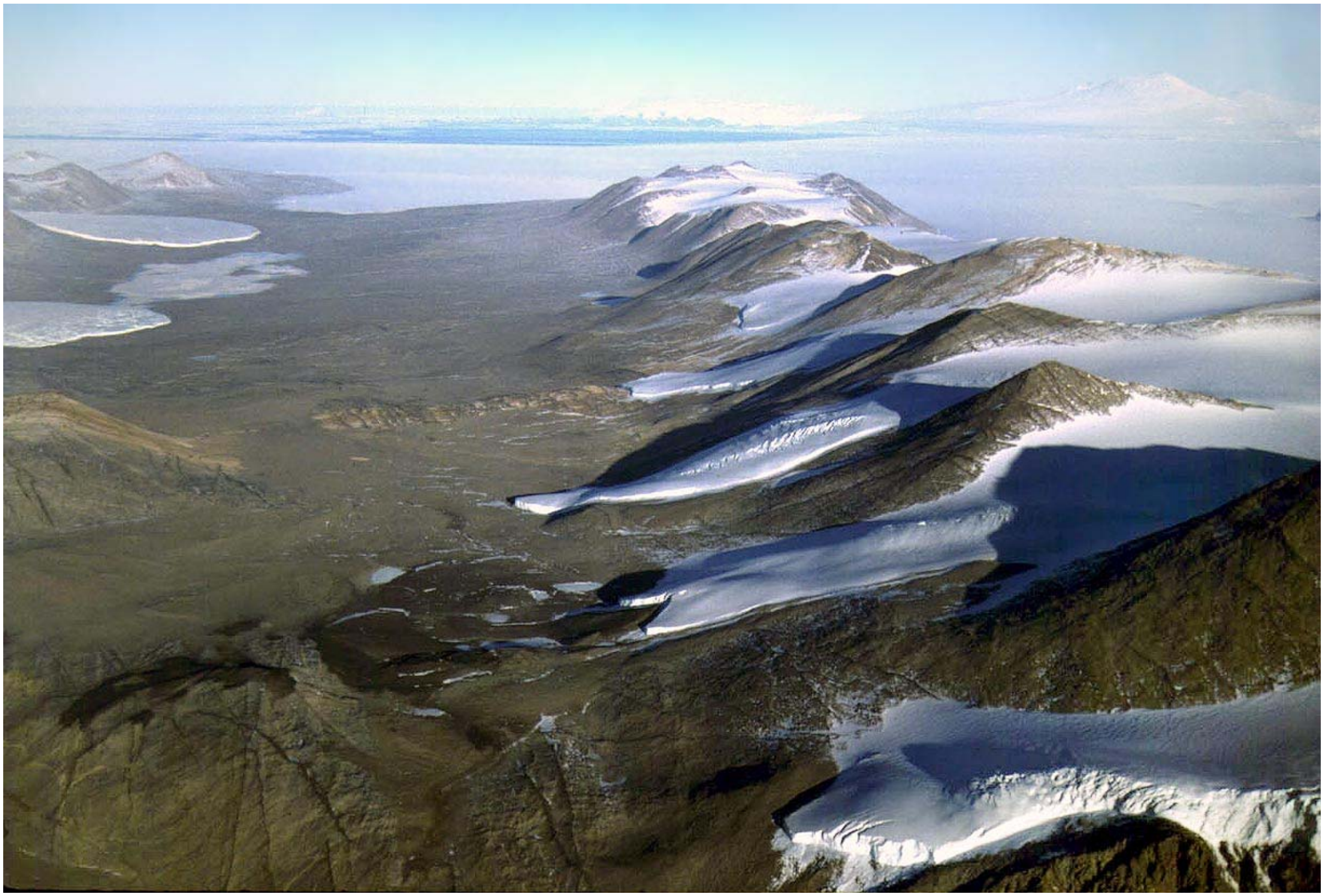
ANDRILL SOUTHERN McMURDO SOUND PROJECT

SCIENTIFIC PROSPECTUS



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ANDRILL CONTRIBUTION 5

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ANDRILL Southern McMurdo Sound Project Scientific Prospectus

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ANDRILL Southern McMurdo Sound Project Scientific Prospectus

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SUMMARY

During the austral summer of 2007 the ANtarctic DRILLing Program (ANDRILL) will drill from a sea-ice platform in southern McMurdo Sound to obtain new information about the Neogene Antarctic cryosphere and evolution of Antarctic rift basins. Target strata are middle Miocene to Quaternary in age (~17 Ma to present) and span several key steps in the evolution of Antarctic climate. Fault- and flexure-related subsidence associated with rifting and volcanic loading has provided accommodation space adjacent to the rising Transantarctic Mountains (TAM) that archived a sediment history of this important region, which is also influenced by three significant components of the Antarctic cryospheric system: the East Antarctic Ice Sheet (EAIS), Ross Ice Shelf (RIS)/West Antarctic Ice Sheet (WAIS), and Ross Embayment sea-ice. The Southern McMurdo Sound Project (SMS) drillcores will also record a tectonic history of the Antarctic Rift system (Victoria Land Basin - VLB), the TAM and the Erebus Volcanic Province. The key aim of the SMS Project is to establish a robust history of Neogene Antarctic ice sheet variation and climate evolution that can be integrated into continental and global records toward a better understanding of Antarctica's role in the past, present and future global system.

To achieve this aim, two drillholes (~500 m and ~700 m) will sample a sequence of strata identified on seismic lines and inferred to represent a lower Miocene and younger sequence of seismic units that expand basinward. Several distinct seismic packages are identified. These units are separated by distinct seismic reflection surfaces, three of which appear to be regional erosional surfaces. The two drillholes will recover a composite thickness of >1000 m of strata that lie stratigraphically above the lower Miocene section recovered at the top of the nearby Cenozoic Investigations in the Western Ross Sea (CIROS)-1 drillcore, and above the 1400 m composite section recovered by the Cape Roberts Project (CRP) (~34 to 17 Ma) (Davey *et al*., 2001; Florindo *et al*., 2005). Two offset shallow drillholes are required for the SMS Project to obtain the complete target stratigraphic section while minimizing the potential for diagenetic loss of opaline silica (and key siliceous microfossil record) in the cored strata. Drilling technology will utilize a sea-riser system and continuous wire-line diamond-bit coring to ensure high-percentage core recovery similar to that obtained by the CRP (e.g. 98% of 939 m in the CRP-3 drillhole).

The recovery of lower to middle Miocene Antarctic stratigraphic sequences is required to evaluate the history derived from global proxy records that invoke a change from a warm climatic optimum (~17 Ma) to the onset of major cooling (~14 Ma) and the formation of a quasi-permanent ice sheet on East Antarctica. Secondary target strata of Pliocene and Pleistocene age from a distal marine setting will complement and build on coastal and fjord sediment records from Dry Valley Drilling Project (DVDP) -10, -11 and CIROS-2 drillcores that are interpreted to reflect repeated Late Neogene alternation between 'interglacial' and 'glacial' conditions. The SMS site is well-connected to the grid of seismic lines in the VLB; hence the recovered sections will provide excellent chronostratigraphic control for regional seismic surfaces and units important for interpreting regional stratal architecture and for dating Neogene and younger subsidence and rift fault history.

Specific scientific objectives are to:

- (a) document the initial onset and subsequent history of sea-ice presence/absence;
- (b) document the evolution and demise of Neogene terrestrial vegetation;
- (c) establish a local Late Neogene sea-level record;
- (d) test whether stable cold-polar climate conditions persisted for the last 15 m.y.;
- (e) document melt-water discharge events from the adjacent Dry Valley/TAM system;
- (f) construct a composite event history of glacial and interglacial events across a coastal to deep basin transect;
- (g) provide chronostratigraphic control for the regional seismic framework in the VLB and western Ross Sea;
- (h) feed new paleoclimatic data into ice sheet and climate models; and
- (i) develop a Neogene subsidence and fault history for the Victoria Land Basin.

All of these objectives will lead toward a better understanding of Antarctica's Neogene climatic and tectonic history.

Potential response of Antarctic ice sheets to projected greenhouse warming of up to 5.8°C by the end of the century is not known. Models on which predictions are based need to be constrained by geological data of the ancient ice sheets during times when Earth is known to have been warmer than today. The marine-based WAIS and its fringing ice shelves are hypothesized (Clark *et al.*, 2002; Weaver *et al.*, 2003; Stocker, 2003) and documented (Scherer *et al.*, 1998) to have collapsed during past 'super-interglacial' warm extremes. Debate over when the EAIS became a stable element continues to raise new questions and produce new information (Webb & Harwood, 1991; Sugden *et al.*, 1993; Flower & Kennett, 1994; G. Wilson, 1995; Barrett, 1996; Miller & Mabin, 1998; Marchant *et al.*, 1996; Hambrey & McKelvey, 2000b) A clearer history of the past timing and magnitude of paleoclimate change and ice sheet variation is vital to understand how Antarctica will interact in the Global System in the future and the threshold level of climate warming and CO_2 increase as the WAIS responds to potential collapse of the Ross Ice Shelf and the EAIS will again become an active agent in driving glacioeustasy.

This prospectus outlines the background and scientific rationale for the SMS Project and identifies scientific questions to be addressed and presents pertinent scientific literature. It provides a basis for prospective Science Team Members to assess the scientific merits of the SMS objectives and guide preparation of their applications to participate in the ANDRILL Program. Interested scientists are directed to http://andrill.org for additional information.

THE ANDRILL PROGRAM: BACKGROUND AND OVERVIEW

ANDRILL is a multinational, multidisciplinary program with objectives to recover stratigraphic intervals for use in interpreting Antarctica's climatic, glacial and tectonic history over the past 50 m.y. at various scales of age resolution (Harwood *et al.*, 2003). A key motivation for ANDRILL stems from a lack of knowledge of the complex role the Antarctic cryosphere (ice sheets, ice shelves and sea-ice) plays and played in the global climate system. Understanding the history of ice volume variation and associated physical changes in the Antarctic region is critical for assessing the interaction of ice sheets with other elements of the Earth System, such as ocean, atmosphere, lithosphere and biosphere. Accurate assessment of the scale and rapidity of changes affecting large ice masses is of vital importance because ice-volume variations: (a) lead to changing global sea-levels; (b) affect Earth's albedo; (c) control the latitudinal gradient of the Southern Hemisphere and thus heat transport via atmospheric and oceanic circulation; (d) generate melt-water discharge that can alter ocean stability and circulation; and (e) influence the distribution of ice shelves and seasonal sea-ice, which are commonly attributed to forming cold-bottom waters that drive global ocean circulation. General circulation models indicate that polar regions are the most sensitive to climate warming, thus projected global rise in mean temperature of 1.4-5.8°C by the century end (IPCC, 2001; Houghton *et al.*, 2001) is likely to be greater in the Antarctic.

The ANDRILL Program recognizes that efforts to understand the role of Antarctic drivers on global climate variability require a fundamental knowledge of Antarctic cryospheric evolution, not only in recent times, which is plainly vital, but also for earlier Antarctic history when global temperature and atmospheric pCO_2 were similar to that which might well be reached by the end of this century. Due to a lack of Cenozoic strata exposed on land and a dearth of drillcores on the continental margin of Antarctica (Webb, 1990, 1991; Moriwaki *et al.*, 1992; Anderson, 1999), our understanding of Antarctica's climate history has relied heavily on inferences from low latitude climate-proxy records, such as deep-sea oxygen isotope and Mg/Ca ratio records (Lear *et al.*, 2000; Zachos *et al.*, 2001; Billups & Schrag, 2002, 2003) and sequence stratigraphic interpretations of non-glaciated passive margins (Haq *et al.,* 1987, 1988) (Fig. 1).

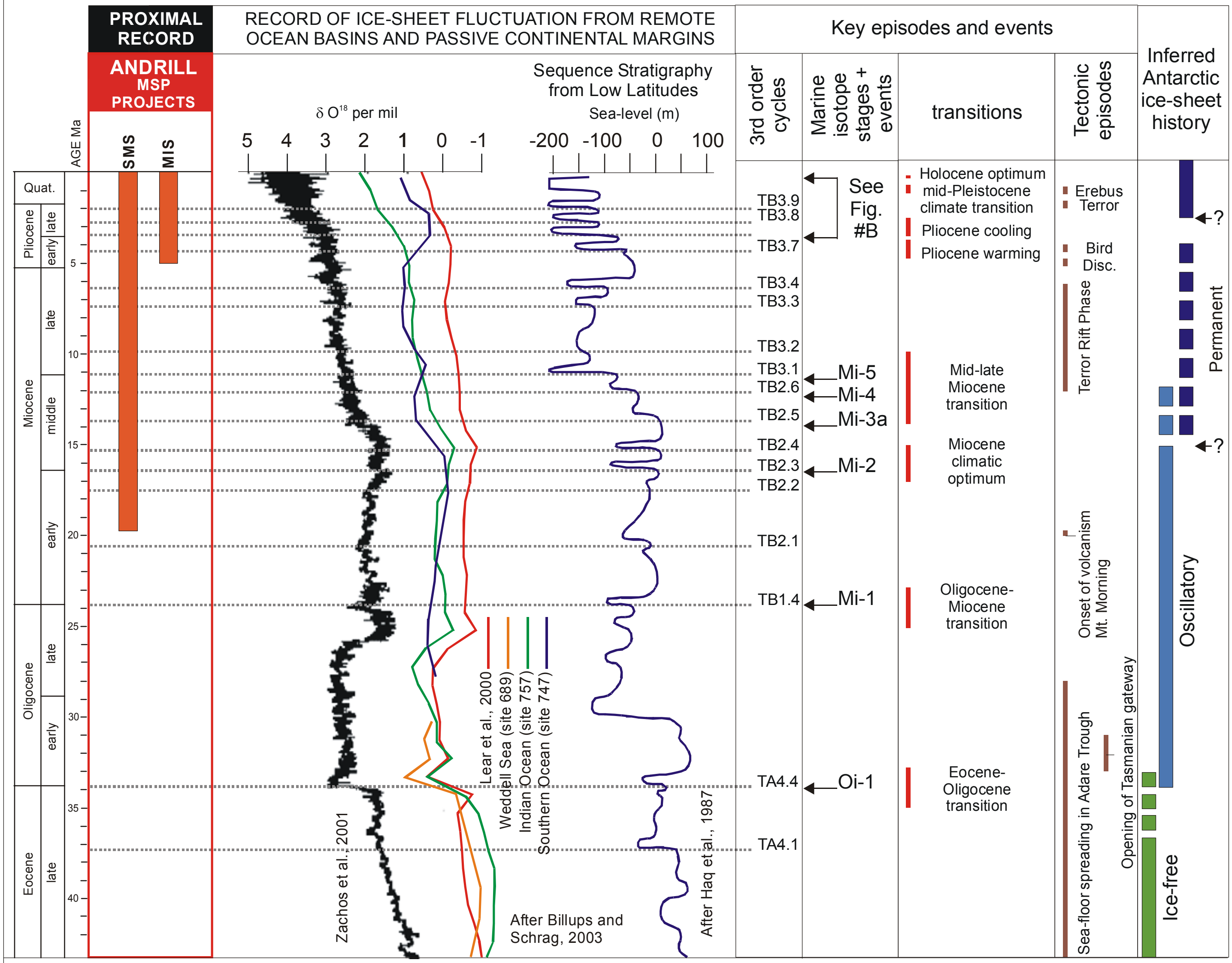


Figure 1. Each ANDRILL McMurdo Sound Project aims to recover stratigraphic intervals that preserve an Antarctic margin record of episodes and events of regional and global importance. These new data will provide direct calibration points for Antarctic cryospheric behaviour and resulting glacio-eustasy that is currently interpreted from remote ocean basins and from passive continental margins (ANDRILL International Science Proposal, 2003).

Although a number of high-quality sedimentary archives that record past ice sheet behavior have become available recently from the CRP (e.g. Naish *et al.*, 2001a; Wilson *et al.*, 2004), from Ocean Drilling Program (ODP) legs 178 (e.g. Domack *et al.*, 2001) and 188 (e.g. Gruetzner *et al.*, 2003), and from fieldwork in the TAM (Prentice *et al.*, 1993; Webb *et al.*, 1996; G. Wilson *et al.*, 1998; Hambrey *et al.*, 2003) and the Prince Charles Mountains (Hambrey & McKelvey, 2000a, 2000b; Whitehead *et al.*, 2003, 2004), they remain too few in number, and are often poorly constrained chronostratigraphically, to allow a comprehensive understanding of Antarctica's influence on Late Neogene global climate. Proxy indicators from the Southern Ocean identify numerous discrete events of paleoenvironmental change, such as short but significant surface water warming events (Bohaty & Harwood, 1998; Whitehead & Bohaty, 2003), and episodes of increased sediment influx from Antarctica (Joseph *et al.*, 2002). These reports, however, require new information from sites proximal to the Antarctica margin to better understand how the cryosphere and high latitude water-masses responded to and/or influenced these events. Other paleoclimatic and paleoenvironmental events identified from Antarctic nearshore (e.g. Barrett & Hambrey, 1992; Ishman & Reick, 1992; Bohaty *et al.*, 1998; Quilty *et al.*, 2000; Harwood *et al.*, 2000; Jonkers, 1998) and seismic sequence stratigraphic records (e.g. Alonso *et al.*, 1992; Anderson & Bartek, 1992; Bartek *et al.*, 1996; DeSantis *et al.*, 1995, 1999; Bart & Anderson, 2000; T. Wilson *et al.*, 2004) require integration into a broader and more robust chronostratigraphic framework that can only be achieved through further drilling on the Antarctic continental shelf. Results from ice sheet and climate modeling will provide the forum to help integrate new ANDRILL data into a broader regional and global context. Initiatives endorsed by the Scientific Committee on Antarctic Research (SCAR), *Antarctic Climate Evolution* (ACE) http://www.ace.scar.org and Antarctic Neotectonics (ANTEC) http://www.geoscience.scar.org/geodesy/antec will help facilitate the integration of new information generated by ANDRILL stratigraphic drilling into climate, ice sheet and tectonic models, and expose the broader scientific community, general public and policymakers to Antarctic paleoenvironmental and geological issues.

Discussions regarding Late Neogene climate evolution of the southern high latitudes center on the history of ice sheet and climate variability and timing of the switch from warm, polythermal ice sheets to cold polar conditions (Moriwaki *et al.*, 1992; Miller & Mabin, 1998). One view supported chiefly by stratigraphic and paleontologic information suggests a dynamic behavior of Neogene ice sheets and transition to the current cold-polar conditions during the late Pliocene (e.g. Webb & Harwood, 1991; Webb *et al.*, 1996; Harwood & Webb, 1998; Hambrey & McKelvey, 2000b; Whitehead *et al.*, 2004). A contrasting interpretation based on landscape evolution in the Dry Valley region and chronology of surface deposits and volcanic ash (e.g. Marchant *et al.*, 1993, 1996; Sugden *et al.*, 1993, 1995, 1999) suggests an earlier onset and persistence of modern, cold-polar conditions by middle Miocene time. Divergent histories also exist from interpretations of proxy records of glacioeustasy, as indicated in deep-sea oxygen isotope records and of sequence stratigraphy from low latitude passive margin settings (Christie-Blick *et al.*, 1990; Poulsen *et al.*, 1998; Abreu *et al.*, 1998; Zachos *et al.,* 2001; Bart, 2001, 2003) (Fig. 1). An independent record of glacioeustasy obtained by drilling to recover sequences proximal to the ice sheet margin will help resolve interpretations of event history derived from these different proxies.

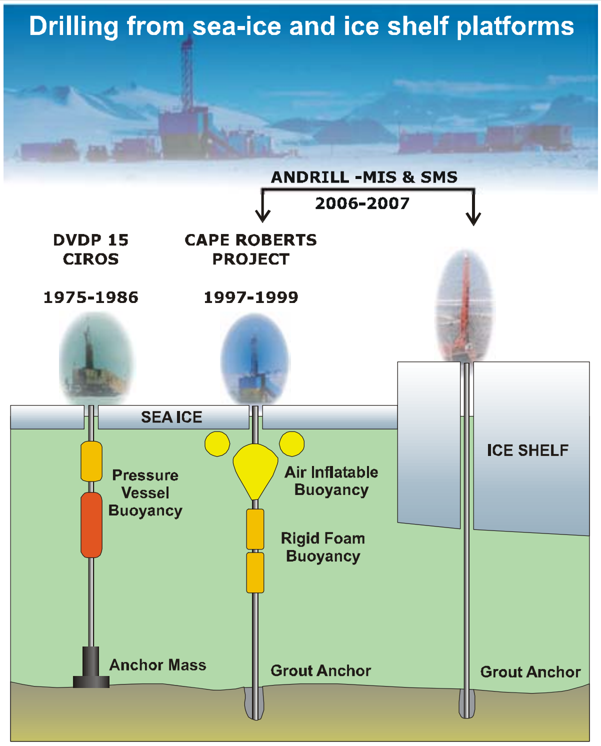


Figure 2. The ANDRILL Programme must address unique logistical and drilling requirements to achieve its science goals. New drilling tools have been developed (drill rig, coring tools, and riser system) from proven drilling technology that was employed during the Cape Roberts Project (ANDRILL International Science Proposal, 2003).

During the next decade, the ANDRILL Program anticipates the drilling of selected targets around the Antarctic margin that are organized and proposed within a series of scientific and operational Portfolios. These are equivalent to ODP 'legs', but due to logistical constraints they span several years. Two projects within the McMurdo Sound Portfolio (MSP) were approved and funded by an international ANDRILL consortium (USA, New Zealand, Italy and Germany) and have been scheduled for drilling. The McMurdo Ice Shelf Project (MIS) will be drilled during 2006. The Southern McMurdo Sound Project (SMS), the subject of this Prospectus, will be drilled during 2007. Both the MIS and SMS Prospectus documents are available at http://andrill.org . Results from these two ANDRILL Projects will reveal the history of the Ross Ice Shelf, including times of advance of the grounded Ross Ice Sheet as well as loss of the West Antarctic Ice Sheet when a broad sea covered West Antarctica.

A new drilling system is being built for the ANDRILL Program that represents a significant technological evolution from the highly successful CRP drill system (Fig. 2). The drilling system will have the capacity to operate on both shore-fast-ice and ice shelf platforms (up to 300 m-thick) and to recover continuous (>95% core recovery), long stratigraphic records (up to 1200 m) from water depths of up to 1000 m. This drilling system utilizes a sea-riser to enable a recirculating mud system that ensures a more stable borehole, continuous wire-line, diamond bit coring system within three sizes of drillstring, and specialized tools, including hydraulic piston coring capability that will enhance recovery of soft sediments.

DRILLING IN McMURDO SOUND

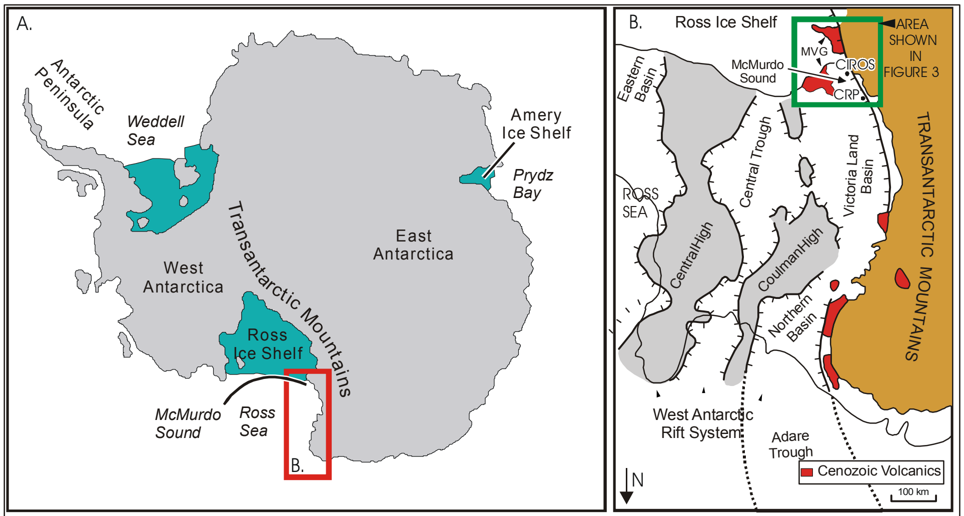


Figure 3. General location of the McMurdo Sound in western Ross Sea adjacent to the northwestern corner of the Ross Ice Shelf and the Transantarctic Mountains. Inset (B) shows the regional tectonic setting and area enlarged in Fig. 3 (ANDRILL International Science Proposal, 2003).

ANDRILL focuses its initial efforts on the McMurdo Sound region due to the reasonably well-understood stratigraphic and tectonic framework and nearby logistical centers at McMurdo Station (U.S.A.) and Scott Base (N.Z.). Furthermore, McMurdo Sound sits at the junction between components of the West Antarctic Rift system, including the VLB the TAM and the Erebus Volcanic Province, which will provide the components required to produce the desired records (Figs. 3 & 4). Fault and flexure-related subsidence associated with rifting and volcanic loading has provided Early Cenozoic to Quaternary stratigraphic accommodation space adjacent to the rising TAM (Fig. 5). The combination of a high sediment supply from TAM and the accommodation space provided by tectonic subsidence of the VLB has allowed the region to act as an 'high-fidelity sedimentary tape recorder' for the past 50 m.y., helping preserve the contained sediments from the erosive effects of glacial advances that often removed other Antarctic ice-proximal records. Proximity to volcanic sources enhances the opportunity for refined chronostratigraphic dating of the recovered sediments through tephrachronology.

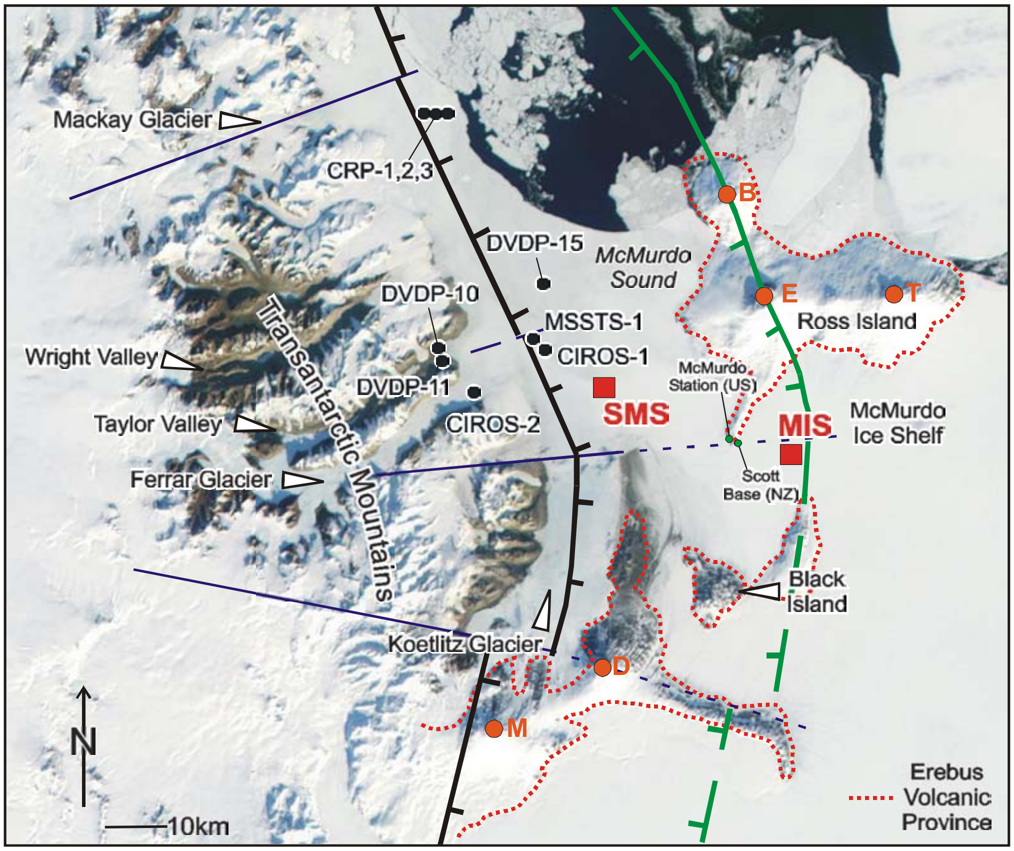


Figure 4. Location of key geographical and tectonic features in southern McMurdo Sound. Dotted coastline outlines the extent of the Erebus Volcanic Province (Kyle and Cole, 1974), while the volcanic centres of Erebus (E), Terror (T), Bird (B), Discovery (D), and Morning (M) are annotated. Drillsites of the currently approved Projects are shown: Southern McMurdo Sound (SMS) and McMurdo Ice Shelf (MIS). MIS and SMS are scheduled for drilling in 2006-2007 and 2007-2008 austral summers, respectively. Also shown are the locations of previous stratigraphic drill holes [DVDP, CIROS, MSSTS, and CRP] in McMurdo Sound (ANDRILL International Science Proposal, 2003). NASA MODIS image I.D.: Antarctica.A2001353.1445.250m.

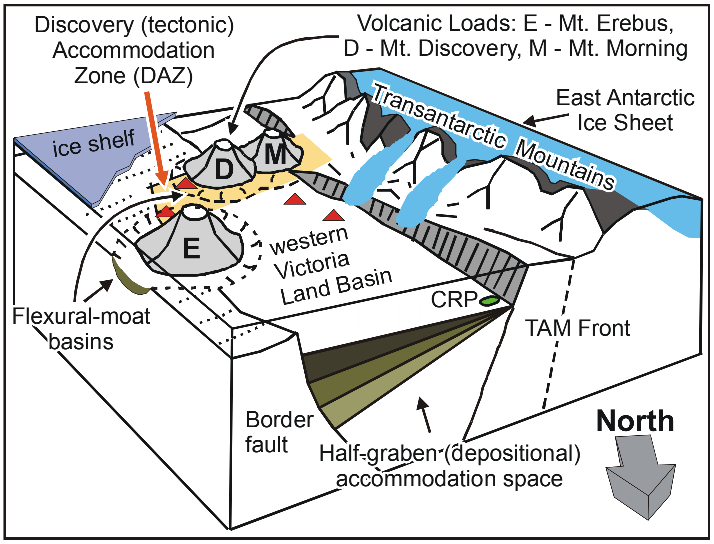


Figure 5. Schematic stratigraphic and structural cartoon of the Victoria Land Basin (VLB) shows development of accommodation space within a half graben, tilted to the east and bounded by a major down-to-the-west border fault system. These features control the stratigraphic architecture of the basin-fill, which dips and thickens to the east. The Discovery Accommodation Zone (DAZ) is a transverse element where the rift-flank steps westward ~100 km (T. Wilson, 1995). Localized accommodation space is superimposed on the rift basin where Neogene volcanoes of the Erebus Volcanic Province have progressively depressed the crust forming flexural-moat basins. The depositional accommodation space provided by the rift and flexural moat basins provides an unparalleled opportunity to recover stratigraphic records with high-resolution chronology provided by the dating of volcanic detritus integrated with biostratigraphic and magnetostratigraphic techniques (ANDRILL International Science Proposal, 2003).

The SMS and MIS Project Science Teams will develop a history of this region by studying cores from new and existing drillsites located in strategic areas (fjords, coastal margins, and open marine [SMS] to deep basin [MIS] environments). An integrated analysis of the cores will be used to develop regional depositional models for glacial and interglacial climate stages under both polythermal and cold-polar glacial-climate regimes (Fig. 6). The paleoenvironmental record of important climate events (e.g. Miocene climatic optimum, Pliocene climatic optimum, last glacial maximum) that characterize end-member climate states will be examined at locations where overlapping stratigraphic intervals are recovered. These new records will be considered within existing data from ice cores, drillcores and outcrop to establish environmental gradients from terrestrial highlands to deep marine basins that will enable examination of local and regional control of, or response to, various climatic, glacial and tectonic events and episodes. These events will be integrated with global event histories through refined chronostratigraphic age control provided by high precision iterative biostratigraphic, magnetostratigraphic and geochronologic synthesis using graphical correlation techniques such as CONOP-9 (Sadler & Cooper, 2003). The full impact of these events on the global system will be realized by input of results into climate and ice sheet models.

Processes within the depositional system in the SMS Project area are complex due to influence by the EAIS outlet glaciers (Ferrar, Taylor) and alpine glaciers in the Dry Valleys/TAM to the west (Blue, Koetlitz), by the RIS and Ross Ice Sheet to the east, and by open marine deposition during times of ice sheet and glacial retreat. Tectonic influences on sediment accumulation include variation in erosion and uplift, subsidence rates, location of depocenters, influence of volcanic loading, and changes in base-level due to all of the above. Provenance of sediment from the TAM (rich in basement rocks) or from the Ross Sea (rich in volcanic rocks) provides a means to interpret varying contribution from these various glacial sources. Sediment facies models developed for different periods of the Cenozoic and applied to CRP, Cenozoic Investigations in the Ross Sea (CIROS) and Dry Valley Drilling Project (DVDP) drillcores (Hambrey *et al*., 1989, 2003; Barrett & Hambrey, 1992; Fielding *et al*., 2000; 2001; Powell *et al*., 2000; 2001), will be compared for application to interpret the new ANDRILL drillcore records. A facies model developed to explain Neogene polythermal glacial deposition in large fjordal and valley outlet systems in other parts of Antarctica, such as the Prince Charles Mountains and Amery Embayment (Hambrey & McKelvey, 2000a; 2000b; Whitehead *et al*., 2003), will also be considered.

The SMS drill sites are bounded to the west by the TAM and the Dry Valley system, which previously drained the EAIS and local glaciers and ice caps of the TAM. The lower Taylor and Ferrar valleys cut through the 2000 m-high Asgard Range and Kukri Hills comprising Late Proterozoic or Early Paleozoic crystalline basement of the Ross Supergroup/ Skelton Group of metasediments and plutons, which were intruded by granite-gneiss dikes of the Granite Harbor Intrusives (Gunn & Warren, 1962; Porter & Beget, 1981). Gravity data suggest that these rocks also underlie McMurdo Sound. Nearly flat-lying Upper Paleozoic and Lower Mesozoic cratonic sedimentary rocks of the Beacon Supergroup overlie these basement rocks below McMurdo Sound and outcrop in the upper and western portions of Ferrar and Taylor valleys, 22 km west of SMS drillholes. Middle Jurassic Ferrar Dolerite sills and dikes intrude the basement and Beacon Supergroup strata, and were erupted as the Jurassic Kirkpatrick Basalt. The valleys in the Dry Valley system were cut by

Paleogene to Early Neogene ice from the EAIS and local TAM ice cap, through the modification of an existing fluvial drainage (Wrenn & Webb, 1982; Sugden *et al.*, 1995, 1999) and filled with deep-water fjord sediments that were uplifted during the Late Neogene (McKelvey, 1991; Ishman & Webb, 1988). Ice advance from the Ross Ice Sheet during the Last Glacial Maximum (LGM) and prior Quaternary glacial advances led to the deposition of glacial sediments rich in volcanic sediment across the coastal margin of the TAM and into the Dry Valleys (Figs. 6A upper right) (Vucetich & Robinson, 1978; Denton & Marchant, 2000).

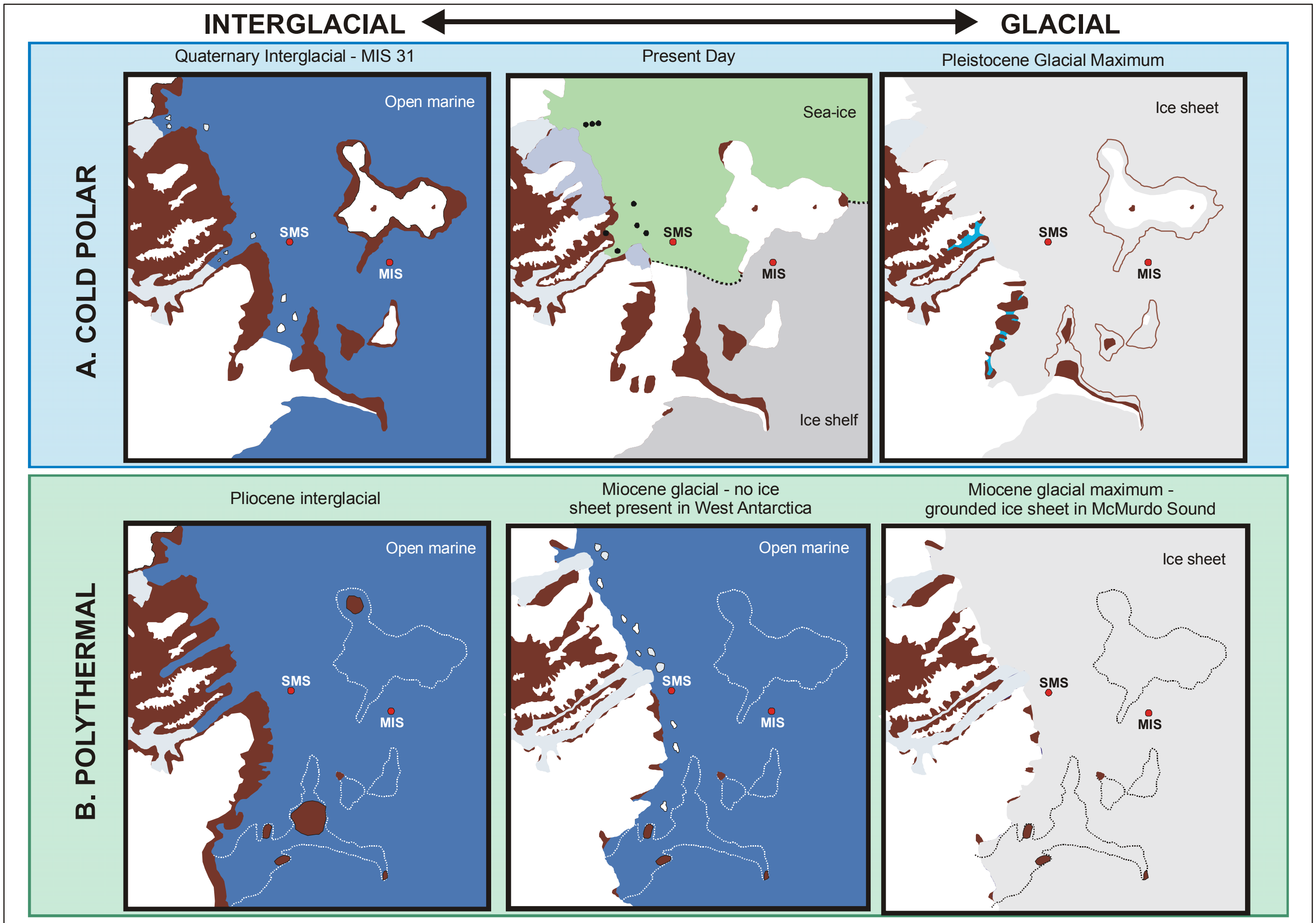


Figure 6. Present-day setting and hypothetical paleogeographic reconstructions of the McMurdo Sound region, showing the locations of current drilling projects, to illustrate generalized interglacial and glacial stages during two distinct climatic regimes. **A. The modern cold, polar glacial regime** of a frozen glacial bed, limited sediment erosion, transport and deposition, little to no meltwater, and the presence of sea-ice and ice shelves as common features of the marine system (?mid-late Neogene to Recent). **B. Warm, polythermal glacial regime** of a wet, active glacier bed, with abundant sediment erosion, transport, and deposition, limited sea-ice and ice shelf extent (late Paleogene to ?mid-late Neogene). Sedimentary processes in the McMurdo Sound region have changed through time due to variable influence of cryospheric components (sea-ice, ice shelf, valley glacier, and ice sheet), shoreline position (due to sea-level change), meltwater input, and katabatic wind strength and direction. Sediment sources have included the uplifting Transantarctic Mountains, eruptions from, and erosion of, numerous volcanic islands, and marine biogenic productivity. All sources provide useful information to aid paleoenvironmental reconstructions.

The TAM and Dry Valleys region is central to a debate regarding the history and character of the Neogene EAIS and southern high latitude climate evolution (Webb *et al.*, 1984; Denton *et al.*, 1984; Clapperton & Sugden, 1990; McKelvey, 1991; Webb & Harwood, 1991; Denton *et al.,* 1991; Sugden *et al.,* 1993; Marchant *et al.,* 1993, 1996; Wilson, 1995; Miller & Mabin, 1998; Wise, 2000). Divergent views persist, in part due to the lack of high-quality stratigraphic sections of marine middle and upper Miocene and Pliocene sediments from the Antarctic continent, proximal to the ice sheet's influence. New ANDRILL drillcore materials will aid in the reassessment of prior interpretations and lead to the development of new, regional depositional and paleoenvironmental models, which will help produce a clearer, more unified history of this complex region. Serendipitous discoveries such as the Quaternary carbonate unit in the CRP-1 drillhole (Bohaty *et al*., 1998; Taviani & Claps, 1998) will continue to reveal important new information. This unit, interpreted to represent an unsuspected 'interglacial' event (Figure 6A upper left) corresponding to Marine Isotope Stage 31 at 1.07 Ma, was deposited during a period of prolonged surface water warming in the absence of sea-ice and possibly the Ross Ice Shelf and WAIS.

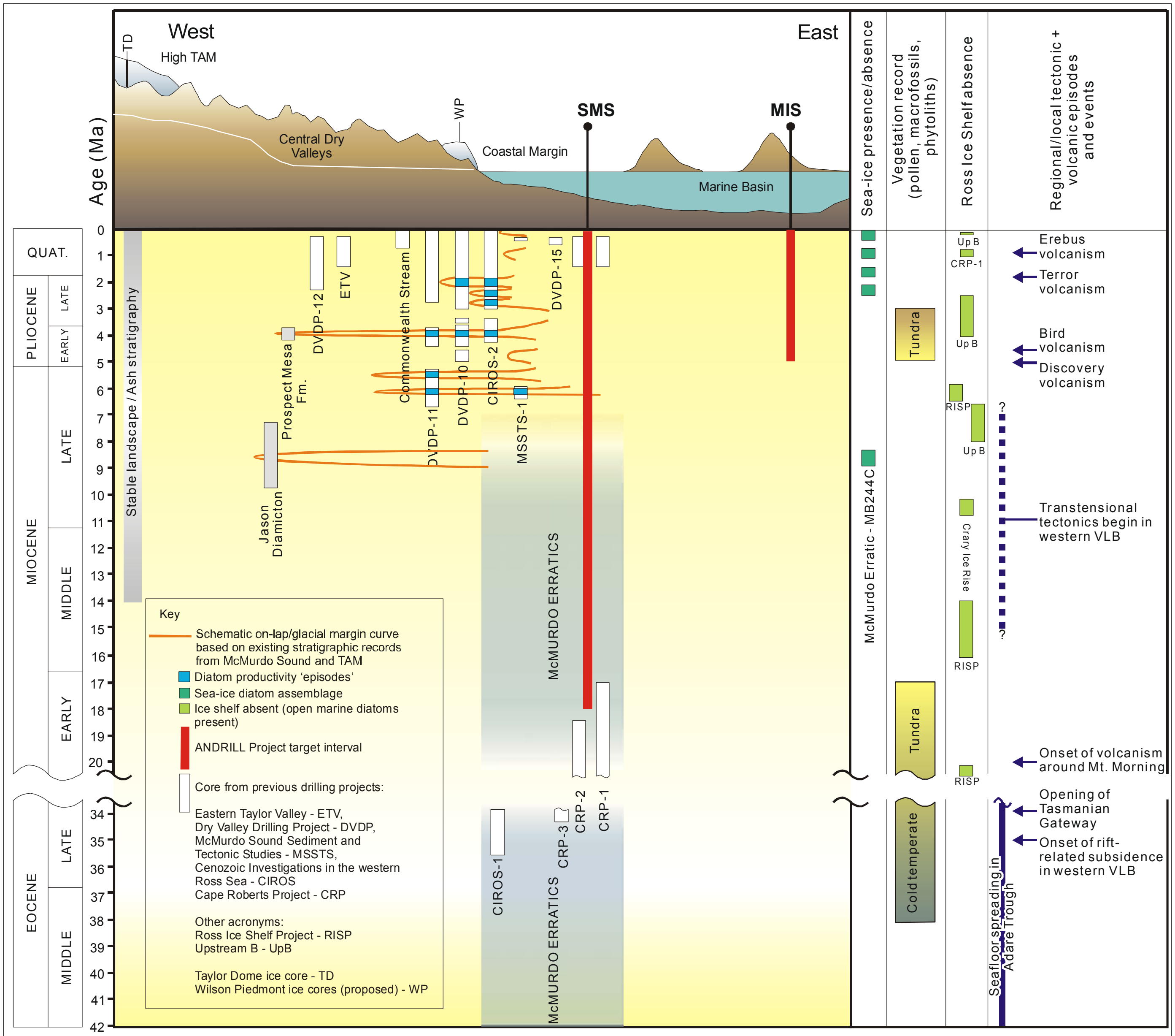


Figure 7. Composite space and time diagram indicating the geographic location of ANDRILL SMS and MIS Project drillsites within a transect from terrestrial highland to deep marine basin setting. The age range of target stratigraphic intervals is presented within the context of age and location of existing ice core, drillcore, and outcrop in this region. A schematic on-lap/glacial margin curve, developed from existing data, highlights a composite paleoenvironmental index of water-depth history, fjord incursion, sea-ice cover and ice shelf absence. The right side of the figure presents paleoenvironmental information about sea-ice presence (e.g. Harwood *et al*., 2002), absence of the Ross Ice Shelf (Harwood *et al*., 1989; Scherer et al., 1988; 1998), terrestrial vegetation in the Transantarctic Mountains (e.g. Askin & Raine, 2000), as well as volcanic episodes (e.g. Kyle, 1981) and timing of rift-related basin development (e.g. Hamilton *et al*., 2001; Fielding *et al*., in press).

Drillsites proposed for the SMS Project are located in the central portion of a Late Neogene west to east transect that will extend more than 150 km (Fig. 7), from inland fjord sites (upper Miocene Jason Diamicton [JD] and Pliocene Prospect

Mesa Gravels [PM]) of Wright Valley, (see Prentice *et al*., 1993), through coastal drillholes (DVDP-10, -11, -15; CIROS-2), past the SMS Project sites, and to a deep marine basin setting at the MIS drillsite located 50 km seaward of the Late Neogene coastline (Figs. 6, 7). Paleoenvironmental information recorded from numerous sites along this transect will help identify the relative input from each of the above glacial sources and provide a clearer picture of paleogeographic and paleoclimatic evolution of Southern Victoria Land. Moreover, SMS drillholes are well-connected to the grid of seismic lines in the VLB (Fig. 8). A mature chronostratigraphic framework will enable the full integration of the wealth of seismic data collected over the past two decades, as well as the dating of regional seismic surfaces and units important for interpreting regional stratal architecture and for dating Neogene and younger rift fault history.

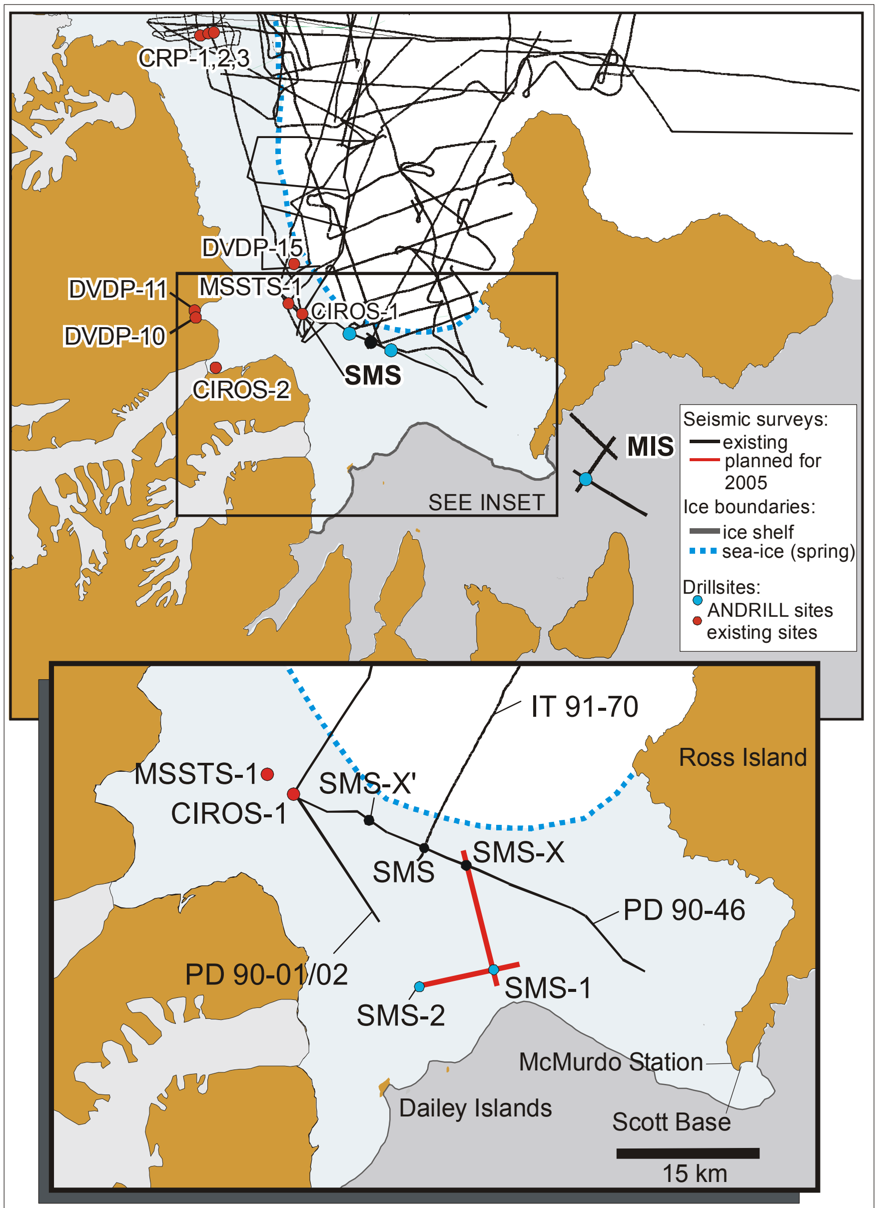


Figure 8: The stratigraphic architecture of the sediment fill of the western Victoria Land Basin in McMurdo Sound is known from the array of existing single channel and multichannel marine seismic data acquired in McMurdo Sound (black lines; Wong and Christoffel, 1981; Bartek and Anderson, 1991; Anderson and Bartek, 1992; Bartek *et al*., 1996; Brancolini *et al*., 1995; Melhuish *et al*., 1995; Hamilton *et al*., 2001; Horgan *et al*., 2005; Wilson *et al*., 2004). ANDRILL drillsites will provide critical new age control to interpret glacial and tectonic events from the seismic stratigraphic and regional basin framework defined by these geophysical surveys. The inset figure presents the location of seismic lines and proposed drillsites associated with the SMS Project. The SMS-X and SMS-X' sites indicate the location of stratigraphic intervals (Figs. 10, 11) identified from PD 90-46 to match the SMS Project objectives. The SMS-1 and SMS-2 sites reflect the approximate location of the primary SMS drillsites, the location of which will be identified on two new seismic lines to be collected in Oct.-Nov. 2005.

ANDRILL's SMS Project Science Team members will document and describe new stratigraphic sequences that will build on our understanding derived from existing interpretations of late Miocene through Pleistocene glacial and climatic history from the DVDP-10, -11, 12 & -15, McMurdo Sound Sediment and Tectonics Study (MSSTS) and CIROS-2 drillcores (Chapman-Smith, 1975; McKelvey, 1981; Barrett & Treves, 1981; Porter & Beget, 1981; Harwood, 1986b; McKelvey, 1991; Barrett & Hambrey, 1992; Ishman & Rieck, 1992; Wilson, 1993; Hambrey & Barrett, 1993; Winter, 1995: Winter & Harwood, 1997). These drillcores and outcrops of marine strata in the Dry Valleys (Webb, 1974; Prentice *et al.,* 1993) suggest a late Miocene to Pleistocene history of 'glacial' advance and 'interglacial' retreat of glaciers with associated marine incursion in the Taylor and Ferrar valleys (Figs. 6, 7). Various influences on deposition and sediment sources are reflected in the interbedded diatomaceous mudstone and diamicton, as well as the varying composition of sands from volcanic (Ross Sea source) to basement and Beacon Supergroup (EAIS and TAM source) (Fig. 9).

Repeated marine incursions occurred deep into the Taylor and Ferrar paleofjords (Figs. 6B lower left, 7), as indicated by the presence of marine sediment of the Jason Diamicton (upper Miocene) and Prospect

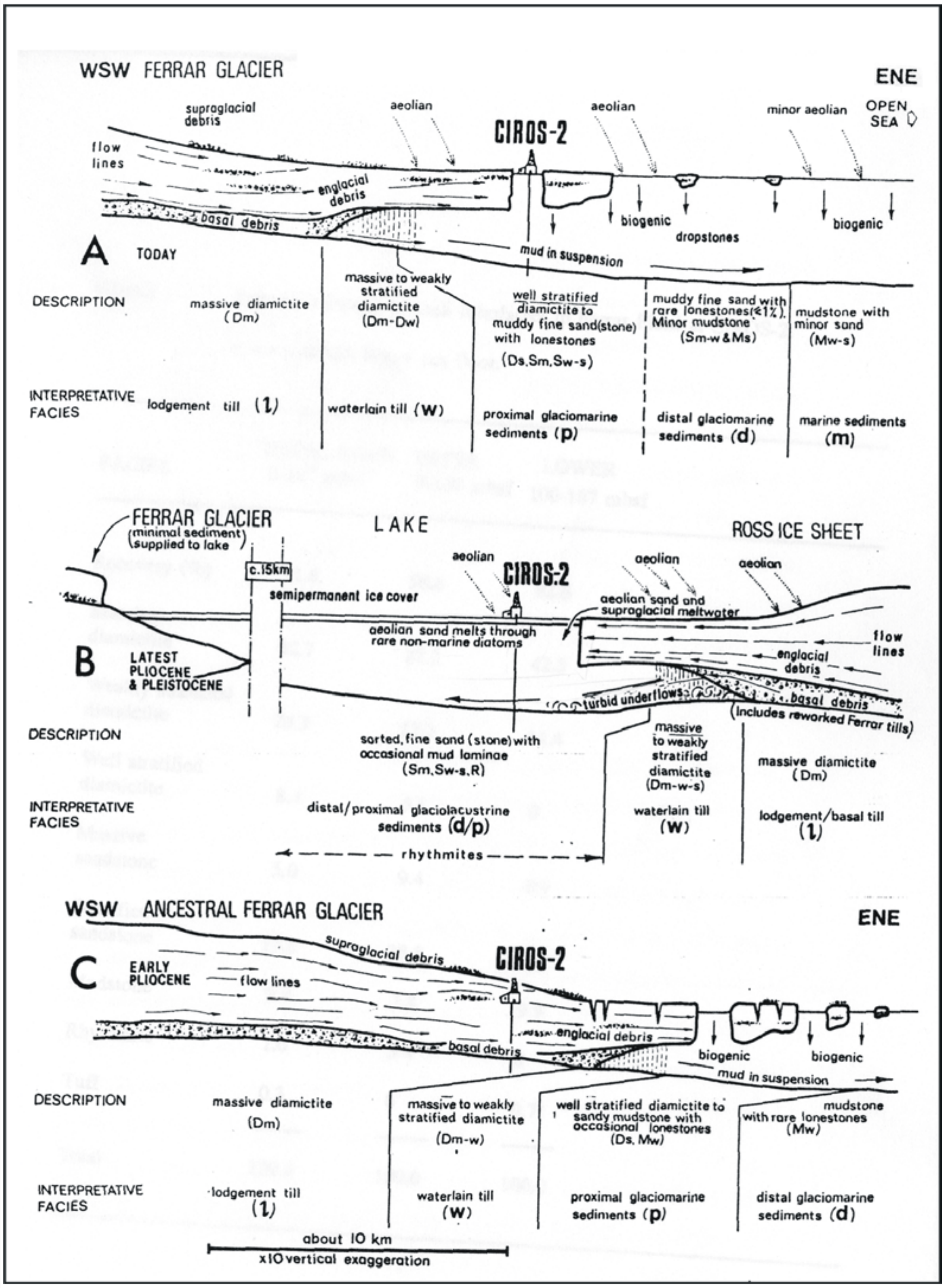


Figure 9. Models for sedimentation in Ferrar Fjord (from Barrett and Hambrey, 1992). The floating glacier tongues are inferred by analogy with modern Ferrar and Mackay glacier tongues today, and supported by lack of any indication of meltwater flows both now and in the CIROS-2 record. A) setting today; B) Setting during deposition of the Pleistocene sandstone beds; C) Setting during the deposition of diamictites derived form Ferrar Glacier; D) The fourth model, not illustrated, would illustrate the absence of ice in Ferrar Fjord and marine conditions in the absence of sea-ice and ice shelf influence.

Mesa Gravels (lower to mid-Pliocene) in central Wright Valley (Webb, 1972, 1974; Prentice *et al.,* 1993). The development of the Late Neogene McMurdo Volcanic province contributed a new sediment source into the McMurdo Sound region. This also resulted in significant modification of McMurdo Sound paleogeography and basin subsidence due to the emergent islands and volcanic load (Kyle, 1981; 1990a, 1990b). Volcanic sands present in the upper intervals of DVDP-10, -11, and –15 and in deposits along Commonwealth Stream (Vucetich & Robinson, 1978) were deposited beneath an ice-covered lake, formed by the damming of valley drainage by the grounded paleo-Ross Ice Sheet (Fig. 9). Ice from a grounded Ross Ice Sheet expanded at least 4 times, perhaps more, up and into the mouths of the Dry Valleys (Denton *et al*., 1970, 1971). Similar fluctuations in the volume and extent of ice from the Taylor and Ferrar outlet glaciers left a record of multiple events that reflect changes in the volume discharge of the EAIS.

SOUTHERN MCMURDO SOUND PROJECT (SMS)

Overview

The SMS Project plans to drill strata from the western flank of the VLB, in two drillholes that together will recover a composite stratigraphic section to address key questions in the climate evolution of the southern high latitudes. These drillcores will sample several units of multiple clinoform sequences identified in seismic refection data. These units are separated by seven distinct seismic surfaces, three of which are widespread erosional surfaces. A composite thickness of >1000 m of strata targeted by the SMS Project lie stratigraphically above the lower Miocene section recovered at the top of the nearby CIROS-1 drillcore (~23 Ma from Roberts *et al*., 2004), and above the

1400 m composite section recovered by the CRP (~34 to 17 Ma) (Davey *et al.*, 2001; Florindo *et al.,* 2005). Recovery of portions of expanded lower, middle, and upper Miocene sections (<17 Ma) is anticipated (see below). Two offset drillholes are required for the SMS Project to ensure the persistence of a diatom fossil record through all recovered strata, by minimizing the potential for diagenetic loss of opaline silica known from deep boreholes (>500 m) in this region.

Victoria Land Basin History Relative to the SMS Project

The recovered strata, and intervals to be recovered by the ANDRILL Program, represent sedimentation on the margin of the Victoria Land Basin. Older portions of the VLB sediment fill were recovered in CIROS-1 (Barrett, 1989) and the CRP (Davey *et al*., 2001; Cape Roberts Science Teams, 1998a, 1998b, 1999, 2000a, 2000b, 2001). Younger intervals of basin fill were recovered in DVDP-10, 11, and 15 (e.g. McGinnis, 1981 and references therein; Brady, 1982; Ishman and Rieck, 1992) and CIROS-2 (Barrett and Scientific Staff, 1985; Barrett and Hambrey, 1992; Winter, 1995). Additional records of Neogene fill will be recovered in 2006 by the MIS Project (anticipated Pliocene to Recent) and recovered in 2007 by the SMS Project (anticipated middle Miocene to Quaternary). The evolution of the VLB is reviewed in Fielding *et al*. (in press) and summarized below, with attention to the younger Phases 4 and 5 that influenced subsidence and accommodation space for the time interval of interest to the SMS Project.

The VLB is a structural half-graben, approximately 350 km-long, hinged on its western side at the TAM front (Fitzgerald, 1992; T. Wilson, 1995; 1999) (Fig. 3). Major rifting in the VLB has occurred since the latest Eocene, perhaps having been initiated in the Cretaceous, and has accommodated up to 10 km of sediment (Cooper & Davey, 1985; Brancolini *et al*., 1995). Late Cenozoic extension in the VLB is associated with alkalic igneous intrusions (e.g. Beaufort Island and Ross Island) and led to the development of the Terror Rift (Cooper *et al.*, 1987).

Upper Eocene sediments are the oldest post-Paleozoic sediments recovered to date by stratigraphic drilling along the western margin of the basin. These Eocene strata unconformably overlie Devonian sediments of the Taylor Group (Davey *et al.*, 2001). Since the late Eocene, sedimentation along the western margin of the VLB has evidently kept pace with or exceeded the rate of subsidence, resulting in the development of a 1.5 to 2 km-thick sediment wedge, which increases in thickness eastward into the Terror Rift to a maximum of approximately 10 km (T. Wilson, 1999).

The wedge comprises glacimarine strata of conglomerate, diamict, and sandstone with interbedded mudstone of nearshore and shelf affinity (Barrett, 1989; Cape Roberts Science Teams, 1998a, 1998b, 1999, 2000a, 2000, 2001; Florindo *et al*., 2005). Numerous unconformities occur within the Oligocene and Miocene strata recovered in CIROS-1 and CRP drillcores (Fig. 3). A number of these unconformities have been correlated with sub-horizontal erosion surfaces in regional seismic lines (Henrys *et al.*, 2000; Fielding *et al.*, 2001), implying widespread grounding of an extensive ice terminus on the continental shelf during glacial periods. Coastal glacier behaviour has been linked to mass changes in the interior EAIS, which feeds through outlet glaciers in the TAM during glacial periods (Wrenn & Webb, 1982; McKelvey, 1991; Barrett & Hambrey, 1992).

The youngest part of the lower Miocene section in CRP-1 and CRP-2/2A comprises thin (<20 m-thick), diamictite-dominated and strongly top-truncated sequences (Fielding *et al*., 1998, 2000). This section corresponds to an interval of well-defined, continuous, mainly parallel and concordant, clinoform reflections on seismic data, and is interpreted as the record of basin evolution Phase 4 (Thermal Subsidence) of Fielding *et al*. (in press). This sequence character is attributed to a slower rate of subsidence (accommodation) relative to the earlier rifting phases, leading to greater erosional removal of the upper (highstand) parts of sequences during the following falling stage and lowstand, and is markedly different from the thicker and more complete sequences accumulated during earlier phases (Fielding *et al*., 2000; Naish *et al*., 2001a). This character is interpreted to persist beyond the top of the lower Miocene section penetrated by CRP (seismic reflector "a" [beige] in Fig. 10 and in Fielding *et al.,* in press). Fielding and others (in press) have also identified the reflector "g" (chartreuse), which is interpreted to record (approximately) the onset of asymmetrical subsidence related to formation of the Terror Rift.

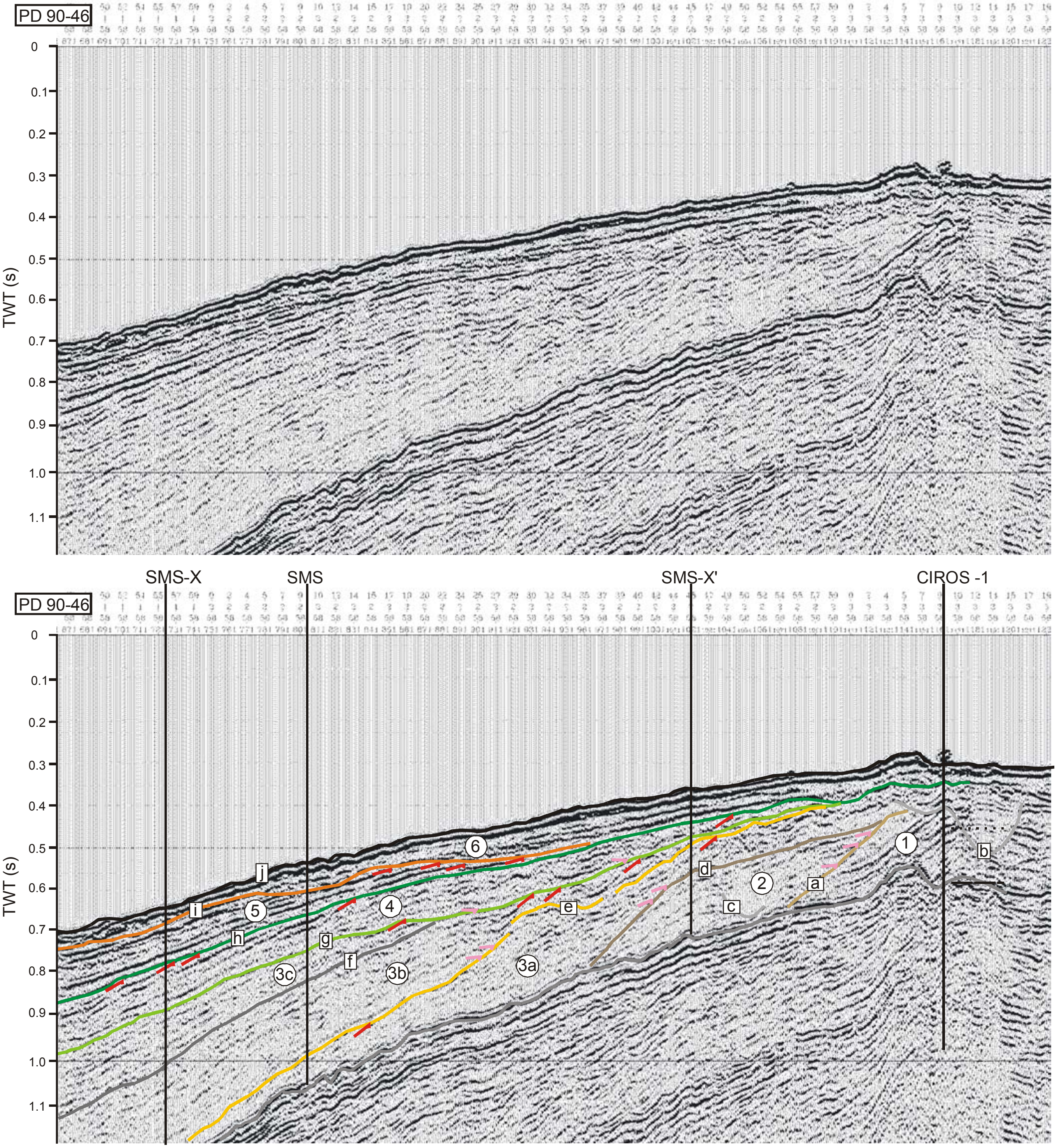


Figure 10. Seismic profile along line PD 90-46 (Fig. 8) showing the stratal geometry of Seismic Units 1 to 6. Two erosional surfaces 'a' (beige) and 'h' (dark green) bound a wedge of sediment that thickens basinward. The >1000 m-thick section above surface 'a' is less than 17 million years old, as indicated through regional correlation of this surface to the CRP-1 drillcore, and is the target of the SMS Project. The SMS-X (near 500 m isobath) and SMS-X' (near 300 m isobath) sites identify the approximate stratigraphic sections (Fig. 11) to be recovered by SMS Project drilling. Equivalent stratigraphic intervals will be drilled at the SMS-1 and SMS-2 sites, which will be located along new seismic lines to be collected in 2005 south of this line (Fig. 8). Seismic units are indicated by numbers 1 (oldest) to 6 (youngest) and bounding reflection surfaces are indicated by letters 'a' (beige) through 'i' (orange).

The causal mechanisms and resulting stratigraphy of the Terror Rift (basin evolution Phase 5) cannot as yet be constrained with any certainty, but a thick (< 1-2 km) section is preserved in depocentres. This succession can be divided into two intervals by Fielding *et al.* (in press), which constitutes a major angular unconformity across much of the basin. The degree of angularity seems to increase progressively on approaching the western shore of McMurdo Sound, suggesting that reflector “h” (dark green) may be associated with either an uplift event in the TAM, or local tilting of a rift fault-block. The age of this event is also open to uncertainty that may be resolved by the SMS Science Team. Although event “h” (dark green) is overlain by Pliocene strata in MSSTS drillhole (Harwood, 1986a), the basin-marginal location of these drilling sites means that successive seismic sequence boundaries have converged and become amalgamated in these areas, and therefore a significant amount of section from above the “h” event (dark green) may be missing.

The Terror Rift (Phase 5 of Fielding *et al*., in press) succession has not yet been sampled beyond the thin, near-surface intersections in MSSTS-1, CIROS and CRP holes. However, it seems likely that since this interval appears to be associated with accelerated rates of subsidence, its sequence character should contrast with that associated with the underlying Thermal Subsidence (Phase 4) described above.

If the climatic regime at this time (early Miocene or younger) was still humid, then the sediment supply would have been comparable to that of the earlier Miocene and thus depositional cycles (sequences) should be relatively thick (at least tens of meters), complete (in terms of systems tracts) and not severely top-truncated by erosion. If, on the other hand, the present-day cold, polar regime had been established by this time (and thus the supply of terrigenous clastic debris drastically reduced), then depositional sequences should be relatively thin and condensed, but still complete in terms of systems tracts since tectonic subsidence is the principal control on accommodation at this time regardless of climate. Resolving the character and age of the Neogene sedimentary wedge along the western margin of the VLB will lead to answers of key questions regarding Late Neogene climate and tectonic history of this region.

One of the principal challenges in the interpretation of stratigraphic sequences recovered by future drilling in McMurdo Sound will be the separation of tectonic signals from those brought about by climate change.

Existing Seismic Information

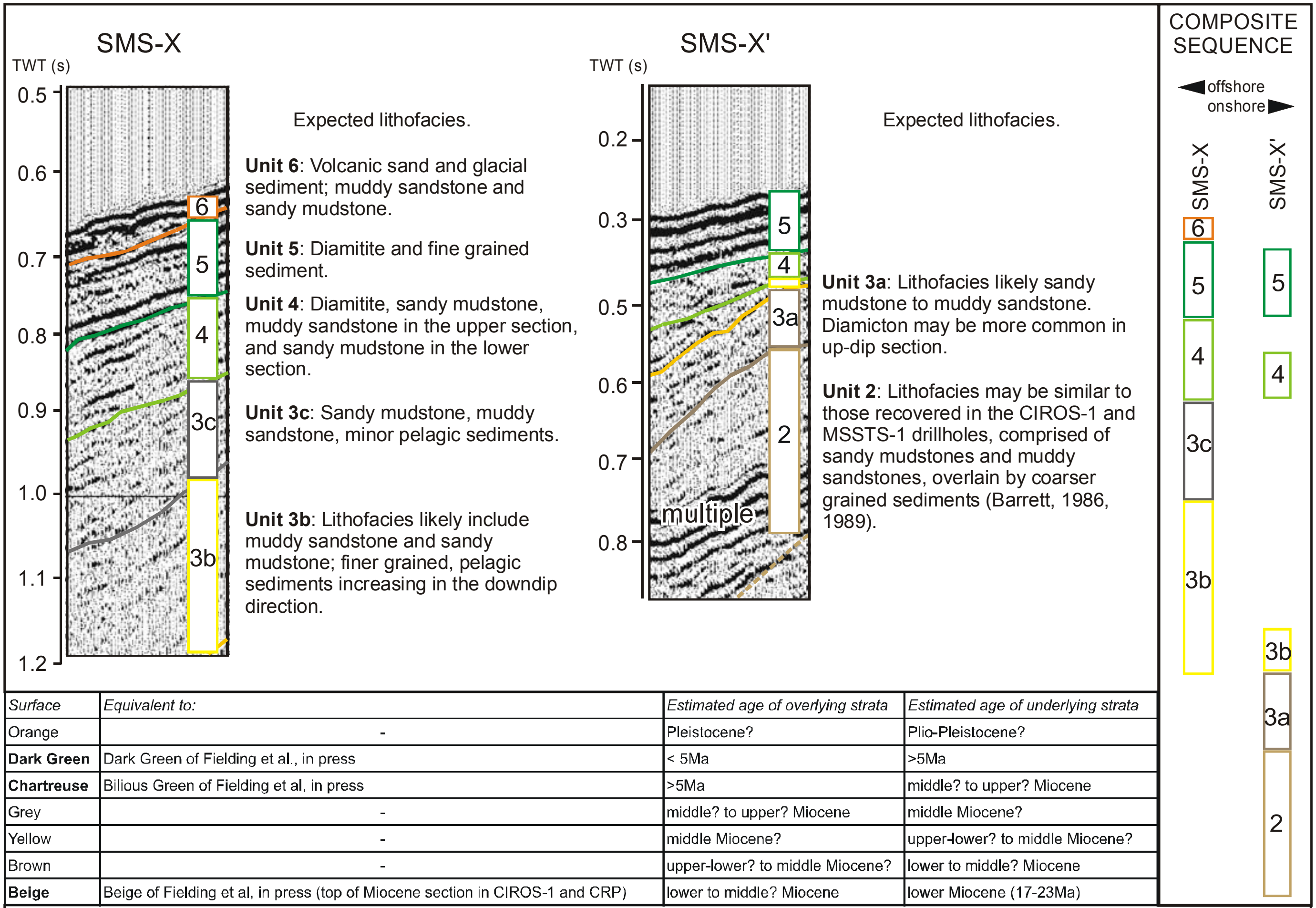
Target strata for the SMS Project are identified on seismic lines PD90-46 [Figs. 8, 10] and PD90-01/02 obtained from *Polar Duke* during the austral summer of 1990 (Anderson & Bartek, 1992; Bartek *et al*., 1996). The interpretation of line PD90-46 differs from that presented by Bartek *et al.* (1996). The portion of this seismic line presented in Figure 10 was reinterpreted by C. Fielding, D. Harwood, R. Levy and S. Pekar in 2003. These strata have been subsequently tied into a broader analysis of seismic sequences as part of a larger project to characterize deformation in the VLB associated with the Terror Rift by C. Fielding, S. Henrys and T. Wilson in 2004. The interpretation of seismic reflectors as unit boundaries is based on identification of truncations / nonparallel geometry in relation to other reflectors, such as offlapping, onlapping, downlapping, and erosional truncations. Seismically bland units may represent bodies of homogenous lithofacies (thick sand or mud).

The SMS Project intends to recover a stratigraphic section that includes a substantial portion of late early Miocene to Quaternary time. Strata of this age are identified along seismic line PD-90-46 as a multiple sequence of clinoform reflectors, which define stratigraphic units that expand basinward (Fig. 10). A strategy to drill at two drillsites will lead to the recovery of a composite thickness of >1000 m of strata identified through interpretation of seismic stratigraphy (Fig. 11). These units lie stratigraphically above a regional erosion surface (seismic reflector “a” - beige) that truncates the upper Eocene to lower Miocene section recovered by the CIROS-1 drillcore (Roberts *et al*., 2005), and also truncates the uppermost lower Miocene (<17 Ma) strata at the top of the 1400 m composite section recovered by the CRP (~34 to 17 Ma) (Davey *et al*., 2001; Florindo *et al.,* 2005). The youngest strata known to be truncated by this reflector are latest early Miocene (<17 Ma). This indicates that the entire section to be sampled by the SMS Project above seismic reflector “a” (beige) is less than 17 m.y. old. The stratigraphic sequences of interest are identified on seismic lines PD90-46 (Figs. 10, 11) as a younger (‘down-dip’) sequence at SMS X and an older (up-dip’) sequence at SMS X’. The SMS drillsite proposed within the ANDRILL International Science Proposal (AISP, 2003) was located at the intersection of this line with seismic line IT91-70 (Figs. 8, 10), at a position between the SMS-X ‘down-dip’ and SMS-X’ ‘up-dip’ sites.

Site Survey

Results of a risk analysis on the proposed SMS site (Falconer & Pyne, 2004) indicate that on an annual basis there is a 7% chance that sea-ice conditions at this primary SMS site will meet minimum requirements for drilling. Alternate sites over the same stratigraphic sequences are sought south and west of the proposed SMS site in order to meet minimum sea-ice thickness requirements for successful drilling in this region; these new sites are labeled SMS-1 and SMS-2 (Fig. 8).

An over-sea-ice, multichannel seismic survey, using an air-gun and snow streamer is planned for October-November 2005 to identify the SMS-1 and SMS-2 drillsites on a region of more stable, secure sea-ice. The new seismic data will allow southward mapping of the seismic sequences identified on PD-90-46 and enable resolution of stratal architecture below the sea-floor multiple. One 15 km seismic line will extend southward from the PD90-46 line east of the proposed SMS site (Fig. 8) along strike to select the location of the SMS-1 drillsite at the end of this new line. A section equivalent to that identified at SMS-X (Figs. 8, 10, and 11) is anticipated at the SMS-1 site. As evident on seismic profile PD90-46, the upper intervals of Seismic Units 3c, 4 and 5 are truncated at the SMS site. However, in slightly deeper water on the 500 m isobath, all of these Seismic Units have more complete upper intervals, with an increase by ~40% (Fig. 10). A 5+ km seismic line is also planned as part of this survey to extend westward (up-dip) from the SMS-1 site (Fig. 8) to identify the location of the SMS-2 drillsite. A section equivalent to that identified at SMS-X’ (Figs. 8, 10, and 11) is anticipated at the SMS-2 site. Results from the 2005 seismic survey will produce the requisite new information to select the drillsites for the SMS project.



Expected lithofacies.

Unit 6: Volcanic sand and glacial sediment; muddy sandstone and sandy mudstone.

Unit 5: Diamitite and fine grained sediment.

Unit 4: Diamitite, sandy mudstone, muddy sandstone in the upper section, and sandy mudstone in the lower section.

Unit 3c: Sandy mudstone, muddy sandstone, minor pelagic sediments.

Unit 3b: Lithofacies likely include muddy sandstone and sandy mudstone; finer grained, pelagic sediments increasing in the downdip direction.

Expected lithofacies.

Unit 3a: Lithofacies likely sandy mudstone to muddy sandstone. Diamicton may be more common in up-dip section.

Unit 2: Lithofacies may be similar to those recovered in the CIROS-1 and MSSTS-1 drillholes, comprised of sandy mudstones and muddy sandstones, overlain by coarser grained sediments (Barrett, 1986, 1989).

Surface	*Equivalent to:*	*Estimated age of overlying strata*	*Estimated age of underlying strata*
Orange	-	Pleistocene?	Plio-Pleistocene?
Dark Green	Dark Green of Fielding et al., in press	< 5Ma	>5Ma
Chartreuse	Bilious Green of Fielding et al, in press	>5Ma	middle? to upper? Miocene
Grey	-	middle? to upper? Miocene	middle Miocene?
Yellow	-	middle Miocene?	upper-lower? to middle Miocene?
Brown	-	upper-lower? to middle Miocene?	lower to middle? Miocene
Beige	Beige of Fielding et al, in press (top of Miocene section in CIROS-1 and CRP)	lower to middle? Miocene	lower Miocene (17-23Ma)

Figure 11. Stratigraphic prognosis for the SMS Project drill sites. Seismic data and interpretations are from PD 90-46. We anticipate that similar sections occur further south along strike at sites to be identified following a geophysical survey to be conducted in October 2005. Several surfaces (shown in bold in the table) identified in PD 90-46 have been mapped regionally and can be correlated to the CIROS-1 and CRP drill sites providing reasonable age control on strata above and below these surfaces. Drilling at two sites (SMS-X and X') will allow recovery of a complete composite section comprising seismic units 2-6. Furthermore, recovery of time-correlative units from two geographic locations will allow characterization and analysis of nearshore to offshore variation in both litho and biofacies.

Description of Seismic Sequences

The seismic units and reflectors identified in line PD 90-46 (Fig. 10) are described below from oldest to youngest.

Seismic Unit 1
Defined by: Stratigraphic interval between the disconformity spanning >9 m.y. recognized at ~366 mbsf in the CIROS-1 drillcore up to seismic reflector "a" (beige) (Fig. 10).
Expected sediment type: sandy mudstone, muddy sandstone, and diamicton, as recovered in the CIROS-1 drillcore (Barrett, 1989).
Discussion: This unit is likely correlative to the interval recovered in the CIROS-1 drillcore between 366 and 54 mbsf. This is the oldest unit observed on the PD90-46 seismic line (Fig. 10). Seismic Unit 1 dips basinward below the water multiple and is truncated above by reflection surface "a" (beige). Regional correlation of reflection surface "a" (beige) by S. Henrys, C. Fielding and T.Wilson indicates that it truncates the top of the lower Miocene interval recovered at CIROS-1 at ~23 Ma and truncates the upper portion of the lower Miocene sequence recovered by the CRP (~17 Ma). All of the reflectors slope downward toward the southeast and northeast (oblique to dip, due to the turn in line PD90-46 [Fig. 8]). A large-scale channel-form reflection "b" is noted within Seismic Unit 1 (Fig. 10).

Beige Reflector "a"
Seismic refector "a" truncates Seismic Unit 1. Its local geometry near CIROS-1 drillcore (Fig. 10) is characterized by a clinoform rollover with prominent onlapping reflectors truncating against the clinoform rollover. The character of this reflection surface cannot be determined in line PD90-46 due to the sea-floor multiple.

Seismic Unit 2
Defined by: Stratigraphic interval from seismic reflector "a" (beige) up to seismic reflector "d" (brown).
Discussion: Most reflectors within this unit are relatively weak and truncate up-dip against the clinoform rollover defined by seismic reflector "a" (beige). They are subparallel to the surface of the upper bounding reflector "d" (brown). A channel-form reflection "c" is noted within Seismic Unit 2. Channel-form "c" appears to be overlain by parallel, gently inclined, reflectors, indicating that incision and subsequent fill both occurred during deposition of Seismic Unit 2.

Brown Reflector "d"
Seismic reflector "d" (brown) is characterized by a pronounced clinoform rollover, with onlapping reflectors, that disappears below the sea-floor multiple reflection. Updip, it truncates against reflector "a" (beige).

Seismic Unit 3a
Defined by: the stratigraphic interval between seismic reflector "d" (brown) and seismic reflector "e" (yellow).
Discussion: This unit is truncated by surface "g" (chartreuse) and "h" (dark green) near CIROS–1 updip and thickens basinward. Internal reflectors are characterized by strong-amplitude, hummocky geometry up-dip above shotpoint 941, and gradually become sub-parallel and faint further down-dip before they disappear below the sea-floor multiple.

Yellow Reflector "e"
This prominent reflector amalgamates with the overlying reflectors "g" (chartreuse) and "h" (dark green). Updip, it is a strong reflection with a hummocky appearance with a concave geometry between shot points 921 and 1021. Further downdip, this reflector becomes less apparent. It is defined by truncating reflectors that onlap onto it, especially in the lower section. Reflector "e" (yellow) also has a prominent clinoformal geometry between shot points 881 and 941.

Seismic Unit 3b
Defined by: Stratigraphic interval from seismic reflector "e" (yellow) to seismic reflector "f' (grey).
Discussion: This unit extends downdip from shot point 1021, where the upper portion of this unit is truncated by what appears to be a major erosional surface "g" (chartreuse). Reflectors in the interval down-dip of shotpoint 881 are relatively faint. This unit thickens immediately down-dip of the clinoform rollover contained within reflector "e" (yellow) between shotpoints 941 and 1001.

Grey Reflector "f"

This reflector "f" (grey) truncates against the overlying chartreuse reflector at shot point 871. It is characterized by offlapping reflections.

Seismic Unit 3c

Defined by: Stratigraphic interval between seismic reflector "f" (grey) and underlying seismic reflector "g" (chartreuse).
Discussion: Reflectors within this unit are mainly parallel and transparent. This unit pinches out against the chartreuse reflector "g" updip and is bounded below by the grey reflector "f". Although offlapping is a prominent characteristic of seismic reflector "g" (chartreuse), it is fairly rare further outboard near proposed site SMS. Seismic reflections are relatively faint in this unit, suggesting uniform sediment accumulation.

Chartreuse Reflector "g"

Seismic reflector "g" (chartreuse) amalgamates up-dip with reflecting surface "e" (yellow) before they offlap from the dark green reflector "h". A second strong reflector appears to mirror it above until around shot point 931. Offlapping becomes more prevalent immediately downdip of where the twin reflector ends.

Seismic Unit 4

Defined by: Stratigraphic interval between seismic reflector "h" (dark green) and underlying seismic reflector "g" (chartreuse).
Discussion: The upper surface "h" (dark green) is characterized by major offlapping, indicating a major erosional event. This suggests a disconformity across this surface. The seismic reflections immediately below are characterized by stronger reflection in the upper interval and lower impedance contrasts in the lower interval. Seismic reflection character is hummocky with moderate to strong amplitude reflections in the updip section. Near the proposed SMS-1 borehole (at the 400 meter isobath), seismic reflections become less hummocky and more parallel downdip.

Dark green Reflector "h"

This reflector "h" truncates numerous reflectors of underlying Seismic Unit 4.

Seismic Unit 5

Defined by: Stratigraphic interval between seismic reflector "h" (dark green) and underlying seismic reflector "i" (orange).
Discussion: This unit pinches out updip at shot point 961. It is characterized by strong amplitude, internal, parallel seismic reflections. These seismic reflections mainly parallel the dark green reflector and are truncated by the overlying orange reflections.

Orange Reflector "i"

This reflector "i" at the base of Seismic Unit 6 onlaps the dark green reflector "h" near shot point 961. It is characterized by offlapping of the underlying reflectors and downlapping of the overlying reflectors, consistent with erosional slope processes.

Seismic Unit 6

Defined by: Stratigraphic interval from sea-floor down to seismic reflector "i" (orange) downdip, and seismic reflector "h" (dark green) updip.
Discussion: This uppermost seismic unit occurs between the sea floor and above the dark green reflector "h" updip of shot point 961, and above the orange reflector "i" downdip (Fig. 10). It is characterized by strong amplitude reflections updip, thinning slightly downdip.

Inferred History of Neogene Sediment Accumulation

We can estimate the amount of time that may be represented in the composite >1000 m section above seismic reflector "a" (beige) by comparing sediment accumulation rates known from the western McMurdo Sound region. The CIROS-1 and CRP drillholes accumulated sediments during the early Miocene and late Oligocene at rates of 30 to 50 m/m.y. and 100 to 120 m/m.y., respectively. Given these rates, it is reasonable to assume that a considerable portion of middle and upper Miocene time (17 to 5 Ma) may be recovered within the >1000 meter composite SMS stratigraphic section. These sediment accumulation rates suggest that a discontinuous stratigraphic interval representing ~8 to ~17 million years of time could be represented in the composite two SMS Project drillholes (Fig. 11).

Upper Oligocene and lower Miocene seismic reflections are characterized by a clinoformal geometry in the southern portion of seismic line PD90-46. Above these clinoforms in Seismic Units 3a to 3c are hummocky reflectors, which could represent erosional/channelized surfaces either due to subaerial exposure or glacial action. Further downdip and just updip of the proposed SMS drillsite, these reflectors lose their hummocky characteristics, suggesting that erosional processes may have been less downdip. A progradational geometry appears to have continued through the early to perhaps middle Miocene. However, at some point during the Miocene, major erosional events took place (i.e. chartreuse "g" and dark green "h" reflectors), which is based on extensive truncations observed on the seismic profiles. It can be speculated that these erosional events shaved off the tops of the clinoforms. This is supported by the idea that in updip and shallower seismic profile PD90-01/02 (Fig. 8) correlative seismic reflectors appear to more heavily truncated compared to those in profile PD90-46.

The following summary presents a tentative history of paleoenvironmental and tectonic events that influenced sediment accumulation on the western margin of southern McMurdo Sound. Although chronostratigraphic control is available for only a few levels in the sedimentary package identified on seismic line PD90-46, a sequential history can be inferred from: (1) the seismic sequences that reflect progradation, truncation, incision and apparent transgression; (2) information known from local drillholes and outcrops in the Dry Valley region; (3) rift and volcanic history in the VLB; and (4) regional and global influences. The sequence, timing and magnitude of the events outlined here will be more clearly resolved with the study of SMS drillcores and integration of new information into a regional and global context. Figures 1, 7, 10 and 11 are of use in tracking this history.

Early Miocene:

Deposition of lower Miocene strata of Seismic Unit 1 at the CIROS-1 and MSSTS drillcores. CIROS-1 penetrated and recovered ~300 meters of this unit, above 366 mbsf (Fig. 10). Regional seismic correlations indicate this sequence is correlative with the lower Miocene interval recovered at the CRP-1 drillcore (17 to 21 Ma) (Cape Roberts Science Team, 1998a, b).

Truncation of Seismic Unit 1 against seismic reflector "a" (beige). This reflector truncates lower Miocene strata of 23 Ma age at CIROS-1 (Fig. 10), but the youngest sediments cut by this reflector are from 17 Ma at the CRP-1 drillcore. This indicates that this erosional event is younger than 17 Ma.

Regional influences and events: Thermal Subsidence Phase 4 of VLB evolution (Fielding *et al*., in press).

Global influences and events: Start of the Miocene Climatic Optimum (Fig. 1).

Early? to Middle? Miocene:

Deposition of Seismic Unit 2. This unit is the next outboard clinoform sequence from Seismic Unit 1, which is correlated to latest Oligocene to earliest Miocene sediments in the CIROS-1 borehole (Fig. 10). However, the age of Unit 2 is likely significantly younger than the sediments recovered at CIROS-1 because reflectors in underlying Seismic Unit 1 are heavily truncated by reflector "a" (beige), which occurs at the base of Seismic Unit 2 and suggests significant erosion and associated missing 'time'. Furthermore, the age of strata underlying the "a" (beige) reflector at CRP is ~ 17 Ma. Therefore, onlap of reflectors in Seismic Unit 2 onto reflector "a"(beige) indicates deposition of Unit 2 likely began after ~17 Ma.

Incision of channel-form "c" into Seismic Unit 2 (Fig. 10). This incision may be due to: (1) erosion by expanded paleo-Ferrar and paleo-Taylor glaciers; (2) glacial or fluvial erosion during a eustatic lowstand; (3) erosion from feeder channels to basin fans, as operating today in southern McMurdo Sound; or (4) as subglacial tunnel-valleys. A similar channel-form "b", which cuts Seismic Unit 1, is traceable in several local seismic lines and appears to trend E-W, parallel to and towards Taylor Valley.

Transgression and onlap of Seismic Unit 3a over Units 1 and 2, updip to the CIROS-1 drillcore (Fig. 10) resulted in the development of reflector "d" (brown) at the top of Seismic Unit 2.

Deposition of Seismic Unit 3a as part of a transgressive-regressive cycle. The hummocky seismic fabric in the landward intervals of Seismic Unit 3a may reflect a down-dip sediment dispersal system, Scours that truncate the upper intervals of sequence boundaries are more prevalent in the shallower reaches of this unit; more continuous and expanding packages occur down-dip into the basin. Onset of deposition of this unit is inferred to have occurred during a phase of eustatic sea-level rise based on the onlapping geometry at the base of the sequence and significant landward migration of reflectors

across the underlying surface "d" (brown). This unit should contain a thicker, more complete, transgressive package than those preserved in Units 3b and 3c. It is expected that fine-grained, pelagic sediments will be recovered in the lower portion of this unit with coarser grained sediments restricted to the landward portion. Much of the deposition of Seismic Unit 3a occurred during the upper progradational – regressive phase.
Regional influences and events: Continuation of Thermal Subsidence Phase 4 of VLB evolution.
Global influences and events: Transition out of the Miocene Climatic Optimum period and enter the Middle to Late Miocene Climatic Transition; TB2.3 and TB2.4 3rd order eustatic cycles; Mi3a isotope event (Fig. 1).

Middle? to Late? Miocene:
Deposition of Seismic Units 3b and 3c. Each successive unit progrades basinward. These units are separated by a surface of truncation "f" (grey), which is most evident near the proposed SMS site (Fig. 10). Faint reflectors in the down-dip portion of Seismic Unit 3b suggests that diamictites may be relatively rare here. The strong amplitude hummocky character of reflections up-dip of shotpoint 881 however, may reflect a greater influence of channels and truncation of upper portions of sedimentary sequences than in the down-dip direction.
Major truncation of the upper portions of Seismic Units 3a to 3c by the regionally-traceable erosional surface "g" (chartreuse). This erosional surface is identifiable across the VLB and is interpreted by Fielding, Henrys and Wilson as the onset of the Terror Rift Phase 5 of VLB evolution.
Regional influences and events: Thermal Subsidence Phase 4 of VLB transitions into the Terror Rift Phase 5 of VLB evolution.
Global influences and events: Middle to Late Miocene Climatic Transition; an important eustatic fall TB3.1 at ~11Ma is noted near the boundary between the middle and late Miocene (Fig. 1). It is tempting to correlate this event with the truncated sequence boundaries "g" (chartreuse).

Late? Miocene:
Deposition of Seismic Unit 4 as a prograding sequence across the truncated surfaces of Units 3a to 3c. The upper interval of Unit 4 is interpreted to contain a regressive unit, which would contain more diamictite beds within pelagic sediments. By analogy with the depositional pattern of Seismic Units 3a to 3c this may also result from a transgressive-regressive cycle. The lower amplitude of reflections in the underlying interval would suggest less contrasting sediments, such as a more marine environment with continuous deposition.
Truncation of Seismic Unit 4 to produce surface "h" (dark green) (Fig. 10).
Regional influences and events: Asymmetrical subsidence due to Terror Rift Phase 5 of VLB evolution.
Global influences and events: Eustatic 3rd order cycles TB3.3 and TB3.4.

Late Miocene? to Pliocene?:
Deposition of Seismic Unit 5. Strong reflectors indicate high impedance contrast, which suggests interbedded diamictite and fine-grained sediment. Age is older than an early Pliocene sample at 18.54 mbsf in MSSTS-1 drillcore (see below).
Truncation of Seismic Unit 5 to produce surface "i" (orange). Offlapping of the underlying reflectors and downlapping of the overlying reflectors on surface "i" is consistent with erosional slope processes.
Regional influences and events: Continued subsidence due to Terror Rift Phase 5 of VLB evolution; repeated marine incursions into central Wright Valley to deposit the Jason Diamicton (upper Miocene) and the Prospect Mesa Gravels (lower Pliocene) in an open fjord setting (Fig. 7) (Prentice *et al.,* 1993); eruption of Mt. Bird and Mt. Discovery (Kyle, 1990a, b).
Global influences and events: Pliocene Climatic Optimum.

Pliocene? to Pleistocene:
Deposition of Seismic Unit 6. An age of early Pliocene is assigned to this unit based on a diatom-bearing sample at 18.54 mbsf in the MSSTS drillcore, which contains marine diatoms *Actinocyclus karstenii, Thalassiosira inura, T. oestrupii, T. oliverana* var. *sparsa*, and *T. torokina*, (Harwood, 1986a). This age is inferred to apply to the strata above a widespread, horizontal pair of reflectors identifiable across the McMurdo Sound region, but not readily visible in line PD90-46. Deposition of volcanic sands by the Ross Ice Sheet, as noted in the upper intervals of the CIROS-2, DVDP 10, -11, -15 drillcores and across Taylor Valley (Vucetich & Robinson, 1978) is expected. These are interpreted to have been deposited beneath the Ross Ice Sheet or proximal to the grounding line as it advanced into McMurdo Sound area after occupying most of the Ross Sea during the Last Glacial Maximum (Licht *et al.*, 1996; Conway *et al.*, 1999; Domack *et al.*, 1999; Hall and Denton, 2000a, b; Fig. 9). During the past 1.0 Ma, this area experienced increased flexural subsidence

due to the volcanic loading from Mt Erebus (refer to MIS Prospectus). It is speculated that increased slope failure suggested by the hummocky seismic fabric may have resulted from an increased slope gradient.
Regional influences and events: Terror Rift Phase 5 of VLB evolution; eruption of Mt. Erebus and Mt. Terror and resultant repeated crustal loading by the building of Mt. Bird, Mt. Terror and Mt. Erebus (Horgan *et al.,* 2005).
Global influences and events: Eustatic 3rd order cycles TB3.3 and TB3.4; and the onset of Northern Hemisphere glaciation results in a non-Antarctic-sourced driver of sea-level change.

Rationale for Two Boreholes

The rationale for drilling two boreholes instead of one long borehole is chiefly based on increased diagenetic effects on microfossils (e.g., diatoms, foraminifers) with depth. The importance of diatoms as biostratigraphic indices for chronostratigraphic control and paleoenvironmental information regarding open water or sea-ice and ice shelf cover, water temperature variation, turbidity, salinity, and productivity, render their recovery vital to the success of the SMS objectives. Similarly, the state of preservation of foraminiferal and molluscan calcite as a repository for geochemical information regarding temperature, salinity, meltwater discharge, ocean composition and Sr ratios is vital to full integration of paleoenvironmental information into syntheses of environmental history. For these reasons, it is imperative that the SMS Project plan for the likely option of relocating the drilling rig to recover two offset sections from shallow depth below sea-floor (<700m) to mitigate the diagenetic loss of these key paleontological proxies. The transition from biogenic opal-A to opal C-T is known to occur as a feature of increasing time, temperature, pressure and host sediment lithology that allows for pore fluid migration. In the VLB this diagenetic transition occurred at 500 mbsf in the CIROS-1 drillcore, at 560 mbsf in the CRP-2/2A drillcore, and at <200 mbsf in the CRP-3 drillcore. Drilling two holes (each <700 m) to recover a 1000+m composite section ensures that recovered sediments will be least affected by diagentic alteration and loss through dissolution.

The two shallow drillholes will also enable the SMS Project the potential to build upon the stratigraphic sections recovered by CIROS-1 and CRP drillholes, by recovery of the remaining overlying stratigraphic section (Figs. 10, 11). The two offset drillcores represent a strategy to recover a composite stratigraphic sequence, the lower portions of which are masked beneath the water multiple reflection.

Site selection and the upcoming 2005 seismic survey will also consider a minimum distance for drill system relocation in order to accommodate the short operational window for drilling on the sea-ice, and a convenient location for a drilling camp between the two drill sites. The drilling program would consider drilling the SMS-1 site first. The decision regarding when to relocate to the SMS-2 site would depend on a variety of scientific and operational factors, including age profile at the SMS-1 drillhole, drilling rate and progress downhole, diagenetic state of biogenic opal at increasing depth, conditions of sea-ice stability and growth history, ability to process out the water multiple with the new 2005 seismic data, etc. Information determined by the age of strata recovered in the SMS-1 drillcore at 500 mbsf should provide sufficient indication whether the transition into the Miocene Climatic Optimum would be reachable by deeper drilling at the SMS-1 site, or whether a move to the SMS-2 site was essential to the full success of the SMS Project's scientific objectives.

SCIENTIFIC OBJECTIVES OF THE SMS PROJECT

The broad list below identifies the range of new information that will result from the SMS Project. New and innovative approaches to resolving questions involving the climatic and tectonic history of this region are sought. In order to address these issues the SMS Project Science Team will need to fully document the recovered materials and integrate specific information into a broader framework of questions. The results of these studies will advance significantly our ability to bring Antarctica's role in the global picture to clearer focus. More details about these scientific objectives are presented in the report (Harwood *et al.,* 2002 – available at http://andrill.org) of the ANDRILL Oxford Workshop, held in April 2001.

Specific scientific objectives are to:

(a) document the initial onset and subsequent history of sea-ice presence/absence;
(b) assess the timing and contributions by sea-ice and the Ross Ice Shelf system to thermohaline oceanic circulation;

(c) construct a history of Ross Ice Shelf and WAIS expansion and retreat in the McMurdo region;
(d) document the evolution and demise of Neogene terrestrial vegetation, largely through palynomorphs records;
(e) investigate whether rates of evolution of the polar marine biota vary with ice sheet fluctuations, changes in paleoceanographic circulation and paleogeography, and variable and extreme environmental conditions;
(f) establish the timing and frequency of appearance of lower latitude marine taxa as a result of southward migrations into the McMurdo Sound region;
(g) establish a Neogene sea-level record for the Antarctic margin, proximal to the ice sheets, to establish whether changes in Antarctic ice volumes (before major Northern Hemisphere ice) have been the primary driver of 10 - 0.01 m.y. cyclicity in global proxy records of $\delta^{18}O$ and sequence stratigraphic eustasy;
(h) test whether stable cold-polar climate conditions persisted for the last 15 m.y.;
(i) establish a history of Neogene sediment accumulation rates and provenance of sediments in the VLB, which will bear on estimates of erosion-induced uplift that produced the unusually high rift flank of the Transantarctic Mountains;
(j) document melt-water discharge events from the adjacent Dry Valley system, such as that proposed for the development of the Labyrinth and other geomorphological features, and assess their impact on marine communities, ocean dynamics and sea-ice formation;
(k) construct a composite event history of glacial and interglacial events across a coastal to deep basin transect;
(l) provide chronostratigraphic control for the regional seismic framework in the VLB and western Ross Sea;
(m) investigate how stratal architecture in a rift-basin system is influenced by glacial processes under different climate regimes;
(n) evaluate the value of different geological indices to distinguish tectonic subsidence from glacio-eustatic base-level changes in a glaciated rift-basin;
(o) feed new paleoclimatic data into ice sheet and climate models;
(p) establish a Neogene subsidence history for the Victoria Land Basin and fault history;
(q) date the episodes of proposed orthogonal and transtensional rifting in the western Ross Sea;
(r) assess whether the McMurdo Sound region of the Antarctic plate interior is characterized by a strike-slip stress regime caused by ice sheet unloading, or a thrust regime caused by plate-boundary forces;
(s) evaluate potential relationships between the stress regime of the McMurdo sound region, the history of the McMurdo Volcanic Group, rift margin tectonics, faulting and glacial loading;
(t) establish a strong chronostratigraphic framework for the Antarctic shelf region so that events in the southern high latitudes change can be well linked into a chronology of globally-recognized changes.

This list of scientific objectives is aligned with similar objectives defined by national and international initiatives (e.g. ODP and IODP). The ANTarctic Offshore STRATigraphy (ANTOSTRAT) group of the Scientific Committee on Antarctic Research (SCAR) emphasized the need for acquiring geological samples via coring and drilling in support of Cenozoic paleoenvironmental studies (Webb & Cooper, 1999). Geological data such as those to be produced by ANDRILL's two inaugural projects MIS and SMS will be used to constrain new paleoclimatic models. The last report of the ANTOSTRAT group recommended that the focus of new research should be on the collection and analysis of ground-truth geological information from around Antarctica and its continental margin (Kristoffersen *et al*., 2000a, 2000b). The newly formed SCAR group Antarctic Climate Evolution (ACE – http://www.ace.scar.org) intends to follow these directives and assist with the integration of new geological information into a diverse set of climate and ice sheet models. Many of the objectives listed above will help reach the goal to realize the potential for integrated numerical model-data studies to produce significant advances in our understanding of Antarctic and global climate evolution.

CONCLUSIONS

The geological and glacial history of the Antarctic margin remains poorly understood, because of the limited number of available stratigraphic records. The McMurdo Sound region presents a complex depositional setting with input from a diverse set of influences. Correct interpretation of these influences will result in the development of powerful tools for paleoenvironmental reconstruction. Late Neogene glacial history of Antarctica is currently debated and conflicting data exist within disparate disciplines of Antarctic Earth science, and from interpretations based on proxy records from outside the Antarctic region. Resolution of these apparently equivocal data sets will reveal much about past Antarctic processes and the history of paleoenvironmental change that influenced them.

Drilling sites for the two approved Projects (SMS and MIS) are located in areas that will maximize recovery of target stratigraphic intervals that bear on climatic and tectonic evolution of this region. Existing stratigraphic data from the McMurdo Sound region will be integrated with the new data acquired during this current phase of Antarctic drilling to develop a 3-dimensional view of processes and controls on basin development and sediment accumulation. This effort will produce spatially distinct (Fig. 6) and temporally overlapping (Fig. 7) records that will allow definition of structural controls on basin development, as well as combined sea-ice, ice shelf, ice sheet and climatic controls on processes of sediment transport and deposition. Primary target strata for the SMS Project include Middle to Lower Miocene sediments which, when recovered, will fill a significant gap in the record of the evolution of Antarctic coastal depositional environments. Data gleaned from these new records will allow Antarctic Earth scientists to address Antarctica's role in key global climatic events and episodes such as the Miocene Climatic Optimum and Mid-Late Miocene Climate Transition. The SMS Project also provides an opportunity to investigate a sequence of incised surfaces and regional erosional surfaces that occur in seismic profiles and may be linked to a global lowstand of sea-level ~10 Ma (associated with the marine isotope Mi5 event).

Secondary target strata of Plio-Pleistocene age in a distal marine setting will complement and build on coastal and fjord sediment records recovered in the CIROS-2 and DVDP-10 and -11 drillcores and the deep marine record to be recovered from moat-filled sequences by the MIS Project. The array of sites will also provide *in situ* stress data around the rift basin margins, resolving stress patterns around major fault systems, flexure zones and volcanoes.

Middle and upper Miocene strata to be recovered by the SMS Project overlap in time with the strata sampled by Deep Sea Drilling Project (DSDP) holes 272 and 273 in the central Ross Sea (Hayes & Frakes, 1975). These coeval records will provide a means of assessing paleoenvironmental history from both ice-proximal and ice distal settings. These records will also be compared to the late Miocene to Quaternary history available from the coastal and fiordal DVDP-10, -11 and CIROS-2 drillcores on the coast of the VLB. A Neogene glacimarine history from the stratigraphic and paleontological studies of the Pagodroma Group in the Prince Charles Mountains on the opposite side of East Antarctica will provide a valuable means to consider whether the history interpreted by the SMS Science Team reflects local-regional or continental-scale paleoenvironmental history on the Antarctic continental shelf.

The McMurdo Sound region has the best-understood marginal sedimentary record in Antarctica due to acquisition over the past 30 years of integrated seismic and drill-core data (McKelvey, 1991; Hambrey & Barrett, 1993; Bartek *et al.*, 1996). These data greatly improve the selection of drill sites with the greatest potential for achieving ANDRILL science goals and for bringing Antarctic history into the broader global perspective. Chronostratigraphic tools are now sufficiently mature, and will continue to improve with further drilling of the MIS and SMS Projects, to enable the transfer of new Antarctic paleoenvironmental data directly into the global datasets for comparison, and as vital data into climate and ice sheet models.

THE SCIENCE TEAM

An interdisciplinary team of international researchers will employ cutting-edge approaches to address fundamental scientific questions and achieve the key scientific objectives of the ANDRILL's SMS Project. It is anticipated that 27 members of the SMS Project Science Team will work on-ice in Antarctic during the period of core recovery and initial characterization. Other members of the SMS Project Science Team will work at their home institutions and receive samples and information about on-ice results on a regular basis. Disciplines and numbers of scientists and technicians required for the on-ice component are summarized in Table 1 below. It is anticipated that an equal number of scientists may be working off-ice at their home institutions. Both the on-ice and off-ice teams would meet at the Core Characterization Workshop several months after the completion of drilling to review the new results, examine the core and select sample intervals for future studies. The composition of the off-ice science team is unknown at this time, pending receipt of applications and description of proposed science activities. It is anticipated that the off-ice team will include a team of geochemists, paleomagnetists, palynologists, paleontologists and other disciplines.

DISCIPLINE / POSITION'S AVAILABLE		DISCIPLINE / POSITION'S AVAILABLE	
Phys Props - Whole core	1	**Petrography (volcanic)**	1
Phys Props - Whole core (T)	2	Thin-section technican (T)	1
Phys Props - downhole	2	**Micropaleontology - Diatoms**	3
Phys Props - downhole (T)	1	Paleontology Technician (T)	1
Seismic Stratigraphy/VSP	1	**Micropaleontology - Foraminifera**	1
Fracture Studies	2	**Macropaleontology**	1
Fracture studies technician (T)	2	**Paleomagnetism**	2
Sedimentology (log)	2	Paleomag samplers (T)	2
Sedimentology (facies/seq.)	2	**Clastology**	2
Sedimentology (smear-slide analyses)	2	**Split Core - XRF**	1
Petrography (sedimentary and general)	1	XRF scanner technician (T)	2
-	-	Science Educators	6

Table 1. List of required on-ice science disciplines and positions available

We invite all scientists who are eligible and interested to apply to be a member of the SMS Project Science Team. (Note: eligibility requires that the nation in which you are currently working is a contributing partner to the logistical and operational costs of the SMS Project). The above table describes the personnel required on-ice. Scientists from other disciplines are encouraged to apply to work off-ice at their home institutions as full members of the SMS Project Science Team. We particularly encourage individuals who can offer new and innovative approaches to Antarctic stratigraphic research to apply. Please contact Dr. David Harwood (Co-Chief Scientist – U.S.A.), Dr. Fabio Florindo (Co-Chief Scientist – Italy) or Dr. Richard Levy (Staff Scientist – ANDRILL Science Management Office) for more information.

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