS.

the north (Fig. 5; Cooper et al., 1987). The bathymetry observed within the SMIS1-3-5 profile is very similar to the bathymetry associated with the Terror Rift in the Ross Sea where there is a broad bathymetric depression, 25 km in width, called the Discovery Graben, and a bathymetric high toward the east, 35 km in width, called the Lee Arch (Cooper et al., 1987).

In the Ross Sea, rifting occurred in two episodes: the first episode initiated in the late Eocene and the second episode initiated in the Miocene continuing to the present within the Terror Rift. In contrast, the presence of up to 400 m of undeformed post-rift strata beneath the SMIS, implies that rifting has not been active within recent times, and may have been short-lived in this area.

Evidence for an earlier Paleogene rift episode in the SMIS region is inconclusive due to the poor reflectivity and resolution within the lower part of the seismic profiles. Stilwell and Feldmann (2000) suggested that an earlier phase of rifting in SMIS region accommodated mid to late Eocene strata, based on the presence of glacial erratics of this age around the margin of the ice shelf. Wilson (2001) proposed that these erratics were derived from the uplifted footwall of a normal fault, SE of the SMIS1-3-5 profile during a recent glacial event, implying that Eocene rift strata are contained within the sub-glacial basin. The structural setting observed in the SMIS1-3-5 profile is consistent with this hypothesis, but only drilling can confirm it.

A less significant tectonic influence within this area is flexure from the emplacement of volcanic loads on the crust. Evidence for this effect was much less pronounced than has been observed around Ross Island (Horgan et al., 2005b). Only one onlap (flexural) horizon has been identified associated with a maximum of 150 m of sedimentary fill. This contrasts greatly with the observations of flexure to the north nearer Ross Island, where 1200 m of flexural fill has been estimated by Horgan et al. (2005b). This difference may be due to higher elastic strength of the lithosphere in the SMIS region where rifting may not have been as pronounced, and to the more distributed volcanic loads.

5.2. Climatic controls

Two erosional unconformities within the SMIS reflection profiles provide evidence for ice sheet grounding events. The first of these occurs within unit IIa (yellow horizon) and appears to underlie the volcanic sequences (unit IIb), and the second is the seafloor. The yellow horizon is an irregular, high amplitude surface, which drops by 70 m in the SMIS1-3-5 profile. This feature may be a glacial trough indicating a SW to NE flow direction, which would have been established prior to emplacement of Minna Bluff between <11 Ma (Wright-Grassham, 1987). Given these approximate age constraints, this horizon may be cautiously interpreted as the mid-Miocene unconformity, which is one of the most prominent unconformities recorded within the Ross Sea (Anderson and Bartek, 1992).

The seafloor is interpreted as an erosional surface based on the presence of several glacio-geomorphic features, which all indicate erosion by a SE to NW flow. This flow direction is consistent with the existing models for flow of a grounded ice sheet in this area during the Quaternary (Denton and Marchant, 2000; Wilson, 2000). It is likely that part of the sedimentary record has been removed by these erosional episodes.

5.3. Volcanic controls

Volcanism has exerted a strong influence on basin evolution. The flexural signature is not as pronounced as was expected, but igneous material and volcanic debris may comprise a large portion of the basin fill, particularly within the NW part of the field area. The ages of the associated volcanic events are broadly constrained by radiometric dates of nearby volcanic outcrops (Table 1) and their deposition appears to overlie the interpreted mid-Miocene unconformity. These units are also draped by up to 150 m of late, post-rift strata. These relationships imply that volcanism occurred after the majority of rift activity had ceased. Volcanism may have exploited existing structural weaknesses associated with the Terror Rift, and/or accommodation zone. The N-S trend of White Island along strike of the major normal fault in the SMIS1-3-5 profile lends support to this hypothesis.

6. Drilling prognosis

Fig. 6 illustrates the predictions for stratigraphic drilling beneath the SMIS from interpretations of seismic reflection data presented here, and compares this with the existing coverage within stratigraphic cores of the Ross Embayment. The most suitable location for drilling would be within the axis of the rift basin near CMP 1050 on the SMIS1-3-5 profile. However, a more NE location would also be suitable, perhaps near CMP 350 in the SMIS4-4× profile, to avoid drilling into igneous material proximal to Minna Bluff. The following succession may be recovered during drilling.

6.1. IV paleogene and/or paleozoic

This unit was not defined within the seismic sections due to the low resolution at depth. If an earlier stage of rifting has occurred within this region then the lower unit may comprise Paleogene rift strata. Such a unit may record the transition from warm, temperate conditions in the Eocene to more polar conditions in the Oligocene. Eocene strata may contain hydrocarbon accumulations or coal beds. If an earlier rift event did not occur in this region, or if it has been completely eroded, stratigraphic drilling may encounter acoustic basement, which is most likely to be Beacon Supergroup strata.

6.2. III early-Miocene

Syn-rift strata, probably comprising coarse sandstones and breccias, interbedded with glacio-marine sediments. The unit will be truncated by an erosional unconformity, which marks the end of the main rift phase.

6.3. II a early to mid-Miocene

Approximately 200-250 m of undeformed, glacio-marine strata, which accumulated after the main phase of rifting within the Terror Rift had ceased. This unit contains an angular unconformity within it, which may be associated with the emplacement of mounts Morning or Discovery. The upper extent of this unit is defined by an erosional unconformity, which may be the mid-Miocene glacial unconformity.

6.4. I late-Neogene

Approximately 100–150 m of undeformed glacio-marine sediments with intercalated ash and volcanic deposits. The upper part of this unit is interpreted as an erosional unconformity overlain by a layer of poorly sorted diamict on the seafloor that has accumulated since the last glacial maximum (~20 000 yr BP).

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