Reconstruction of LGM and Post LGM Glacial Environment of McMurdo Sound: Implications for Ice Dynamics, Depositional Systems and Glacial Isostatic Adjustment

THESIS

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By

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McMurdo Sound represents a landscape at the crossroads of the West and East Antarctic Ice Sheets and has seen repeated occupation by both cold and warm based ice. Current ice sheet reconstructions place grounded ice across McMurdo Sound at the Last Glacial Maximum (LGM), thus the seafloor is expected to display morphologic features recording the LGM glaciation. Analysis of high-resolution multibeam bathymetry data and seismic surveys documents landforms marking glacial-geological processes beneath and at the margins of the ice sheets and are used to help determine the extent and style of glacial behavior on glacially influenced continental margins. The dominant morphologic features on the seafloor of McMurdo Sound are channel systems emanating eastward from the fjords of the Transantarctic Mountains (TAM) coast and northward from beneath the McMurdo Ice Shelf. A wide range of channel systems is observed. MacKay Sea Valley, at the northern limit of McMurdo Sound, displays a 6-8km wide, u-shaped valley with lineations formed by streaming ice of the expanded MacKay Glacier. A large submarine outwash fan extends 10’s of km eastward from the mouth of the sea valley. The Wilson and Taylor Sea Valleys cross and incise the western shelf and slope of McMurdo Sound, and show characteristics of sediment gravity flow transport and deposition. Wilson and Taylor Sea Valleys are .5-2km wide, do not contain features indicative of streaming ice, and appear to splay into numerous generations of fan systems at channel mouths. These channel/fan systems display cross-cutting relationships that
record the changing position, over time, of the ice margin along the TAM coast. In the Erebus Basin, the ~north-south trending moat in eastern McMurdo Sound with depths >900 m, a continuous, broad, anastomosing channel system transports material derived from beneath the McMurdo Ice Shelf and/or the steep eastern slope of Ross Island along the axis of the Erebus basin. The dominance of channel systems indicates abundant water from ice margins, leading to sediment gravity flow depositional systems and large-scale sediment transport across the Sound and ultimately northward out of the Sound. Flat-topped mounds at ~500 mbsl in southeastern McMurdo Sound may represent subglacial erosion of preexisting features, placing a constraint on grounded ice limits. A prominent, linear escarpment is observed on the western slope at ~500mbsl and may record the waning ice sheet to ice shelf transition along the TAM coast during the waning phase of the LGM. Together these observations suggest that the McMurdo Ice Sheet was grounded throughout McMurdo Sound at the LGM and may have experienced a rapid break out at 11 and 10 $^{14}$C ka BP, that restricted grounded ice to depths of <~500 meters. A new, integrated digital elevation model from Ross Island across McMurdo Sound and into the TAM reveals how seafloor features are connected to glacial features observed on land and provides a means to reconstruct regional ice thickness. Improved understanding of the LGM glacial record in McMurdo Sound provides a template for regional reconstructions of glacial behavior important for interpreting records from seismic data and sedimentary rock cores, for modeling of glacial isostatic adjustment.
Dedication

This document is dedicated to my family.
Acknowledgments

I would like to extend a great thanks to my advisor, Dr. Terry Wilson, committee members Dr. Larry Krissek and Dr. Peter Webb, research group including Cristina Milan, Stephanie Sherman and Bill Magee and fellow graduate students and professors of the School of Earth Sciences and Byrd Polar Research Center at The Ohio State University. This material is based in part upon work supported by the National Science Foundation. The primary marine geophysical data used for this research were acquired on the NBP04-01 geophysical cruise, funded by NSF Award ANT-0125624. Data acquired by the ANDRILL project, Prime Award ANT-0342484 to University of Nebraska-Lincoln, with Subaward to Wilson/Ohio State, provided the age determinations for seismic horizons. Research to reconstruct ice history and ice volume in the McMurdo Sound region was partially supported by this ANDRILL award, and by the POLENET project, NSF Award ANT-0632322. Additional data was obtained from the SCAR- and NSF-sponsored Seismic Data Library System, and the NSF-sponsored Marine Geophysical Data System, Southern Ocean Portal. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. An Educational Grant from Schlumberger Information Solutions to Wilson/Ohio State provided the GeoFrame software suite used for seismic interpretation.
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Fields of Study

Major Field: Geological Sciences
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Introduction

In the McMurdo Sound region (Figure 1), seafloor morphology and terrestrial glacial features are expected to display a clear record of ice configuration at the last glacial maximum (LGM), whereas sedimentary cores and seismic data provide a record of Pleistocene and older glaciations. Improved understanding of the LGM glacial record can provide a template for understanding past glaciations in the McMurdo Sound region. This is important for regional reconstruction of glacial history and dynamics from the regions surrounding sedimentary rock cores obtained in McMurdo Sound including CIROS (CIROS Science Team), Cape Roberts Drilling Project (CRP Science Team) and ANDRILL 1B-2A sites (ANDRILL Science Team).

The existing model of glacial dynamics in the McMurdo Sound region for the LGM hypothesizes that a grounded ice sheet flowed north along the eastern edge of the Erebus Volcanic Province then turned west around Ross Island, into McMurdo Sound and up into glacial valleys along the Transantarctic Mountains coastline (Figure 2, Denton and Marchant, 2000). The model is based on a reconstruction of ice surface elevation and flow directions using terrestrial glacial data including glacial striations, drift composition, and drift provenance. If this model is correct, an assemblage of megascale glacial lineations (MSGL), drumlins, grounding zone features and other features typical of grounded ice should be preserved on the seafloor in McMurdo Sound, as found elsewhere.
in the Ross Sea (Shipp et al., 1999). Ice flow patterns must be consistent with any flow
direction indicators on the seafloor and with ice dynamic controls.

In this study, marine bathymetric and seismic data acquired in 2004 are integrated with
ice surface elevation data to test the current LGM reconstructions for the McMurdo
Sound region. Ice thickness and surface slope reconstructions will be used to test ice
flow dynamics inferred for the region. Detection of any features diagnostic of grounded
ice or flow direction indicators will aid the reconstruction of the flow dynamics. Ice
thickness will be obtained using the existing terrestrial ice elevation data and new
bathymetric data from McMurdo Sound. If the new data provide evidence that is
inconsistent with the grounded-ice sheet model for McMurdo Sound, then regional ice
dynamics will need to be re-evaluated.

The McMurdo Sound region is a unique area for such a study as it is one of the few
regions in Antarctica that have the essential data sets available and because it is
interpreted to be a region containing records of interaction between the East Antarctic Ice
Sheet (EAIS) and the West Antarctic Ice Sheet (WAIS) (Naish et. al. 2009). Glacial
behavior in this region at LGM and preceding glaciations must be understood to more
effectively relate regional climatic events to events identified in sedimentary cores in
McMurdo Sound.

In order to meet these goals, this study: 1) mapped morphologic features indicative of
streaming ice and grounded ice from bathymetric data, 2) mapped channel systems
indicative of abundant melt water flow, 3) merged bathymetric data with terrestrial digital
elevation models to create a continuous basal surface of the LGM ice sheet, 4) created a
digital LGM ice sheet upper surface from the Denton and Marchant compilation, 5) derived a thickness and volume of the LGM ice sheet by differencing the upper ice surface from the seafloor surface (inferred to be the basal ice surface), and 5) established a new glacial model for McMurdo Sound.
Background

Geologic Setting

McMurdo Sound is located along the western margin of the Victoria Land Basin (VLB) and is situated between the Transantarctic Mountains (TAM) and Ross Island (Figure 1). The TAM represent a rift-shoulder mountain belt that forms the western margin of the West Antarctic Rift System (WARS) and separates East from West Antarctica. The TAM, which represent the western limit of McMurdo Sound, are composed of Precambrian metamorphic rocks of the Koettlitz Group, Granite Harbour Intrusives of Ordovician age, the Beacon Supergroup of Devonian-Triassic age and the extrusive and intrusive Kirkpatrick Basalts and Ferrar Dolerite of Jurassic age (Barrett et al., 1995).

Development of the present-day mountain belt has been chronicled using apatite fission-track thermochronology data (Figure 3, Fitzgerald 2002). Events in the Cretaceous related mostly to the initial breakup of Gondwana and development of extensional low-angle detachment surfaces in the Ross Sea region (Fitzgerald and Baldwin, 1997). The Cenozoic record, which applies most directly to this study, is the result of rift-related and climate-tectonic interactions and indicates an exhumation rate of 100m/m.y., which is low compared with other tectonic regimes (Fitzgerald, 2002). By 36 Ma, granitic basement of the TAM had been exposed and granitic material began to be deposited in VLB (Barrett et al., 1989). The period between 40 and 15 Ma is inferred to represent an interval of waning exhumation due to a shift to polar climatic conditions as Antarctica...
became isolated from the rest of the continents (Fitzgerald, 2002). Evidence from cosmogenic isotope analysis of preserved tills and glaciated bedrock surfaces suggests that very low rates of erosion have persisted since 14 Ma (Sugden et al., 1995 and Sudgen et al., 2006).

Seismic stratigraphy and faults identified on seismic profiles from the Victoria Land Basin show 5 phases of basin formation starting in the pre-late Eocene (Fielding et al., 2006). Recorded by apatite fission track analysis of Fitzgerald (1992 and 2002), phase one involved the early Cenozoic uplift of the TAM and the deposition of TAM clasts at the base of the VLB sedimentary succession. Phase 2 (34–29 Ma) was characterized by the development of horsts and grabens and the deposition of locally confined glacigenic siliciclastic sediments related to early rift evolution (Fielding et al., 2006). The main rifting phase began at 24 Ma with the deposition of glacigenic sediment packages thickening to the east but unconfined from the earlier horst and graben topographical barriers (Fielding et al., 2006, Wilson et al. in prep.). Glacial advance and retreat cycles along with regional subsidence began to control the deposition of shallow glacimarine sediments (Fielding et al., 2008). Phase 4 (24 –younger than 17 Ma) is characterized by a much lower subsidence rate and diamictite-dominated sheet like deposits which record cycles of glacial advance-retreat along the western basin margin (Fielding et al., 2006). Re-initiation of extension younger than 17 Ma is recorded by an eastern and western thickening sediment package into a single depocenter (Fielding et al., 2005). This package is crosscut by magmatic rocks of the McMurdo Volcanic Group and shallow faults related to the Terror Rift (Cooper et al., 1987, Hall et al., 2007; Henrys et al, 2007).
Phase 5 sediment packages show large clinoform sets dipping toward the Terror Rift depocenter which may be related to a younger uplift of the TAM (Fielding et al., 2008). Active (transtensional?) tectonics, as shown by the presence of the Neogene McMurdo Volcanic Province and faulting along the Terror Rift, may have persisted into the present (Figure 4; Hall et al., 2007; Henrys et al., 2007). The uppermost seismic package, present within the moat around Ross Island, records the development of accommodation space by flexural loading by the Erebus volcano (Fielding et al., 2008, Whittaker, 2005). Figure 5 shows a schematic view of the tectonic setting of McMurdo Sound in addition to ice from both the Ross Ice Shelf and the East Antarctic Ice Sheet.

Volcanic Setting
Ross Island, formed from amalgamated volcanoes including the active Mt. Erebus volcano, forms the eastern margin of McMurdo Sound. Kyle (1990) has described the morphology and evolution of the Erebus Volcanic Province, which is located at the southern end of the Terror Rift and surrounds southern McMurdo Sound. The first main phase of volcanism, 19-10 Ma, consisted of trachytic rocks while the second main phase, 10 Ma-present, is basanitic to phonolitic and is presently active (Kyle, 1990). Mt. Erebus has experienced 3 main phases of development, with the main phase starting ~1 Ma (Esser et al., 2001). Two major caldera collapses have been identified using geomorphology and the composition of lava flows with one occurring on the northeast flank of Mt. Erebus around 700 ka and the other occurring along the southwest flank of Mt. Erebus between 25 and 11 ka (Esser et al., 2004). Small parasitic cones and vents are observed on the flanks of Mt. Erebus and immediately offshore as displayed by the
Dellbridge Islands (Kyle, 1990). Volcanic cones were first observed in older seafloor studies of the 1980s and then in more detail from multibeam bathymetry and seismic data reviewed in this study (Barrett et al., 1983). The western margin of McMurdo Sound has also been influenced by volcanism of the Erebus Volcanic Province displayed both by the presence of Dailey Islands and by previously uncharted volcanic ridges observed in the multibeam bathymetry. In the Royal Society Range, over 50 volcanic vents have been mapped and dated, yielding age ranges of ~2 Ma-0.08 Ma (Kyle, 1990). Similar, yet older vents have been observed in Taylor and Wright valleys (Wilch et al., 1993; Kyle, 1990). Volcanism around McMurdo Sound has had profound effects on basin development by volcanic loading and flexure within the basin, by adding sediment to the basin via eruptive activity, by caldera collapse and gravity flows, and by supplying material that can be dated in the stratigraphic record (Esser et al., 2004; Fielding et al., 2008, Naish et al., 2007).

Glaciological Setting

Currently, McMurdo Sound is at the crossroads of the two great Antarctic Ice Sheets. The East Antarctic Ice Sheet (EAIS) is mostly contained in East Antarctica, but along its eastern margin, the EAIS spills over and down the TAM to terminate in the Ross Embayment (Denton and Hughes, 2000). The West Antarctic Ice Sheet (WAIS) nucleates from the topographically higher parts of West Antarctica and flows into the Weddell, Bellinghausen, Amundsen and Ross Seas via outlet glaciers or ice streams (Anderson et al., 2001). In the case of the Ross Embayment, the WAIS is drained by
major ice streams of the Siple Coast and is buttressed by the Ross Ice Shelf. Figure 6 shows the LGM Ross Sea drainage patterns and ice extent reconstructed by Denton and Hughes (2000). During glacial periods, the WAIS expanded quite significantly with the West Antarctic Ice Sheet extending to the continental shelf margin (Anderson et al., 2002).

The Ross Sea ice sheet reconstruction and timing for the LGM has been undertaken by many, including geologists investigating terrestrial glacial features e.g. Denton and Marchant (2000), extensive marine geological mapping of grounded ice sheet features e.g. Anderson et al. (2002) and examination of seismic stratigraphy and piston cores e.g. Bartek (1989) and McKay et al. (2008). The combination of grounded ice sheet geomorphic features, such as megascale glacial lineations (MSGLs), drumlins and grounding zone wedges on the sea floor, with seismically mapped glacial unconformities map the past extent of grounded ice within the Ross embayment (Anderson et al., 2001). Domack et al. (1999) and Shipp et al. (1999) investigated the extent of the expanded Ross Ice Sheet and recorded the timing of expansion and retreat through geological and geophysical methods.

Timing is determined using radiocarbon dating of terrestrial and marine deposits and, while it is subject to uncertainties, provides quantitative age relations (Domack et al., 1999). Figure 7 shows the geomorphic features of the expanded West Antarctic Ice Sheet from the Last Glacial Maximum (Shipp et al., 1999). Using radiocarbon dates from diamictons, Domack et al. (1999) found that the West Antarctic Ice Sheet occupied the continental shelf margin at 23ka +/- 3.5ka (corrected). In the western Ross Sea, the
LGM grounding line lies just north of Coulman Island while grounded ice extended to the continental shelf edge in the central Ross Sea (Domack et al., 1999). Shipp et al. (1999) identified the seismic character of many glacial features and found that the grounding line southerly retreat in the Western Ross Sea must have occurred by 11 ka. The grounding line subsequently retreated rapidly to the deep basins surrounding Ross Island by ~10,100 \(^{14}\)C years BP and it was here that an ice shelf was maintained until ~8900 \(^{14}\)C years BP, with the calving line of the Ross Ice Shelf pinned to eastern Ross Island (Figure 8; McKay et al., 2008). By mapping and dating terrestrial glacial features such as glacial drift elevation, composition and provenance, Denton and Hughes (2000) and others found that ice remained grounded along the TAM coast until 10,794 \(^{14}\)C years BP. A key observation that helps determine drift provenance is that Ross Island contains a unique bedrock assemblage consisting of peralkaline phonolite (termed Kenyte) which, when found in glacial deposits, is an indicator of a Ross Island provenance (Denton and Marchant, 2000). Evidence for a lingering grounded ice sheet at 8340 \(^{14}\)C years BP was found in New Harbour at the mouth of Taylor Valley (Denton and Marchant, 2000). By 6450 \(^{14}\)C years BP the grounding line continued to recede to the south and the McMurdo ice shelf formed by the thinning of the grounded ice sheet (Denton and Marchant, 2000). The retreat history of Denton and Marchant (2000) roughly agrees with work by McKay et al (2008) yet Denton and Marchant (2000) displays the complex retreat history in the New Harbor/Southern McMurdo Sound between ~8-6 ka. The apparent past behavior of the grounded ice sheet in McMurdo
Sound region is unique in that this area is the only region along the TAM coast where grounded ice flowed landwards (Figure 2).

At the LGM, TAM outlet glaciers, such as the Ferrar and Taylor glaciers, blocked the mouths of their respective valleys when landward-flowing grounded ice filled McMurdo Sound (Denton and Marchant 2000). These glaciers did not permit further landward penetration of the grounded ice sheet. A 162 m core at the mouth of the Ferrar Glacier gives clues to the glaciers past extent and interaction with the grounded ice sheet (Barrett and Hambrey, 1992). The top 100 m of core represents the Pleistocene to present age. Figure 9 shows the history of the Ferrar Fiord interpreted by Barrett and Hambrey (1992). Key observations include the enrichment in volcanic sand (derived from Ross Island) in the diamicritles, interpreted to record interaction between the Ferrar Glacier and the grounded ice sheet in McMurdo Sound.

Interpretation of seafloor features offshore as part of this study are integrated in order to contribute to understanding the above outlined interactions.

The reconstruction of the ice extent and behavior in McMurdo Sound at the LGM can serve as a template for interpretation of past glaciations seen in the ANDRILL cores obtained from Southern McMurdo Sound and beneath the McMurdo Ice Shelf. The ANDRILL cores, along with other drill cores in the region and seismic data, provide a deep time perspective of multiple glacial cycles in the McMurdo Sound region (Naish et al., 2009). Younger geomorphic features on land and those observed on the seafloor provide a record of the LGM and Post-LGM. A key link between the LGM and older glaciations is the most recent deposits in McMurdo Sound. These deposits are bounded
by a recent erosional unconformity overlain by flat-lying deposits interpreted to have accumulated since the LGM (Whitaker, 2005). Recent seismic data have identified paleo-channels that were part of past drainage systems across the western shelf. (Whitaker, 2005, Henrys, 2011 (ISAES)). These channel networks show the preferred flow paths throughout the evolution of the basin and are used to provide clues on channel incision, in fill and geographic location of the paleo-channel systems.
Methodology: Reconstructing Ice History in McMurdo Sound

Terrestrial Glacial Geomorphic Data

The upper limits of the grounded ice sheet surface and ice sheet movement directions at the LGM have been mapped using terrestrial glacial-geologic data collected in the McMurdo Sound region (Figure 10, Denton and Marchant 2000; Hall and Denton, 2000; Hendy and Denton, 2000). The data include glacial drift elevation, age, composition and provenance along with geomorphic features such as glacial meltwater channels and glacial striations (Table 1). The study area of Denton and Marchant (2000) covers the perimeter of Ross Island and associated volcanic islands to the southwest and extends northward along the TAM coast, surrounding McMurdo Sound (Figure 11).

The upper surface of the Ross Ice Sheet has been digitized in ArcGIS and has been used in conjunction with the integrated digital terrain model (IDTM) to determine volume calculations and to assess glacial dynamics. Previously mapped and dated terrestrial features are primarily used for age control on geomorphic features relevant to interpretations made from bathymetric and seismic mapping. For example, features in the New Harbor area that constrain the timing and influence of the Ross Ice Sheet and Glacial Lake Washburn are investigated due to their proximity to the western slope channel systems and serve as the source area for much of the sediment observed on the seafloor.
Topographic, and Bathymetric Data

*Digital Topography*

The terrestrial elevation data cover an area approximately 225x100km in the Transantarctic Mountains as well as all of Ross Island. These data are available from the U.S. Geological Survey (USGS) and from Land Information New Zealand (LINZ) who produced the 1:50,000 digital topographic maps with 20m contour intervals using photogrammetric methods.

The process for creating the terrestrial DTM is relatively simple. The digitized contours are loaded, in ArcGIS 10 and the ‘Topo to Raster’ tool is used to create a continuous interpolated surface. This raster model can then be clipped with a shapefile of the coastline to model only areas that contain known data. Finally, gridding at 20m spacing allows for integration with bathymetric data to produce the fully integrated digital terrain model of the region of interest.

*Bathymetry*

*Low Resolution Bathymetry*

The Geological and Nuclear Sciences of New Zealand has undertaken a new compilation incorporating all the bathymetric data acquired since 2008 and this is the most complete compilation of bathymetry data to date. An added improvement is inversion of 1-minute resolution satellite derived gravity data to fill the gaps that exist in the ship-borne data (Black et al., 2011). The work by Black et al. (2011) is built from the framework
provided by Stagpoole et al. (2004) and Davey (2004). The Stagpoole et al. (2004) map, at 1: 5,000,000 scale, covers a much larger area while the Davey map, at 1: 2,000,000 covers a more localized area around the western Ross Sea. The maps were constructed using all preexisting bathymetric data and quality control was performed on each dataset (Stagpoole et al., 2004; Davey, 2004) The final compilation by Black et al. (2011) has been constructed at a finer scale (100m, horizontal) for McMurdo Sound to enable the highest quality possible for this region. These maps will be used to provide broader coverage and to fill data gaps in the multibeam bathymetry.

**High Resolution Multibeam Bathymetry**

Multibeam bathymetry is a sonar system used to map the seafloor in a much more efficient way than single beam sonar collection. Using an array of up to 120 transducers that are attached to the hull of a ship, the continuous swath of sound covers a distance on each side of the ship which that with depth. The sound waves are reflected off the seafloor and received by the collection system at slightly different times. The signals are processed on board and, using a velocity value for water, are converted to water depths to produce a continuous bathymetric map with a horizontal accuracy of 20 meters.

The primary swath multibeam bathymetric data for this study is the NBP0401 dataset and was collected aboard the RVIB Nathaniel B. Palmer from January 19 to February 18, 2004. The NBP0401 data was collected using the Kongsberg-Simrad EM120 system while the MB-System software package was used onboard for editing and processing of the raw data (Wilson et al., 2004). As the raw data streamed in, the science team edited
individual pings, which produced a first order cleaning of the data. Sea ice conditions at the time of data acquisition resulted in poor acquisition and data gaps. In addition to data gaps, physical conditions, such as the presence of sea ice, forced the science party to modify the speed of the research vessel which resulted in various artifacts in the data (Wilson et al., 2004). The wide beam angle (75°) used throughout the cruise produced a noticeable artifact. The edge effects or “roll-off” of the data at the outer beams is enhanced with a very wide acquisition angle of 75° (Wilson et al., 2004). Further processing by Stuart Henrys was undertaken to remove the edge effects produced by the wide beam width angle. The first step was to edit the data using a simple filter that flagged the individual beam if the along-track dip varied significantly from the local bathymetry and pings with more than 50% flagged beams were then rejected (Henrys, 2006). The greatest control on the quality of the bathymetric data is the correction made for water column refraction and the resulting artifacts from refraction-related anomalies can produce apparent topographic features that could be misinterpreted as seafloor features (Henrys 2006). The refraction correction was performed on one relatively flat area and produced a distinctive curl down effect (anomalously deep) on the outer edges of the beam (Henrys, 2006). Once an optimum refraction correction was chosen, the correction was applied to the dataset as a whole. Additionally, quality control was performed by comparing this dataset to over 16,000 single beam survey points in the region which were provided by GNS (Henrys, 2006; Davey, 2004; Stagpoole, 2004). The correlation between the two datasets shows a close agreement with a slightly higher
correlation at shallower depths (Henrys, 2006). The NBP0401 data set resulting from post-cruise processing and quality control by Henrys (2006) is used in this study. Additional multibeam data provided by other Palmer cruises and very recent cruises by the Icebreaker Oden (NBP9407, NBP9501, NBP9601, NBP9602, NBP9702, NBP9802, NBP9902, NBP0001, NBP0301, NBP0306, NBP0402, NBP0409, NBP0602, NBP0801, OSO0910 and OSO1011) have been integrated with the NBP0401 data, in this study. These data sets are used to fill gaps in areas not surveyed by the extensive NBP0401 cruise. These data were downloaded from the Marine Geoscience Data System (http://www.marine-geo.org/index.php), an open source database housed at Lamont-Doherty Earth Observatory at Columbia University. The bathymetric data were downloaded in MBSystems format (i.e. .mb77) which is a data format read only by MBSystems, an open source bathymetric data acquisition and processing software package, maintained and serviced by the Monterey Bay Aquarium Research Institute and Lamont-Doherty Earth Observatory (http://www.mbari.org/data/mbsystem/html/mbsystem_home.html). The data were converted from MBSystems format to standard ASCII (XYZ) format for further processing and visualization using ArcGIS 10 and the IVS3D suite of software applications such as Fledermaus and DMagic (Gordon and Stutz, 2011). The combined coverage and tracklines of all the multibeam bathymetry are shown in Figure 12. All of the integrated multibeam bathymetric data, including the NBP0401 data post processed by Henrys (2006), were processed using the Combined Uncertainty and Bathymetry Estimator (CUBE) editing algorithm within D-Magic, a processing software
developed by IVS3D, to create a “cleaned” digital bathymetric surface of the McMurdo Sound region (Mallace and Robertson, 2007). The CUBE method is an algorithm that fits a surface to a series of data points, places a “window” around the surface related to a standard order of accuracy of the survey and gives the user the opportunity to reject soundings that fall outside this “window” (Mallace and Robertson, 2007). This CUBE method aids in eliminating bad data along beam edges and data collected during times of difficult physical conditions. At the time of acquisition, physical conditions of the seas, such as the presence of sea ice, rough seas, or extreme cross winds caused the multibeam data to become degraded and occasionally mad it impossible to collect data (Wilson et al., 2004). Further manual editing by Chris Gordon and Jie Chen has been done on a local scale to produce a cleaner high resolution data set (Gordon and Stutz, 2011). The CUBE algorithm has been used on all swath bathymetric data used in this study.

*Integrated Digital Terrain Model (IDTM) of McMurdo Sound, Ross Island and the Transantarctic Mountains*

To determine the limits of LGM ice extent and to correlate geomorphic features seen on the ocean floor with those seen on land, an integrated map of onshore (TAM and Ross Island) topography and offshore bathymetry (regional and high resolution) is required. The process involves utilizing the “Mosaic to New Raster” functionality in ArcGIS 10. After quality control has been performed on all 3 main inputs (low resolution bathymetry, multibeam bathymetry and terrestrial elevation data)) to the IDTM, they are mosaicked in a logical order depending on overlapping extent using the “first” method, which gives
preference to the first file loaded into the “Mosaic to New Raster” tool: First the multibeam bathymetric compilation is preferred over the lower resolution bathymetry to produce a bathymetric DTM. Then the terrestrial data are mosaicked on top of the bathymetric DTM to produce the first fully integrated digital terrain model of southern Victoria Land, McMurdo Sound and Ross Island (Gordon and Stutz, 2011). Additionally, satellite imagery, LIDAR images and interpretive maps have been superposed on the IDTM for co-visualization. Interpretive maps consist of LGM grounded ice limits, onshore subglacial topographic maps, offshore depositional patterns, and on and offshore tectonic and volcanic features (Denton and Marchant, 2000; Calkin, 1974; and Bartek, 1989). The upper surface of the McMurdo Ice Sheet (of Denton and Marchant, 2000) has been digitally reconstructed using ArcGIS. This is overlain on the bathymetry and topography to determine ice thickness and volume of the McMurdo Ice Sheet at LGM. Glacial dynamics, such as flow direction and a floating versus grounded ice model, are tested using this integrated thickness map.

Seismic and Marine Geologic Data

Seismic Data

Single and Multi-Channel Seismic Data

Seismic data from multiple surveys are used to interpret the recent glacial history of the McMurdo Sound region. Seismic data was collected by the USGS in 1984 followed by Italian surveys in 1990, single channel surveys aboard the RV Polar Duke in 1990, NB Palmer cruises in 1994 and finally extensive seismic acquisition by the NB Palmer in
2004 (Figure 13, Cooper et al., 1987; Salvini et al., 1997; Bartek, 1996; Wilson et al., 2004). The NBP0401 dataset consists of over 2500 km of seismic reflection data with a total of 15 seismic lines in McMurdo Sound, in addition to bathymetric, gravity and magnetic data. Shipboard processing by the seismic team was undertaken using a processing suite developed by the Institute for Geological and Nuclear Sciences. Detailed description of acquisition and processing is described in the Cruise Report for NBP0401 (Wilson et al., 2004).

**BATHY-2000 Sub Bottom Profiler**

Sub-bottom profiling Bathy-2000 chirp data was also part of the NBP0401 suite of data (Wilson et al., 2004). Bathy 2000 data were gathered using the Ocean Data Equipment Corporation’s BATHY–2000, a hull mounted, CHIRP pulse sub-bottom profiler system that was installed aboard the RVIB Nathaniel B. Palmer in 1993. A CHIRP pulse is an acoustic signal of continuously varying frequency (averaging 3.5 kHz) with time, providing vertical resolution as fine as 0.8 m between reflectors with bottom penetration to over 75 m. In order to filter background noise and error generated from ship-movement during collection, the BATHY-2000 incorporates several automatically and manually set systems (Howat and Domack, 2003 and ODEC 1996). Bathy 2000 data were analysed using standard seismic stratigraphic techniques for glacial and glaciomarine deposits which involves acoustic sequence analysis and acoustic facies analysis (King and Fader 1986; Shipp et al. 1991; Stoker et al. 1997; Shipp et al 1999, and Howat and Domack 2003). Bathy 2000 profiles are subdivided into acoustic facies
based on bounding reflector geometry, continuity and internal acoustic density or structure (Howat and Domack, 2003). These data are used to identify the internal structure of the upper ~20 meters in the sedimentary succession and display geomorphic features such as grounding zone wedges (GZWs), slumps, and infilling of channel forms.

*Marine Geologic Data*

Sedimentary rock cores of the Dry Valley Drilling Project, Cape Roberts Drilling Project, CIROS and ANDRILL constrain the timing and geologic significance of events observed in the seismic record and are used to provide a deep time perspective on the observed glacial-geologic regime (DVDP, CRP, CIROS and ANDRILL science teams). Additionally, shallow piston core analysis by Bartek (1989), Kaharoeddin et al. (1988), Bartek and Anderson (1991) and Mackay et al. (2008) are used to provide age control and to assess the depositional environments of bathymetric features observed on the seafloor. There is a limit to using age dating from piston core work due to the variability in sedimentation rates, percentage of reworked carbon and/or differences in the CO2 exchange between the ocean and the atmosphere (Andrews et al., 1999). For example, local sedimentation rates may vary from .01 cm/yr to .19 cm/yr depending on whether the deposit is an open sea hemipelagic mud/ooze facies or a turbidite facies (Mckay et al., 2008). While problems with absolute age dating are evident, generalized mapping of interpreted depositional environments are most useful in this study.

*Submarine Landform Analogs*
Using the cleanest collection of multibeam bathymetry data, McMurdo bathymetric features are compared with analogs from other regions with demonstrated assemblages of glaciogenic features. Some key regions that may serve as analogs to this area include other regions of the Ross Embayment as described by Shipp et al. (1999), the Antarctic Peninsula (Cofaigh et al., 2008, Anderson et al., 2008, Shaw et al., 2008, Jakobson, 2011), the margins of Greenland (Moncrieff and Hambrey, 1990), Svalbard (Fairchild and Hambrey 1995), the North Atlantic (Jakobsson et al., 2004, Gupta et al., 2007, Thieler et al., 2007), offshore of the Svalbard archipelago (Robinson and Dowdeswell, 201; Pedrosa, et al., 2011) and the continental margins of the Arctic Ocean (Lajeunesse and St-Onge, 2008, Jakobsson, et al., 2008). Key geomorphic features such as grounding zone wedges, mega scale glacial lineations, drumlins and meltwater channels are ubiquitous in previously glaciated regions and are considered landforms in this study. The work by many others forms the knowledge base for the interpretation of marine geomorphic features observed in this study. Examples and details of common glacial geomorphic features are given in the interpretation section.

The existing interpretation of LGM ice sheet behavior shows that the ice sheet was grounded throughout McMurdo Sound and flowed landward toward the TAM coast (Denton and Marchant, 2000). If this interpretation is valid, an assemblage of geomorphic features produced by grounded ice should be preserved on the seafloor.
Observations

Bathymetric Provinces of McMurdo Sound

In this study, McMurdo Sound is sub-divided into 6 main bathymetric provinces defined by overall geographic location and geomorphic character. The bathymetric provinces include the Western Slope, Ross Island Slope, Erebus-Bird Basin, Beaufort-Bird Corridor, Beaufort Island and Mackay Sea Valley (Figure 14). The eastern and western margins of McMurdo Sound are defined by the Ross Island and TAM coastline, the southern margin is the present day McMurdo Ice Shelf extent, and the northern margin is defined by the northern slope of the Mackay Sea Valley and the northern slope of Beaufort Island. The definition and morphology of each bathymetric province are described below. It should be noted that significant portions of the Western Slope are only covered by the low resolution bathymetric data.

*Western McMurdo Sound Slope Morphology*

Along most of the TAM margin, an offshore shallow (0-100mbsl) coastal slope passes eastward into a shelf platform, then into the slope. The P6 and P2 profiles show small basins superposed on the platform (Figure 15 and 16). Seaward, a shelf/platform gradient range of .08°-1.19° with an average of .56°, a width range of 9.1-20.6 km and an average width of 14.8 km. The shelf-slope break is defined by inspection of topographic profiles. The shelf-slope break has a variable location offshore and ranges 13-37 km from the
TAM coastline ranging between 200-400 mbsl. The western McMurdo Sound slope has
gradient range of 0.765°-3.61 with an average of 1.83° and a width range of 6.8-53.6 km
with an average width of 22.7 km (Figure 15 and 16, Table 2). The seaward change in
gradient of the western slope transitions into the Erebus-Bird Basin in all profiles
(Figure 16) The most prominent features of the western McMurdo Sound bathymetric
province are channels emanating from the TAM coast and prominent linear escarpments
trending ~north-south (Figure 17). The channel systems of the western slope are the
Taylor Sea Valley (TSV) and the Wilson Sea Valley (WSV).

**Prominent Linear Escarpments**

Prominent linear escarpments are observed on the western slope of McMurdo Sound.
The longest and most continuous escarpment, Escarpment A, extends at least ~68 km and
in some places splays into two or three sub-parallel escarpments ranging from 9-17 km
long (Figure 18). A distinct slope change defines the crest of the escarpments. The
average slope landward of the crest is 0.4°, while the average gradient seaward of the
escarpment is 5.4° with a maximum of 7.2°. The along-strike slope of Escarpment A
changes, with the southern extent plunging slightly to the south (0.045°), while the
northern extent plunges slightly to the north 0.097°. The marked change in slope occurs
north of the TSV at a point where Escarpment A splays into three discrete escarpments,
escarpments A, C and D (Figure 19). The average depth of the Escarpment A is 499
meters below sea level but has a range of 480-510 mbsl. Escarpments B-D occur at 476,
538 and 580 meters below sea level and all slope North on average 0.1°. In areas with
multiple escarpments, sub-bottom profiler data shows a high-intensity, discontinuous
upper reflector (<1 m thick) and high-intensity internal hyperbolic reflectors in the lower reaches of the slope (Figure 20, C-C’). In areas with one main escarpment, the high intensity upper reflector is continuous while the internal seismic character is transparent and chaotic, underlain by a thin subdued-intensity chaotic reflector (Figure 20, B-B’). Multi-channel seismic data reveals the internal structure associated with the escarpments (Figure 21). A prominent wedge, ~50 m thick, with seaward dipping clinoforms overlying an erosional surface is observed. A chaotic facies with multiple “ramp” features occurs downslope from this wedge at the escarpment.

Similar to escarpments A-D, 3 escarpments, (WSVE 1-3) are observed nearly perpendicular to the Wilson Sea Valley. The escarpments of the WSV have a similar character to the Escarpments A-D but trend ~30°-60° to them. Also, the WSV escarpments change spacing with the maximum spacing observed near the main channel and the minimum spacing observed in the lower reaches of the WSV. The WSV escarpments average 6.1 km long, and slope .74° to the northeast. The average depths of the WSVEs are 550, 602 and 650 mbsl for WSVE 1-3 respectively. Average spacing between WSVE1 and 2 is 883 m and the spacing between WSVE 2 and 3 is 1446 m. The lowest escarpment, WSVE 3 is the northwestern bank for the WSV as it extends down slope into the Bird Basin.

*Taylor Sea Valley (TSV) System*

The origination point of this channel system at the coast is unknown due to lack of high resolution bathymetric data, but the TSV does emanate from New Harbor. The channel system has an overall east-west trajectory all the way to the edge of the Erebus Basin.
The TSV is an unleaved channel complex containing a main channel that bifurcates into a main branch (TSV1) and secondary branch (TSV2) (Figure 22). TSV1 extends eastward from the mouth of New Harbor and is nearly 43 km long with an average slope of .02, average width of .7 km and an average depth of 60 m. TSV1 becomes wider and shallower in its lower reaches. TSV2 averages .5 km in width and 50 m in depth. TSV1 is slightly u-shaped in the upper reaches of the multibeam data and becomes more v-shaped in the lower reaches. Both branches change to channel-fan complexes with many smaller subchannels. Some subchannels divert at an angle to the slope only to recollect into one main branch whereas others continue in a straight path downslope. The TSV appears to lack a sediment drape in the upper reaches (Figure 23a) but contains fill with some internal stratigraphy in proximity to the fan complexes (Figure 23 c). Multichannel seismic data reveal clues to the channel history (Figure 24). Continuous, flat seismic reflectors underly TSV1 and do not show strong incision by the channel system. Buried channel forms of comparable size to TSV are observed in the underlying seismic units. Beneath the channelized fan of TSV2, the seismic package appears to be aggradational with a complex of small buried channel forms above the continuous, flat, unincised reflector underlying TSV1. Both TSV1 and TSV2 cross cut the linear escarpments and “die out” into an unchannelized depositional fan downslope. These channels are less pronounced than above the escarpment yet continue down slope of the escarpments and terminate at a ridge complex near the floor of Erebus-Bird basin. Sub bottom profiler data shows the presence of an intense upper seismic unit throughout the TSV fan area, which diminishes acquisition of sub bottom structure. The lack of multichannel seismic
data in the fan area of TSV does not allow the dimensions of the fan to be calculated accurately. The surface area of the proposed fan is ~96 km$^2$.

*Wilson Sea Valley (WSV)*

The WSV is a single channel. The channel extends eastward from New Harbor, turns 90° to run northward parallel to the TAM coast for nearly 15 km, then turns nearly 90° again to trend into the Erebus-Bird Basin (Figure 25). The channel is ~75 km long, has an average slope of .006, an average width of 1.5-2 km, and an average depth of 80 meters. It is u-shaped along its upper reaches and slightly v-shaped in its lower reaches. The WSV crosscuts the linear escarpments on the western slope, and contains a noticeable knick point where it cuts escarpment A. Locally, the channel narrows and steepens near this knick point. A smaller (~10km long, 20 m deep, 50m wide) isolated secondary channel is observed directly to the south of the mouth of the WSV. This channel appears to start abruptly at escarpment B at a water depth of ~540m and connects into the WSV downslope. As the WSV extends into the Erebus-Bird Basin, it becomes less defined (600 m wide, 15 m deep), yet maintains a sinuous channel form for a minimum of 10 km, eastward into the basin. The WSV contains a complex fan system at its mouth where the dimensions change markedly.

The BATHY 2000 sub bottom profiler data shows evidence of sediment infilling and sediment drape on the WSV floor in all profiles. Some sub bottom profiles show a continuous high intensity reflector close to the seafloor, suggesting a sandy sediment drape, while others display a series of high return reflectors suggesting layers of sediment infilling (Figure 26). Multi-channel seismic data displays a levee complex which records
channel incision and fill history (Figure 27). A broad zone containing multiple channel forms is observed in the sedimentary succession of the western shelf around WSV, dating back to at least 17 Ma (Personal Communication, Henrys, 2011).

**Hummocky Terrain**

An area containing many enigmatic mound like features is observed just south of the TSV system (Figure 28). These landforms consist of parallel linear ridges and sub-arcuate ridge sets, streamlined elongate 4-sided “islands” and small gully forms. Parallel linear ridges observed north of TSV 2 are, on average, 6052 meters long, 5 meters in relief, 300 meters wide and have 997 meters average spacing (Figure 29 a). These ridges have a similar trend and slope to escarpment A which is located directly downslope. Sub arcuate ridge sets are observed directly south of TSV1 and between TSV1 and TSV2 (Figure 28). They are on average 786 meters long, 293 meters wide, 6.3 meters in relief, spaced 452 meters apart and have variable landward and seaward slopes of 2.7-6.7° and 1.9-8.6, respectively, and highly variable trend of the ridge long axis, with some trending 45° (northeast) to the slope of the shelf. Similar sub-arcuate ridge sets are observed on top of and south of Taylor Knob which is a prominent sub-circular seaward-tilting knob located immediately south of the main trunk of the TSV. The composition of Taylor Knob is unknown. These ridges on top of Taylor Knob, are quite subdued and have local relief of less than 5 m.

The lower reaches of TSV1 contain two streamlined elongate “3 sided islands” that have relatively flat upper surfaces and are bounded on all sides by channels (Figure 29 B).
The ‘islands’ are ~40 meters in relief, have elongation ratios of 6.5, variable trends of their long axis, lee sides tilted seaward and sloping 2.2°, stoss sides tilting landward 6.7°. Gullies are observed at the eastern edge of the hummocky terrain. These gullies are on average 1,700 meters long, 7.6 meters deep and 571 meters wide. Larger gullies are observed at the southern limit of the hummocky terrain and occur as two distinct channel forms in their upper reaches and form one channel that joins into the main Erebus Sea Valley. These larger gullies have an average length of 2200 meters, average width of 600 meters and an average depth of 12.5 meters. The recollected channel downslope is 1100 meters wide while maintaining the 12.5 meter depth.

The BATHY2000 data displays a pervasive upper seismic unit with high-intensity return and many antiformal diffractions (Figure 28, inset). Very little internal structure is observed below this high intensity seismic unit. In a few locations, a thin, transparent and chaotic unit is observed and generally is overlain by a flat, continuous diffraction free high intensity seismic unit. These areas lie along the southern edge of the hummocky terrain. The presence of the intense seismic unit and diffractions implies the presence of a hard substrate possibly sandy material.

Curved Trough

One feature at the southwestern extent of the multibeam coverage has a tuning fork type shape. This feature cross cuts escarpment A, is 619 meters wide, 2795 meters long and ~15 meters deep. (Figure 30) The subbottom profiling data shows this feature has a chaotic internal structure with a discontinuous hummocky high intensity upper reflector with multiple diffractions (Figure 30, inset).
Erebus-Bird Basin Morphology

The Erebus-Bird Basin is an elongate basin marking the flexural moat of the Ross Island volcanic edifice. The basin trends north, with a long axis over 65 km long and a short axis of 11 km at its maximum (Figures 16 and 31). The average slope of the basin north-south is quite low with a range of .001-.01°. The slopes into the basin are ~1°, 1.5°, .2° and ~5° on the southern, western, northern and eastern margins respectively. Seismic data shows a sequence of flat-lying basin-filling sediments in the basin, accumulated over the last ~2 Ma (Fielding et al., 2008). The Erebus-Bird Basin is characterized in the south by a broad platform (Figure 16, P1&2), channel forms, many small conical forms and an overall irregular topography. In the north, the Erebus-Bird Basin is flat, with smooth topography characterized by low relief channels and a field of streamlined linear ridges.

Erebus Channel System

The Erebus Channel System (ECS) is a 80+ km long, low slope (.16°), sinuous multi-channel system extending from southern McMurdo Sound through the entire length of the Erebus Basin and out of McMurdo Sound through the Bird-Beaufort Corridor (Figure 31). The ECS has many tributaries from the eastern, western and southern margins of the Erebus-Bird Basin. There are multiple channels near the central region of the Erebus-Bird Basin. In the southern extent of the Erebus-Bird Basin, a relatively dense network of tributary channels, which emanate from beneath the McMurdo Ice Shelf, feed into the main Erebus Channel System. At the head of the ECS, near the southern slope, the ECS is 25-40 meters deep and 1,250 meters wide, while in the center of the basin, the channel
system is ~10 meters deep and on average ~600 meters wide (Figure 31, B-B’ and C-C’). The ECS is anastomosing and contains multiple channels that remain continuous for over 50+ km. Local variations in trend are clearly related to submarine volcanism as the main course of the ECS is diverted around larger cones and dikes. This is observed in Wohlschlag Bay (Figure 37). Subbottom profiling data of the ECS reveals a thin continuous high intensity upper reflector with a few profiles containing a subdued chaotic thicker reflector (Figure 31).

**Patchy Linear Ridge Set**

A set of discontinuous, patchy linear ridges is observed along the north-central Erebus-Bird Basin (Figure 32). These ridges range in length from 1-20 kilometers, with the average length 6.6 kilometers. Local relief is between 4 and 6 meters, average depth is 842 meters below sea level and an average along-trend slope is .1° to the northeast. Spacing between each observable ridge is on average 372 meters. Bathy2000 shallow seismic profiles perpendicular to the trend of the ridges show a series of sharp ridges with an irregular spacing formed in a seismic facies characterized by moderate intensity and chaotic nature (Figure 32, inset).

A field of hummocky terrain is observed north of the linear ridges. Individual hummocks in the terrain are of similar relief, water depth, spacing and trend to the patchy linear ridges described above (Figure 32).

**Bird-Beaufort Corridor**

Channel forms are observable on the seafloor directly north of Mt. Bird (Figure 33). The anastomosing channel forms are on average 5-10 meters deep, 460 meters wide and
extend parallel to the lower reaches of the Erebus Sea Valley for over 18 kilometers. Local high areas between closely spaced channel forms are “streamlined” with gentle slopes with the long axis trending parallel to the trend of the channel forms. Figure 33 shows a distinct wide zone containing multiple channels; this wide zone is bounded by flat banks containing a thin drape of a transparent seismic unit. In the more streamlined region to the east, channel forms are confined to a much narrower corridor leading out of McMurdo Sound

*Ross Island Slope Morphology*

The eastern slope of McMurdo Sound is characterized by the steep flank of the Ross Island volcanic edifice and does not contain a traditional flat shelf (Figure 16). Along this flank, the shelf is generally nonexistent, but Erebus Bay may contain shallowest depths along the widest (10.2 km) and lowest slope (2.7°), of all margins of Ross Island. The average gradient of the Ross Island slope from the coastline to the Erebus Basin is 5.34° but local maxima over 8° exist. The average width of the Ross Island slope is 5,500 meters wide. Many seafloor features are observed, including flat-topped mounds, a set of linear ridges, volcanic cones and fissure dikes and tributary channels into the Erebus-Bird Basin. Erebus Bay contains a broad platform in water depths of 550 and 650 m. This platform is ~4 km wide and ~17 km long sub-parallel to the coastline and has numerous flat topped mounds with local relief of ~80 meters. There is no physiographic expression of the Erebus Basin in this platform area.

*Flat-Topped Mounds*
Flat topped mounds of McMurdo Sound are mostly found within the platform area located along the southwestern slope of Ross Island (Figure 34, 35). The majority of the mounds occur in a distinct 10 kilometer-long lineament trending to the northeast (Figure 34). The individual mounds along this lineament are sub-circular, yet appear to coalesce into an elongated ridge. On average, mounds have seaward-dipping tops with shallow .77° slope, 12.89° landward-dipping slopes and 10.2° seaward-dipping slopes. Average long- and short-axis lengths are 1,323 and 718 meters (Figure 34). The depths of the flat tops range between 530 and 640 mbsl with an average of 547 mbsl. Local relief of the flat-topped mounds is between 40-100m. Observations from subbottom profiles reveal a very intense, chaotic upper-most seismic facies, with scattered antiformal diffractions. Very little internal structure is observed (Figure 34). Multi-channel seismic data shows the presence of antiformal pull-ups of the seismic stratigraphy. Some profiles display continuous, horizontal, upper seismic reflectors overlying a thick, chaotic, low-intensity seismic package which in turn overlies a package of continuous, parallel, sub-horizontal reflectors (Figure 35). Seismic line NBP0401-119 shows a series of ridges with chaotic, antiformal velocity “pull-ups” overlain by a continuous bright upper seismic reflector. NBP0401-124 shows a package of sub-horizontal, continuous seismic reflectors overlain by a subdued, chaotic seismic package with many seaward-dipping clinoforms. This sequence is capped by a bright continuous upper seismic reflector. These two lines pass over the same lineament and in the foreground of Figure 35, they cross showing the cap of flat lying reflectors and the underlying chaotic seismic facies.

*Linear Ridge Set*
A set of 7 parallel linear ridges is observed on the west-central Ross Island slope in southern Wohlschlag Bay (Figure 36). These ridges range in length from 700 - 4,500 meters, have an average relief of three meters and have a spacing range between 163 and 385 m with an average spacing of 316 meters. The crests of the ridges lie between 760 and 780 meters below sea level and extend ~6 km from the coastline of Ross Island.

Volcanic Cones and Ridges

Sixteen large volcanic dike forms are observed with varying dimensions but a common seismic character of extremely high intensity return and complete “washout” of any subsurface structure (Figure 37). Two of these landforms have conical shapes with elongation ratios of 1.1 and 1.3, 12 are elongate with axial ratios of 1.75-4.55, and 2 are extremely elongate with axial ratios of 8.0 and 17.7. Average lengths and widths of these features are 2,187 and 1554 meters, average depths are 715 meters below sea level, local relief is 20-140 meters, and average slopes and 19.4°. The trend of the long axis for the elongate ridges varies between 025° and 285° with ridges in the south having a northeast trend and features in the north trending to the northwest. In Wohlschlag Bay, a fissure dike trending ~285° is cross cut by a ridge trending due north.

A ridge complex of en echelon linear dikes is observed at the termination of the TSV system (Figure 38). The ridge complex, composed of 3 ridges trending roughly 300°, are ~3km long with local relief ~30 m and have steep (6-11°) sides. Sub bottom profiling data shows a high intensity chaotic seismic character similar to the features observed in Wohlschlag Bay and southern McMurdo Sound (Figure 38 inset)
Mackay Sea Valley

The Mackay Sea Valley (MSV) is a major physiographic feature on the seafloor and defines the northwest limit of McMurdo Sound (Figure 14). Mackay Sea Valley emanates from Granite Harbor. The valley can be divided into 2 distinct provinces: the upper MSV and the lower MSV (Figure 39). The upper MSV averages 3.5 kilometers in width, has a depth range of 350-950 meters below sea level, has a length of ~ 27 km, and has valley walls that slope steeply at 15°. The lower MSV averages 13.6 kilometers in width, has a depth range of 530-950 meters below sea level and extends 28+ kilometers out into McMurdo Sound. Each province of the Mackay Sea Valley contains a unique assemblage of seafloor features

Upper Mackay Sea Valley

The upper MSV contains scoured bedrock (Barrett et al., 1995) in the form of streamlined linear bedforms. The bedrock here is crystalline bedrock of Paleozoic age. These features can have up to 50 meters of relief, extend 1.5 kilometers and have distinct lee and stoss sides. Four distinct “overdeepened” elongate basins are located along the axis of this part of the valley. These basins are roughly 1.5 kilometers wide, 5 kilometers long and are over 200 meters deeper than the average depth of the sea valley. The basins are not connected via channel forms and are isolated topographic lows.

Lower Mackay Sea Valley

The lower MSV contains parallel, streamlined elongate bedforms and broad transverse to valley elongate ridges. Highly elongate ridges are over 20 km long, 4-6 meters in relief and have an average spacing of ~200 meters (Figure 39). The long axes of these
streamlined elongate ridges are roughly parallel with the trend of the sea valley itself and these ridges extend through the entire length of the lower MSV. In the lower reaches of the lower MSV, the elongate ridge sets curve from east-west to northwest-southeast. Four distinct, high-relief, broad elongate ridges are observed. Two MSV transverse ridges, have ~90 meters of local relief and extend 4.5 km across the lower MSV. Two larger broad elongate ridges rise from 700 mbsl to 549 mbsl and have local relief of up to 140 m. The most completely imaged of these ridges is over 10 km long and ~6 km wide. Numerous escarpments are observed on the down-valley slopes of these ridges and the escarpments have a local slope of up to 10° compared with the overall slope of 1.5°. The up-valley slope is up to 3°. Superposed on the broad ridges are sets of highly elongate, valley parallel, linear ridge sets.

*Mackay Fan*

A large fan-shaped mound extends eastward from the Mackay Sea Valley (Figure 40 and 41). This fan has local relief of over 100m relative to the surrounding deep troughs to the North and South and extends 60+km outboard of the most prominent bedrock knob within the MSV. Bedrock here is defined as Cenozoic sedimentary rock of the Victoria Land Basin. Multichannel seismic data reveals a flat-lying seismic package overlying dipping sediments (Figure 41). A distinct package of sediments overlying this angular discordance is interpreted as sedimentary deposits of the fan (Figure 40). Seismic profile USGS 414 shows a strike oriented cross sectional profile of this fan with fan deposits mapped above the angular discordance between dipping and flat lying reflectors. (Figure 40).
Beaufort Island Region

The region around Beaufort Island is shown in Figure 42. The major physiographic features of this bathymetric province are two volcanic seamounts, broad wedge-shaped platforms with eastward-facing linear escarpments, elongate streamlined ridges and the volcanic Beaufort Island. Beaufort Island lies above sea level and has volcanics near the summit dated at ~6.77-6.8 Ma. The seamounts to the east and north of Beaufort Island are dated by dredge samples to 1.94 Ma and 3.75-3.96 Ma, respectively (Rilling et al., 2009). A trough ~7.5 km wide, 50 m deep and 45 km long is observed and trends ~east-west directly between the 3.75 Ma seamount and Beaufort Island. This trough contains many linear escarpments and streamlined bedforms on its north and south banks and contains fewer streamlined bedforms along the axis of the trough.

Broad Wedge Shaped Platforms

Numerous wedge shaped bodies with flat tops and eastward facing escarpments are observed and trend roughly north-south with individual escarpments 5-13 km long. These features occur primarily near the flanks of the volcanic seamounts and are absent within the trough north of Beaufort Island. The wedges have elongate streamlined ridges on top of them, generally trending east-west, perpendicular to the trend of the escarpments. Multichannel seismic data reveal the internal structure of these features (Figure 43). The wedge-shaped sediment packages contain eastward-dipping clinoforms. Seismic profile NBP 0401-103 shows two distinct wedges with stacked eastward-dipping reflectors. Wedges are over 2.5 km long and approximately 250 meters maximum thickness.
**Elongate Streamlined Ridges**

Fields of elongate streamlined ridges are observed both near the seamounts and within the broad 75 km wide trough north of Beaufort Island. These ridges are most well defined along the northern slope of Beaufort Island where they occur in a very distinct field. The ridges are laterally continuous for 18+ km, spaced 180-260 meters apart and have local relief of 2-4 meters. Sub-bottom profiling data shows these ridges to be formed in a thin acoustically transparent seismic unit overlying an intense continuous chaotic seismic facies (Figure 42, inset).
Interpretation

Grounded Ice Footprint in McMurdo Sound

McMurdo Sound has experienced repeated occupation by grounded ice and a lingering ice sheet has been proposed to have been present in McMurdo Sound until ~8 ka (Denton and Marchant, 2000 and Mackay et al., 2008). Absolute dating of grounded ice extent is impossible in this study. The required age data are not available yet cross cutting relations and terrestrial age data from the Dry Valleys and Scott Coast as well as McMurdo Ice Sheet retreat history constructed by other researchers forms the basis for LGM reconstruction in McMurdo Sound. It is hypothesized that the West Antarctic Ice Sheet began retreat from the shelf edge at ~12 kya and lingered in the McMurdo Sound area until retreating to its current position ~8kya (Mackay et al., 2008, Denton and Marchant, 2000, Shipp et al., 1999 and Domack et al., 1999). Using these data, a framework for the ice extent at the LGM in McMurdo Sound can be constructed.

It is well known that glaciations tend to destroy, fill in or plane off signatures of previous glaciation, therefore, most landforms on the seafloor are indicators of the most recent glacial advance and retreat cycle. Further, landforms that indicate rapid advance, such as Mega Scale Glacial Lineations (MSGLs) and drumlins, are generally best preserved in areas of rapid retreat (Wellner et al., 2006). Slowly advancing ice sheets do not produce a distinctive assemblage of landforms while retreat features of slow-moving ice sheets
tend to destroy or modify features produced during advancing and produce a series of back-stepping features such as corrugation ridges or grounding zone wedges which are typically associated with the grounding zone (Wellner et al, 2001, Dowdeswell et al, 2008 and Jakobsson et al, 2011). These concepts are integral to interpreting ice mass grounding and the speed at which it moved.

Features marking the maximum extent of grounded ice behavior in McMurdo Sound are now used to construct the footprint of grounded ice.

*Mackay outlet Glacier System*

The Mackay Glacier is a large glacial system and serves as an outlet of the East Antarctic Ice Sheet that flows across the Convoy range and into Granite Harbor. The Mackay Glacier, presently, has a drainage basin of 4600 sq. km and has a surface velocity along its 165 km long flow line of 250 m/yr (Macpherson, 1987). Currently, the Mackay Glacier is grounded offshore and has a floating glacier tongue that extends into Granite Harbor (Powell et al., 1996). The modern grounding zone has been observed and is discussed in Powell et al. (1996). The last major ice advance occurred 18-21 kya and is responsible for the current morphology (Barrett et al, 1995 and Powell, 2001). The ancestral Mackay Sea Valley was possibly formed as early as the early Miocene, as suggested by offshore drilling and sediment fill (MCGinnis, 1981; Hambrey and Barrett, 1993; Barrett et al., 1995; Powell et al, 1998; Cape Roberts Science Team 1998, 1999, 2000; Powell, 2001, Williams et al., 2011). Leventer et al. (1993) and Domack et al. (1999) provide evidence for recent Holocene advances of the Mackay Glacier system. Recent studies by the Mackay Sea Valley Seismic Project, part of ANDRILL’s efforts to
obtain high resolution records of Holocene events, have imaged numerous sedimentary mini-basins containing horizontal reflectors that once drilled and cored will add to the current knowledge of the Holocene activity of the Mackay Glacier system (Williams et al., 2011).

Observations of the seafloor and interpretations of landforms, in this study, agree with the above interpretations and add new detail. Features found in the upper MSV, such as scoured bedrock and overdeepened basins, are signatures of grounded ice and show the extent of glacial erosion (Barrett et al.; 1995 Hooke, 2005 and Howat, et al., 2008). In the lower MSV, the highly elongate, valley-parallel, low-relief bedforms are interpreted as Mega Scale Glacial Lineations (MSGLs) from morphologic analysis and comparison with similar features observed around the world. MSGLs form in soft diamictons and generally record the last advance of grounded streaming ice (Shipp et al, 1999 and Wellner, 2006). The ridges transverse to the valley trend are interpreted as dipping sedimentary layers forming topographic highs where the retreating ice tended to stop in times of still stands and provides a shallow pinning point for the ice. This interpretation is based on investigations undertaken on marine terminating glaciers in Greenland and the potential for these ridges to serve as pinning points for a retreating glacier (Howat et al 2008). The observation of many escarpments within the lower MSV, may record local movements of the grounding line. Deposition of grounding line sediments may provide further information of local retreat history during a short window in time. It is observed that once the ice retreats past these topographic highs, the retreat accelerates until the next bedrock high is encountered (Howat et al., 2008).
The Mackay Glacier outlet system contains a very large outwash fan that extends 10s of km into northern McMurdo Sound and the style of deposition appears to have delivered abundant sediment to the northern limit of Erebus-Bird Basin, Wilson Sea Valley and the Beaufort Island region, as seen by statistical analysis of stratigraphic intervals of piston cores throughout McMurdo Sound (Figure 44, Bartek, 1989). The age of this fan is disputed but a Holocene age is suggested and is determined with diatom assemblages and radiocarbon dating of bulk organic carbon (Bartek, 1989, Leventer et al., 1993 and Domack et al., 1999). The numerous lineations observed in the Beaufort Island region and outboard of the Mackay Sea Valley fan have a trend and morphologic expression similar to those of the MSGLs of the Mackay Sea Valley. Further, the linear escarpments and wedge structures are interpreted to represent grounding zone wedges (GZWs) of a retreating, greatly expanded Mackay Glacier (Paleo Ice Stream?) Preserved MSGLs found stratigraphically on top of retreat features (GZWs) indicate that retreat between stillstands were rapid (Dowdeswell et al., 2008).

The morphology of the Mackay Sea Valley is used in this study as a local analog for interpretations of grounded streaming ice from the LGM to present.

*Grounding Line Reconstruction*

*Grounding Zone Wedges*

Features considered as analogs to the prominent linear escarpments of Western McMurdo Sound include Shelf Edge Deltas, Contourites and Grounding Zone Wedges (Table 3). The escarpments appear to be most closely related to GZWs considering surface morphology, subsurface structure and simply that this region has seen repeated
occupation by grounded ice in the past. Observations of GZWs in other previously glaciated marine environments show prominent seaward-dipping clinoforms with chaotic seismic facies packages down-slope overlying unconformities as typical subsurface signatures (Figure 45), Anderson et al., 2002, Howat and Domack, 2003, Heroy and Anderson, 2005, Cofaigh et al., 2008 and Dowdeswell et al., 2008). On the other hand, the absence of features typically associated with GZWs, such as MSGL overprinting and drumlins does suggest caution when categorizing these features as typical GZWs. The thickness of the wedge of sediment below the escarpment is much thinner than in a typical GZW, yet this wedge contains all of the attributes typically associated with a GZW (Clinoforms, chaotic “slump” features and underlying unconformity).

Alternatively, this wedge may represent a “shelf-edge delta” yet is not located at the shelf-slope break and does not show any history of formation (aggradation, progradation).

Ross Island Margin

Flat-Topped Mounds

The flat-topped mounds of southeastern McMurdo Sound are interpreted here as features indicating grounded ice. Extensive flat tops and a consistently steeper landward slope vs. seaward slope, with the latter being indicative of drumlinized features, can be used to interpret past ice movement (Menzies, 1979; Benn and Evans, 1996). Local analogs are found farther to the north in the Ross Embayment (Magee and Wilson, 2010), where flat-topped mounds associated with Neogene faulting are observed and are interpreted at subglacial drumlinized volcanoes (Magee and Wilson, 2010). Drumlins, tuyas, tindars,
mud volcanoes and carbonate mounds are considered as possible origins of the features seen in this study (Table 3, Figure 46). Surface morphology reveals similar characteristics to the seafloor hills of Magee et al. (2010). Compared with features of Magee et al. (2010), the flat topped mounds have similar elongation ratio, steep vs. shallow slopes and geographic orientation relative to present interpretations of grounded ice flow direction; taken together, this suggest these features indicate grounded ice. The Bathy2000 sub-bottom profiling data used in this study shows an intense chaotic uppermost seismic facies with some profiles showing many antiformal diffractions. This seismic character implies a hard substrate that does not allow the penetration of energy to the underlying units. The internal structure, as seen through multi-channel seismic data, provides the key to interpreting the origin of these features. Seismic profile NBP0401-119 crosses directly over the linear array of mounds and ties to NBP0401-124 (Figure 34). NBP0401-119 shows many diffractions, seismic pullups of internal reflections, a continuous upper seismic package and partial washout of subsurface stratigraphy below 1 second (twt) (Figure 34). Proximity to known volcanic features, such as the Dellbridge islands and noticeable elongate submarine volcanic cones and fissure dikes suggests a volcanic origin for these mounds. A key difference from the surrounding volcanic features, the flat tops, is interpreted as the result of ice contact “planing off” tops by an over-riding ice mass. NBP0401-124 shows the internal structure of the flat top of a mound (Figure 34). A discontinuous, sub-horizontal seismic package is overlain by a thick, highly chaotic seismic facies which is capped by an intense, continuous sub horizontal package. The uppermost seismic package is interpreted to be grounding zone
glacial sediments deposited by over-riding ice, while the underlying internal structure is interpreted as underlying volcanic material. An alternate hypothesis would be the formation of flat tops due to cold water carbonate mound development via coral colonization. Key similarities with other observed cold water carbonate mounds include similar water depth range and relief but cold water carbonate mounds typically have an elongate form, rarely have flat tops and are associated with flow features such as sand waves (Mienis et al., 2006). Without direct sampling of these features and using all available data and analogs, the formation of these features by sub marine volcanism and subsequent drumlinization is favored in this study. The development of a steep landward dipping slope and a shallow seaward dipping slope provides the critical observations to interpret these features as marking the previous extent of locally grounded ice. Direct sampling of these features will help determine their origin and will result in a more robust interpretation.

**Morainal Ridges**

The linear ridge set found along the Ross Island margin in Wohlschlag Bay are interpreted as recessional moraines formed by a retreating ice mass nucleating from Ross Island. The moraines mark the extent of ice extending from the Ross Island coast at the time the inferred moraines were formed, restricting the ice expansion to ~16 km offshore to depths of nearly 780 mbsl. Proximity to flat topped mounds, interpreted to constrain grounded ice extent, provides evidence that these features were formed by a similar ice mass. Similar recessional moraines are observed in southern McMurdo Sound (Figure 47, Greenberg and Jakobsson, 2011 and Anderson and Jakobsson, 2010). These
recessional moraines occur in much shallower depths (415-440 mbsl) and in higher frequency but have similar local relief, occur in parallel sets and have a coastline-parallel orientation.

*Northern and Southern McMurdo Sound Margins*

No evidence of submarine landforms marking a grounding line exist in the northern or southern margins of the Erebus-Bird Basin. In the south, limited multibeam data does not allow to complete characterization of the seafloor. Along the northern margin of Erebus-Bird Basin, only grounded ice flow features are observed and are the landforms used for reconstructing the grounded ice footprint in this area.

*Streaming vs. Slow Moving Ice Advance*

Mega Scale Lineations

The linear ridges located in Bird Basin/Northern Erebus Basin are compared with other linear ridge sets on polar marine continental margins on the basis of morphology, orientation and relation to previous ice models and inferred flow patterns (Table 5, Figure 48). The orientation (070°) of these ridges is consistent with the interpreted ice flow direction of Denton and Marchant (2000), but does not provide clues as to the ultimate direction of ice flow (NE vs SW). Mega Scale Flood Lineations (MSFLs), which are formed by counter rotating, longitudinal vortices in broad turbulent subglacial meltwater floods, or Mega Scale Glacial Lineations, which are lineations formed by subglacial scouring of a low shear strength sedimentary substrate by grounded ice are, processes responsible for similar features throughout previously glaciated continental margins (Shipp et al., 1999, Cofaigh et al., 2008 and Shaw, 2008). While similar in process to
MSGLs, an alternative hypothesis of Shipp et al (2001) shows the formation of patchy lineations that are found in a thin lodgement till with high shear stress and is interpreted as forming from a slow moving grounded ice mass. While it is difficult to differentiate between the potential processes, this study favors formation by grounded ice in a thin sedimentary unit of high shear stress, namely a lodgement till. This interpretation is based on analog with other features observed in the Ross Sea, as well as the absence of transitional rapid ice flow features such as grounding zone wedges and drumlinized features, which are usually closely associated with MSGLs. The implication for this interpretation is that at the time of formation of these features, the overlying ice mass was in direct contact with the seafloor. Direct sampling of the seafloor may help determine sediment type and provide age control for these features.

Mega-Scale Glacial Lineations

The Mackay Sea Valley and the Beaufort Island region are the only areas containing evidence for streaming ice on a soft sedimentary substrate. The parallel streamlined ridges appear in many orientations and are used to infer ice movement. MSGLs closely associated with the MSV appear to emanate eastward out of the MSV and turn slightly to the southeast into an area lacking high resolution bathymetry data. In the Beaufort Island area, MSGLs are oriented east-west and at their western extent appear to bend to the northwest. The implication of the bending MSGLs of both the MSV and Beaufort Island areas is that two different ice masses constructed these landforms. This be a signal of interaction of an expanded Ross Ice Sheet with an advancing Mackay Paleo-Ice Stream.
The region, lacking high resolution multibeam data, has a potential to highlight a complex and possibly time varying interaction (Figure 49).

Streamlined Landscape

A transition zone of landforms in the Bird-Beaufort corridor marks the previous position of grounded streaming ice transitioning to stagnant-slow moving ice. The nature of this grounded ice remains enigmatic as this corridor is the traditional path of icebergs and currents into McMurdo Sound. This transition is quite marked and lies between the downstream end of the Erebus Channel System and the streamlined landscape of the eastern Bird-Beaufort Corridor. The “mini-basin” (Figure 33, in purple) shows many channel forms and appears to be the nexus of ice/water moving out of and into McMurdo Sound. This area shows a complex interaction of processes controlling sedimentation and landform production and should be the site of further analysis.

Retreat Signal in McMurdo Sound

The appearance of landform sets transform to ice flow direction provides evidence for episodic slow retreat of grounded ice. Parallel grounding zone wedges on the western slope of McMurdo Sound, as well as the morainal ridges of Wohlschlag Bay, show that retreat toward the coastline was episodic and relatively slow as compared with retreat in the MSV and Beaufort Island areas. Figure 50 shows the mapped landforms indicating retreat style and provides the framework for interpreting post LGM ice behavior.

Grounded Ice Volume
If the LGM extent were completely grounded, the total volume of ice, mapped by Denton and Marchant (2000) would have been $1.73 \times 10^4$ km$^3$ giving a total mass of $1.59 \times 10^{16}$ kg. After a period of rapid break out at 11 and $10^{14}$C ka BP, nearly 1,500 km$^2$ would not be covered by grounded ice. Rapid break-out in the McMurdo Sound removed nearly $2.1 \times 10^3$ km$^3$ of ice that had previously been grounded within the Erebus-Bird Basin. Depths of flat-topped mounds, grounding zone wedges, recessional moraines and mega scale lineations provide the maximum depth and extent of grounded ice and are used to define the “ungrounded” area. By integrating seafloor observations and operating on the interpretation that part of the Erebus-Bird Basin was ungrounded at some time post-LGM this study can constrain ice volume at particular intervals of time. Assumptions for these volume calculations include: 1) these features do in fact record LGM and post LGM footprints and; the LGM terrestrial upper surface of the ice sheet is correct. Absence of direct age data does not permit assigning absolute ages to seafloor features, in this study. Ice-Proximal Features in McMurdo Sound

*Channelized (Meltwater) Sediment Transport*

Many channelized features are observed on the seafloor of McMurdo Sound. The most striking are the Taylor, Wilson and Erebus Sea Valleys. These channelized features were responsible for delivering major amounts of sediments to local basins and have a range of morphologic characteristics (Table 7 and Figure 51, 52). Channelized features found in previously glaciated terrains are characterized by their mode of formation: mainly proglacial vs subglacial. Proglacial channel forms, or gullies, are generally observed beginning at the continental shelf break and are observed to incise the continental slope
Gullies, initiated at the shelf break, are up to 1 km wide, have depths less than 100 m and extend as much as 10 km downslope where they merge to form deep sea channels (Wellner et al., 2006, Rebesco et al, 2007). Gullies are interpreted to form at the terminus of grounded ice where meltwater, originating from deformation till in glacial troughs, is thought to be released (Wellner et al., 2006).

Subglacial channel forms have been observed mainly in crystalline bedrock associated with the upper reaches of paleo-ice stream troughs (Anderson and Shipp, 2001, Lowe and Anderson, 2003 and Domack et al., 2006). Lowe and Anderson (2003) identified 3 different types of channels in crystalline bedrock and interpreted the channel forms as forming during subglacial flooding by meltwater. Meltwater must have been widespread over many advance and retreat cycles in order to erode some channels up to 600 meters into crystalline bedrock. Subglacial channels are controlled by the structural grain of the bedrock as shown by channels intersecting at 50° to 75° in the paleo ice stream of the Palmer Deep (Domack et al., 2006) Typical defining characteristics of subglacial channels are deep (up to 600m) incision into bedrock, undulating along-channel profiles, diversion around bathymetric highs, and connecting glacial overdeepenings (Lowe and Anderson, 2003, Domack et al, 2006, Benn and Evans, 1998). Meltwater on a crystalline bedrock tends to channelize due to the influence of overlying ice pressure and rugged topography of the bed and undoubtedly influences velocity and stability of overlying ice (Lowe and Anderson, 2003). Tunnel valleys are also observed in a sedimentary substrate as seen in the western Ross Sea and in the Canadian Arctic (Wellner et al., 2006 and
Kristensen et al., 2008). Tunnel valleys formed in sedimentary substrate can create a network of stacked valleys observed in multichannel seismic data, which provides detailed time slices of individual tunnel valley development (Kristensen et al., 2008). Channel forms of non-glaciated terrains are also considered in this study. Turbidite channels and deep sea channels are included as analogs for other sediment transport mechanisms. Typically, turbidite channels are found in most upper submarine fans of major rivers of the world such as the Mississippi, Amazon, Indus, Bengal, Zaire, Toyama and Rhone, as well as many smaller examples (Deptuck et al., 2003). Turbidite channels develop extensive channel-levee systems and typically have a “gull wing” form in seismic profiles (Bouma et al., 1985, Rebesco et al., 2006). These channels act as great conduits delivering sediments to the deep sea, typically, in the form of lobe-fan deposits at the transition from the slope to the deep sea (Deptuck et al., 2003). Deep sea channels are linked to turbidity currents. Deep sea channels are long (100s of kilometers), sinuous channel forms of the deep marine environment. Like turbidite channels, deep sea channels are constructed by turbidity currents which are a mixture of water and suspended sediment that are transported along the seafloor as underflows. Analogous to meandering rivers, deep sea channels have high sinuosity, bend cutoffs, chute channels and pools and crevasse splays, as well as point bars and scroll bars (Das et al., 2004).

Erebus Channel System

The Erebus Channel System is interpreted here to be non-glacial in origin and initiated by sediment-laden water from beneath the McMurdo Ice Shelf. The channel system is actively fed by sediment gravity flows from the Ross Island slope (Bartek 1989).
Analogous to deep sea channels, the Erebus Channel system plays a vital role in transporting sediments into the Erebus-Bird Basin and out of McMurdo Sound via the Bird-Beaufort corridor. The mechanisms that formed this channel are unknown but modern currents, sediment gravity flows and sub-ice shelf-sourced meltwater may be leading processes delivering sediments and fluid to the channel system. This system appears to be active today and has persisted since the last time grounded ice occupied this region, potentially at or prior to LGM.

Wilson Sea Valley

The Wilson Sea Valley is a much longer-lived sediment transport feature than the TSV. This is seen by the development of sediment onlapping surfaces and a rich history of channelized features dating back to 17 Mya (Henrys, personal communication). This system most likely records long term transport of material derived from New Harbor. Surely, turbidity currents are an active process shaping the WSV as seen by mapping of terrigenous sediment sourced from the western platform (Bartek 1989). The channel appears to be structurally as there are distinct ~90° bends along the course of the Sea valley unexplained by traditional shelf-slope relations. Further, gravity data shows a distinct ridge outboard of New Harbor and it is interpreted that the channel emanating out of Ferrar Fjord is deflected significantly around this knob (Wilson, G., personal communication). The WSV does not appear to be a feature formed by subglacial erosion due to the lack of associated characteristics of subglacial channels but it is linked to the New Harbor region and it represents a relatively minor conduit for transport of material out of New Harbor and into the Erebus-Bird Basin. Most closely related to turbidite
channels, the WSV is most likely most active during interglacials and provides a preferred flow path for proglacial meltwater.

Taylor Sea Valley

Taylor Sea Valley is interpreted to have been formed by recent discharge of sediment-laden water sourced from subglacial lakes in the TAM or from the catastrophic flooding of a large proglacial lake located in Taylor Valley. This study used the LGM ice sheet configuration and reconstruction of Glacial Lake Washburn (GLW) of Hendy et al. (2000). Using the integrated DTM, this study is able to accurately determine the volume of water in Glacial Lake Washburn (GLW). At its maximum, GLW would have contained ~38 km$^3$ of water and locally had the potential to hydraulically lift the grounded McMurdo Ice Sheet off its bed and drain beneath the ice out into McMurdo Sound.

The subsurface structure shows a newly formed channel and little development of levees typically associated with long lived channel forms such as turbidites. Additionally, the TSV is associated with many other interpreted flood features described below as part of non-channelized sediment transport landforms. TSV2 bifurcates into a sharp v shaped channel oriented roughly 45° to the slope of the seafloor. This sharp bifurcation at a high angle to the slope is also indicative of flood morphology (Baker and Nummedal, 1978). Sediment waves are observed within and bounding the TSV network and record sheet-flow of sediment-laden water.

Gullies of Hummocky Terrain
Gullies observed at the downslope extent of the hummocky terrain are features formed by channelized incision of sheet flood flow as the gradient of the western slope increases. These features are linked to the flood associated with the Taylor Sea Valley system discussed above.

Non-Channelized Sediment Transport

Sand Waves

Observed as discontinuous arcuate ridges, the sand waves of the western platform are indicative of sheet flow of sediment-laden water along the western slope. Although observed to be quite irregular laterally, locally, these occur in small sets of three to four sub-parallel ridges with similar wavelengths. A discontinuous set occurs between TSV1 and TSV2 that shows fluid flow at ~45° to the slope into the Erebus-Bird Basin. Again, these forms are linked to the TSV yet represent non-channelized flow outside the channel area. In this case, the volume of channelized flow exceeded the volume of TSV1 and TSV2 and spilled out of the channelized area and continued downslope with great energy. The discontinuous nature of the hummocky terrain may be linked directly to the topographical barrier of the Taylor Knob. Sheet flow would have been deflected around the Taylor Knob, producing local areas of stronger flow. This is observed in the two distinct sets of sand waves situated north and south of Taylor Knob.

Islands

The features identified as islands represent yet another landform indicative of flood flow. In this case, fluid flow split around the islands, eroding their upstream ends and converging on the downstream ends of these landforms. These features are bounded by
channel forms and have a flat top. Observed directly in the Scablands of Washington State by Baker (1978), “islands” are erosional remnants of basalt and loess that formed during the Lake Missoula floods. The flow split around these features and left a relatively undisturbed cap of loess, which is eroded away in the channelized areas.

Sediment Deposition Features

Fans

The TSV system contains an area of deposition in the lower reaches of its path. Downslope of the escarpments, the TSV is composed of 3 distinct channel forms that appear to die out into sharp linear ridges possibly of volcanic origin. The surface morphology of this area has a positive relief mound at the mouth of a prominent channel form originating from TSV1. This mound is interpreted to represent downslope deposition of sediments coming out of TSV. Multiple small channel forms continue to the linear ridge complex and are no longer traceable into the Erebus-Bird Basin. Therefore, TSV does not appear to significantly contribute sediment to the Erebus-Bird Basin.

Wilson Sea Valley appears to have a very distinct control on sedimentation in the Erebus-Bird basin, as observed by Bartek (1989). Terrigenous sediments linked with the WSV are observed in high abundance up to ~16 km from the mouth of the WSV. Morphologically, a well-organized fan system is observed and represented by the WSV escarpments 1-3. The WSV continues downslope, albeit more shallow and sinuous where it joins with the flat bottom of the Erebus-Bird basin. The location where the
WSV becomes less discrete is associated with the WSV escarpments 1-3. The notion that the WSV escarpments are the depositional signature of the mouth of the WSV is considered. The escarpments are features similar to the prominent escarpments of the western slope, yet trend at nearly 45° to them and appear to converge downslope. Further, the deepest escarpment is the northwestern bank of the modern WSV which suggests that the WSV flanks are products of a downslope-migrating channel. The WSV escarpments are interpreted to be the depositional product of a long lived channel and show the relatively low contribution of sediment to the Erebus Bird basin. This is purely one hypothesis and another equally viable hypothesis would be that the WSV escarpments formed by a process similar to the process that formed the prominent linear escarpments of the western shelf. In this case, grounded ice would be flowing faster in the WSV region and the location of the grounding zone would thus be linked to the WSV. Meltwater within the WSV would create a slightly different retreat style for the WSV area relative to the entire western shelf and slope.

Submarine Erebus Volcanic Province

The cones and dikes of the Erebus-Bird basin and Ross Island slope are interpreted to represent volcanism related to the Erebus Volcanic Province. Fissure dike trends appear to be linked with volcanoes of Ross Island yet some trend at peculiar angles. With the absence of composition and age data, these features remain enigmatic in regards to their associations.
Discussions and Implications

LGM and Post-LGM Glacial Environment: a working hypothesis

LGM Environment

Starting with the LGM boundary conditions of a fully grounded Ross Ice Sheet throughout McMurdo Sound, outlined by Denton and Marchant (2000), as a framework for timing of glacial events, a timeline of events since the LGM is constructed here. The only features in McMurdo Sound that may be interpreted as LGM features are the MSGLs of the Beaufort area. These MSGLs show an east to west advance north and south of Beaufort Island. Near the unnamed seamount to the north of Beaufort Island, MSGLs recording the advancing RIS take a turn north into the deep Drygalski trough directly north of MSV. The streamlined landscape of the eastern Bird-Beaufort corridor may be a record of streaming ice as it moves westward around northern Ross Island. The patchy lineations of the northern Erebus-Bird Basin may record the reduced speed of the RIS as ice enters McMurdo Sound. The lack of additional advance features in McMurdo Sound is possibly the consequence of stagnant grounded ice frozen to the bed or it is possible that sub-glacial features were formed but have been covered by post-LGM depositional processes. This study favors stagnant basal ice in this area since the driving force for the westward-flowing ice sheet is reduced drastically by the moat and the extensive eastern bed slope from the TAM coast to the Erebus-Bird Basin. The timing of
this LGM ice grounding event would last from 26.8-12.7 $^{14}$C ka BP (Figure 53) Denton and Marchant, 2000)

*Post LGM Environment*

Retreat of the RIS has been documented by many researchers and most agree that retreat initiated from the Antarctic continental shelf ~12 ka (Anderson et al., 2003, Denton and Marchant, 2000, McKay et al., 2008). McKay et al. (2008) interpreted piston core data to record rapid RIS retreat near Ross Island between 11 and 10 $^{14}$C ka BP. By ~8.9 $^{14}$C ka BP there were open marine conditions just north of Ross Island (Figure 54) (McKay et al., 2008). Using these age data and the interpreted landforms of McMurdo Sound, this study invokes a rapid break-up of the grounded ice sheet in McMurdo Sound. In this scenario, between 11 and 10 $^{14}$C ka BP the grounded ice sheet along the deep axis of Erebus-Bird Basin and Drygalski trough broke out, due to buoyancy forces, and retreated rapidly, leaving remnant grounded ice in the shallower areas surrounding local highs such as Franklin and Beaufort Islands and the coastal regions of the Scott Coast and Ross Island. Retreat around local highs in the areas north of Beaufort Island are recorded by grounding zone wedges that indicate anomalous ice retreat motions to the west and north. Retreat to the coastal margins is recorded by the locations of recessional moraines on the Ross Island coast and the extensive grounding zone wedge on the western slope of McMurdo Sound. Episodic retreat of the coastal grounded ice over the ensuing few thousand years (until ~6.5 $^{14}$C ka BP, Hall and Denton, 1999) would produce the observed recessional moraines and grounding zone wedge along the eastern and western slope, respectively. Absent of grounded ice, the Erebus-Bird Basin began to develop a
channel network at the southern extent of grounded ice. This channel network, the Erebus Channel System, was fed by glacial outwash from eastern, western and southern retreat of grounded ice. This process is presently shaping the Erebus-Bird Basin via fluid flow from the south from beneath the McMurdo Ice Shelf (Figure 55).

During the period between 10-6.5 $^{14}$C ka BP, extensive blockage of Taylor Valley by grounded ice would dam Glacial Lake Washburn and, if this lake were to rise to the height of the ice dam, the potential for hydraulic jacking existed and outburst floods would have been possible. This may be the mechanism that formed the Taylor Sea Valley system and sheet flow features of the western slope (Figure 56). The Wilson Sea Valley is much larger and appears to be much longer lived than the Taylor Sea Valley. Evidence for this comes from the observation of a levee complex and paleo-channels as old as 17 Ma (Henrys, personal communication).

In order to test this working hypothesis of LGM and post LGM glacial environment, additional data must be collected. Adding more data to key areas such as southern McMurdo Sound, western Taylor and Wilson Sea Valleys, northern Erebus Bird basin would drastically improve our ability to understand this area. Absolute age data on individual landforms will provide the temporal resolution needed to make landform analysis more robust. For example, radiocarbon dating of diatoms in the deposits in the grounding zone wedge region should give ages of 10-6.5 $^{14}$C ka BP. Additionally, higher resolution glacial retreat models should be developed and used to test the feasibility of inferred glacial behavior.

Template for the Past
The landforms observed on the seafloor of McMurdo Sound show a complex history of grounded ice, fluid flow and volcanism of many styles and potentially of different ages. Floods, turbidity currents and deep sea fluid flow are dominant processes reshaping the seafloor post LGM. The implications for the above interpretations show that meltwater has played an important role in the extent and style of deglaciation and associated sedimentation. Inferred magnitudes of such processes observed in sedimentary rock records can be compared with features currently shaping McMurdo Sound and may provide insight on glacial vs. nonglacial erosion and deposition.

It should be noted that, a large control on the dynamic environment is caused by local volcanism. For example, the weight of the Ross Island volcanic edifice has created a flexural moat enabling, locally, the great depths of the seafloor. Additionally, anomalously high heat flow can be associated with volcanic activity and relatively thin crust. These key aspects of the Victoria Land basin, namely volcanism of Ross Island, were in effect ~1-3 Ma therefore application of observed sedimentation and glacial behavior must be applied to the deep time record with caution. Flow paths of both meltwater and ice would be drastically different than those observed within most recent record.

Constraining Ice Volume

This study has provided a range of potential ice volumes for McMurdo Sound at the last glacial maximum. Further, this study has shown the extent of TAM outlet glaciers, namely Mackay Glacier, to be quite significant and may provide clues to amount of ice loss from East Antarctica. An important implication for reconstructed ice volume is its
value to modelers of post glacial rebound and the overall influence of the Antarctic Ice Sheet on global sea level. Values of mass load can be used by modelers to constrain the effects of grounded ice on the solid earth.
Conclusion

In conclusion, this study has reviewed the bathymetric provinces of McMurdo Sound using swath bathymetry, seismic data and the available sedimentary record. Full integration of marine data with terrestrial data has proven to provide the most robust interpretation of the interlinked processes that formed the assemblage of observed landforms. Further, reconstruction of the LGM and post LGM environment has provided a window into the past that may be applied to the deep time record in the area.

Future work shall focus on obtaining high resolution sedimentary and age records of the features described to obtain a more robust timing of interpreted events. The above description and interpretation of such features can form the framework for future work and outline the need for more high resolution mapping of the seafloor.
References


Domack, E., Amblas, D., Gilbert, R., Brachfeld, S., Camerlenghi, A., Rebesco, M., Canals, M. and Urgeles, R. 2006. Subglacial morphology and glacial evolution of
the Palmer deep outlet system, Antarctic Peninsula. Geomorphology 75 Pg. 125-142.


Figure 1 Regional geography of the McMurdo Sound Region with regional bathymetric contours and the NBP0401 multibeam swath bathymetry data set shown. Regional bathymetry courtesy of Black et al. (2011), topographic reconnaissance map courtesy of USGS.
Figure 2. Flowlines and surface contours of the grounded ice sheet that deposited Ross Sea Drift in the McMurdo region (data compiled by Denton and Hughes, 2000). Flow directions are determined from the distribution of erratics, the trend of meltwater channels, the trend of striations and the slope of the Ross Sea drift. From Denton and Marchant, 2000.
Figure 3. Apatite fission track age versus elevation for the TAM (from Fitzgerald (2002).
Figure 4. MODIS image overlain by multibeam bathymetry showing major structural features and drill core locations within the McMurdo Sound. Cape Roberts Project, CRP; ANDRILL Southern McMurdo Sound, SMS; ANDRILL McMurdo Ice Shelf, MIS. Red Dot-Dashed lines= major Erebus Volcanic Province features, solid black lines = faults, dashed black lines=inferred faults.
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Figure 6. Reconstruction of the entire Ross ice drainage system at the LGM with box around McMurdo Sound. From Denton and Hughes (2000).
Figure 7. Present continental-shelf setting with location of seafloor geomorphic features used to reconstruct the extent of the expanded ice sheet in the Ross Sea. Notice the lack of features in McMurdo Sound. After Shipp et al, 1999.
Figure 8. Map of McMurdo Sound showing core sites used by Mckay et al., (2008). Interpretations from these cores will provide age constraints for grounded ice sheet vs floating ice shelf interpretations of this study. From Mckay et al., (2007). BI=Black Island, CB=Cape Bird, CC=Cape Crozier, HP=Hut Point Peninsula, MB=Minna Bluff, MD=Mount Discovery, WI=White Island, WPG=Wilson Piedmont Glacier, MIS=McMurdo Ice Shelf.
Figure 9. Models for sedimentation in Ferrar Fiord. A) modern setting, B) setting during late Plio-Pleistocene, C) Early Pliocene setting. From Barrett et al., 1992.
Figure 10. Example aerial photo of volcanic rich Ross Sea Drift in the Royal Society Foothills at the western coast of McMurdo Sound. RSD is easily mapped from satellite imagery and aerial photos like this oblique aerial photo. After Denton and Marchant (2000).
Figure 11. Regional map of McMurdo Sound with letters corresponding to field site data compiled by Denton and Marchant (2000). Table 1 gives pertinent data related to the site.
Figure 12. Swath bathymetry tracklines of McMurdo Sound. Black lines=NBP0401 survey, other surveys in various colors. Base map: USGS 1:250,000 topographic reconnaissance map.
Figure 13. Seismic lines of the McMurdo Sound region pertinent to this study. Black lines = NBP0401 survey, red lines = NBP9407 surveys, blue lines = NBP9601, magenta lines = Italian surveys, olive lines = Polar Duke surveys and green lines = USGS surveys. Base map: USGS 1:250,000 Topographic map
Figure 14. Regional bathymetry of McMurdo Sound with bathymetric provinces labeled. Inset shows location in Antarctica. Dashed white line shows the termination of the McMurdo Ice Shelf and the black dashed line represents the northern limit of McMurdo Sound.
Figure 15. Regional bathymetry with locations of regional profiles of Figure 16 labeled. White lines represent thalwegs of Mackay Sea Valley (MSV) and Erebus Channel System. (ECT)
Figure 16. Regional bathymetric profiles of McMurdo Sound. Locations shown in Figure 15. Star indicates the approximate location of the Shelf-Slope break, A= artifact of IDTM, P= Platform of Ross Island Slope, EBB=Erebus-Bird Basin, NH= New Harbor, WSV=Wilson Sea Valley.
Figure 17. Perspective view of the Western Slope. Inset and arrow show location and orientation of perspective view. Notice the prominent Taylor and Wilson Sea valleys (TSV, WSV). Also notice the prominent linear escarpment cross cut by the TSV and WSV.
Figure 18. Bathymetric map showing Escarpments A-D. Topographic, Subbottom and Multichannel seismic profile locations shown on the map. Profiles located in Figure 20.
Figure 19. Plot of elevation points along strike of Escarpment A. High variability found in the data are artifacts of swath multibeam bathymetry and are considered background noise. Inset shows location on the perspective view and also shows the geomorphic relationship associated with the prominent change in slope observed on the profile.
Figure 20. Topographic and Bathy2000 subbottom profiles of the Escarpments A-D. Locations are indicated in figure 18.
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Figure 22. Bathymetric map of the Taylor Sea Valley (TSV). Labeled are the two major branches of the TSV, TSV1 and TSV2. Profile is the extracted along channel profile originating in New Harbor passing over the broad platform of the western slope and onto the slope. Topographic and subbottom profile locations are indicated on the map and can be found in figure 23.
Figure 23. Topographic and Subbottom profiles of the TSV system. Locations of profiles found in figure 24.
Figure 24. Perspective view and seismic profile of the TSV. Inset and arrow show location and orientation of perspective view. Arrows show small buried channel forms and green reflector shows the continuous, flat-laying nature of the sediments below TSV.
Figure 25. Bathymetric map of Wilson Sea Valley. Topographic and Subbottom profiles are labeled and can be found in figure 26. Inset shows location of bathymetric map. Escarpments A, C, D and WSV Escarpments labeled.
Figure 26. Topographic and subbottom profiles showing the overall infilling of the WSV. B-B’ shows a continuous drape of sediments within the channel and on the banks. Locations of profiles can be found in figure 25.
Figure 27. Seismic profile NBP-0401 118 along the western shelf. Wilson Sea Valley (WSV) shown in inset. Notice the presence of numerous channel forms and onlapping of sediments on the southern margin of WSV.
Figure 28. Bathymetric map showing the Hummocky Terrain. Insets show topographic profiles of arcuate ridge sets and (A, B, C-A', B', C'). D-D' shows sub bottom profile across the gullies of the hummocky terrain. Notice the relationship of the arcuate ridges and gullies to TSV and Taylor Knob.
Figure 29. A) Slope-Aspect map showing linear ridge sets of Hummocky Terrain. This map shows the aspect (direction of dip) of surfaces and the “pinwheel” is the legend to the aspect. Subbottom profile data shows the set of linear ridges upslope from Escarpment A. B) Bathymetric perspective view of “Islands” inset shows location within the TSV system.
Figure 30. Bathymetric map of “Tuning fork” feature. Topographic cross section (A-A’). Sub-bottom profile data shows a highly reworked nature and internal structure of this feature. Inset shows location and arrow shows orientation of the figure.
Figure 31. Bathymetric map, topographic and sub-bottom profiles of Erebus Channel System. A) Along channel profile of Erebus channel system.
Figure 32. Color bathymetric image and greyscale hillshade relief map showing the patchy lineations found on the north central Erebus-Bird basin. Inset shows location of the area. Sub-bottom profile, white dashed line, shows these sharp ridges formed in a discontinuous moderate intensity seismic unit. The hummocky terrain of this area is labeled and referred in the text.
Figure 33. Perspective view of the Bird-Beaufort corridor showing the streamlined channelforms (B-B’) and the erosional remnant of the wide channelized area in purple (A-A’). Subbottom profiles reveal a relict sediment drape on the flat edges of the wide channelized area. Inset shows location and orientation of perspective view. The flanks of Mt. Bird and Beaufort Island are labeled. White arrows represent slope into “mini-basin”
Figure 34. Bathymetric maps, topographic and subbottom profiles of the Mounds and cones of the Ross Island slope. Notice the flat tops observed in B-B’ and D-D’. A-A’ and E-E’ shows many diffractions and high intensity returns. Southeastern McMurdo Sound displays the Ross Island platform very well.
Figure 35. Perspective view of Bathymetry and Seismic data co-visualized. Inset and arrow indicate location and orientation of figure. Notice the flat lying seismic character of the line on the left (NBP-0401-124) while the line on the right contains many antiformal velocity pull ups (NBP0401-119, blue arrows).
Figure 36. Bathymetric map and topographic profile across morainal ridges of Wohlschlag Bay. Inset shows location of main figure.
Figure 37. Subbottom profile across linear fissures of Wohlschlag Bay. Notice high intensity and numerous diffractions associated with these fissures. Inset bathymetric map shows how the Erebus Channel System (Dashed white line) diverts around these ridges. Orange line marks the location of the profile and the small yellow and red figures mark the start and stop points.
Figure 38. Bathymetric map, topographic profile and 3 subbottom profiles across the ridge complex downslope of the Taylor Sea Valley system. Notice the high intensity seismic return and numerous diffractions in the sub bottom data. Locations of profiles shown on map.
Figure 39. Bathymetric map, topographic profiles, sub bottom profile of MSGLs and along channel profile showing the major features of the Mackay Sea Valley. A-A’ depicts the upper Mackay Sea Valley while B and C show the lower Mackay Sea Valley.
Figure 40. Topographic and Seismic profile of the Mackay Fan. Inset shows locations of profiles. See Figure 41 for the down fan dip profile. Inset shows the lower Mackay Sea Valley and regional fan morphology, seismic line is along Profile M1.
Figure 41. Seismic profile IT90a-75 showing the dip profile of the Mackay fan. Prominent dipping reflectors overlain by flat unconformity marks the Mackay fan and shows the history of this depositional feature. Seismic Line is in the same location as Profile MSV (figure 40).
Figure 42. Bathymetric map and subbottom profile of the Beaufort Island area. Notice lineations (red) and note acoustically transparent seismic unit associated with these lineations. Escarpments (black) are generally associated with lineations. Inset shows location of bathymetric map.
Figure 43. Seismic profiles across escarpments located along the flanks of Beaufort island and unnamed seamount. Orientation of the line is East (right) to west (left). Notice distinct wedges of eastward dipping clinoforms. Profile extent is shown in figure 42.
Figure 44. Lateral extent of Facies N of Bartek (1989). This facies is described as sediment gravity flow associated with a recent advance of the Mackay Glacier. Maps such as these serve as a key observation for interpreting sedimentation styles of McMurdo Sound. Mapped features include WSV, TSV, Escarpments, ECS and Mounds (green).
Figure 45. Considered landforms for Escarpments of McMurdo Sound. A= Idealized landform assemblage of streaming ice, B= typical grounding zone wedge, C=Idealized carton of grounding zone wedge, D= Swath bathymetry of GZWs.
Figure 46. Features considered as analogs for Flat-topped Mounds. A=Tuya, B & E =Drumlins, C=Cold water carbonate mounds, D=Mud volcanoes and F=Drumlinized subglacial volcanics.
Figure 47. Recessional moraines of Erebus Bay near the channel into McMurdo Base. From Anderson and Jakobsson, 2009. Considered landforms for Patchy lineations found in north-central McMurdo Sound. A=MSGLs, B= alternate formation process associated with MSGLs  and C= Lineations formed in lodgement till as opposed to soft till.
Figure 48. Considered landforms for Patchy lineations found in north-central McMurdo Sound. A=MSGLs, B= alternate formation process associated with MSGLs and C= Lineations formed in lodgement till as opposed to soft till.
Figure 49. Bathymetric map showing mapped features that provide ice flow direction. Arrows indicate potential ice flow direction. MSGLs=Mega Scale Glacial Lineations, SL=Streamlined Landscape.
Figure 50. Bathymetric Map showing the retreat signal in the study region. GZWs=Grounding Zone Wedges, RM=Recessional Moraines. Arrows point in the direction of inferred retreat. Blue area indicates breakout region.
Figure 51. Considered landforms for channelized features observed in this study. A) Gullies of Shipp et al. (1999), B) Subglacial Channels of Domack et al. (2006), C) Tunnel Valleys of Wellner et al. (2001), D) Subsurface structure of a turbidite channel, Niger Delta (Courtesy Stutz 2009) and E) Schematic examples of Contourite and Turbidite Channels (Rebesco et al., 2007).
Figure 52. Bathymetric map of McMurdo Sound showing the mapped channel systems of this study.
Figure 53. Boundary conditions for LGM. Grounded ice throughout McMurdo Sound from ~26-12 Ka (Denton and Marchant, 2000; McKay et al., 2008; Conway et al., 1999). Black arrows indicate flow direction at LGM.
Figure 54. Ice break out configuration at ~11-10 Ka. Arrows indicate retreat as seen recessional moraines and grounding zone wedges. Red stars show approximate locations of major volcanic islands and seamounts.
Figure 55. MIS retreat and potential Ice Configuration from ~6.5 Ka-Present. Western slope channel systems fully developed and Erebus Channel System initiated by ~6.5 Ka. Erebus Channel System maturing up to present.
Figure 56. Reconstruction of LGM environment at the mouth of Taylor Valley. The maximum extent of Glacial Lake Washburn in both plan and profile view. Inset shows locations and orientation of perspective view. Profile is from Fryxell basin into New Harbor.
### Appendix B: Tables

Table 1. Location and Drift limit withing McMurdo Sound. See figure 11 for locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Ross Sea Drift Upper Elevation Limit</th>
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<tbody>
<tr>
<td>A Minna Bluff</td>
<td>637 m</td>
</tr>
<tr>
<td>B Mt. Discovery</td>
<td>519 m</td>
</tr>
<tr>
<td>C Brown Peninsula</td>
<td>365 m (east slope) &amp; 255 m (w. slope)</td>
</tr>
<tr>
<td>D Black Island</td>
<td>522 m</td>
</tr>
<tr>
<td>E White Island</td>
<td>561 m</td>
</tr>
<tr>
<td>F Cape Crozier</td>
<td>720 m</td>
</tr>
<tr>
<td>G Cape Bird</td>
<td>590 m</td>
</tr>
<tr>
<td>H Cape Royds/Cape Barne</td>
<td>329 m</td>
</tr>
<tr>
<td>I Cape Evans</td>
<td>100 m</td>
</tr>
<tr>
<td>J Turks Head/Hut Point Peninsula</td>
<td>N/A</td>
</tr>
<tr>
<td>K Scott Coast (Cape Bernacchi to Koettlitz Glacier)</td>
<td>255 m (headlands), 315 m (Walcott Bay), 310 m (s-w) - 290 m (n-e) (Hald Is)</td>
</tr>
<tr>
<td>L Ferrar Glacier Valley</td>
<td>400 m (coast), 200 m (near Overflow Glacier)</td>
</tr>
<tr>
<td>M Taylor Valley</td>
<td>350 m</td>
</tr>
<tr>
<td>N Scott Coast (Cape Bernacchi to Koettlitz Glacier)</td>
<td>16.5–21 m (discont. Wilson Drift)</td>
</tr>
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</table>
Table 2. Measured data from regional bathymetric profiles across McMurdo Sound. See figures 15 and 16 for location of profiles

<table>
<thead>
<tr>
<th></th>
<th>Profile 1</th>
<th>Profile 2</th>
<th>Profile 3</th>
<th>Profile 4</th>
<th>Profile 5</th>
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<td>69.147</td>
<td>90.3</td>
<td>59.7</td>
</tr>
<tr>
<td>Western Shelf Gradient (°)</td>
<td>1.19</td>
<td>1.03</td>
<td>0.08</td>
<td>0.138</td>
<td>0.382</td>
<td>0.3656</td>
<td>1.19</td>
<td>0.08</td>
</tr>
<tr>
<td>Western Shelf Width (km)</td>
<td>20.6</td>
<td>16.4</td>
<td>14.3</td>
<td>13.6</td>
<td>9.1</td>
<td>14.8</td>
<td>20.6</td>
<td>9.1</td>
</tr>
<tr>
<td>Western Slope Gradient (°)</td>
<td>3.61</td>
<td>2.29</td>
<td>1.33</td>
<td>1.192</td>
<td>0.765</td>
<td>1.5374</td>
<td>3.61</td>
<td>0.765</td>
</tr>
<tr>
<td>Western Slope Width (km)</td>
<td>2.9</td>
<td>6.8</td>
<td>28.9</td>
<td>21.6</td>
<td>53.6</td>
<td>22.76</td>
<td>53.6</td>
<td>6.8</td>
</tr>
<tr>
<td>Erebus Basin Gradient (°)</td>
<td>0.5</td>
<td>0.009</td>
<td>0.043</td>
<td>0.192</td>
<td>0.002</td>
<td>0.1492</td>
<td>0.5</td>
<td>0.002</td>
</tr>
<tr>
<td>Erebus Basin Width (km)</td>
<td>0.7</td>
<td>8.5</td>
<td>11.4</td>
<td>11.5</td>
<td>13.3</td>
<td>9.08</td>
<td>13.3</td>
<td>8.5</td>
</tr>
<tr>
<td>&quot;Platform&quot; Gradient (°)</td>
<td>0.5</td>
<td>0.29</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>0.395</td>
<td>0.5</td>
<td>0.29</td>
</tr>
<tr>
<td>Platform Width (km)</td>
<td>5</td>
<td>3.8</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>4.4</td>
<td>5</td>
<td>3.8</td>
</tr>
<tr>
<td>Eastern Slope Gradient (°)</td>
<td>4.39</td>
<td>13.8</td>
<td>6.8</td>
<td>7.06</td>
<td>4.88</td>
<td>7.388</td>
<td>13.8</td>
<td>4.88</td>
</tr>
<tr>
<td>Eastern Slope Width (km)</td>
<td>7.2</td>
<td>1.5</td>
<td>3.6</td>
<td>5.5</td>
<td>6.9</td>
<td>4.94</td>
<td>7.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Table 3. Comparison chart for considered landforms in relation to the flat-topped mounds.

<table>
<thead>
<tr>
<th>Considered Landform</th>
<th>Morphology Description</th>
<th>Subsurface Structure</th>
<th>Useful References</th>
<th>Comment in relation to Flat-Topped Mounds</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drumlin</strong></td>
<td>ER=2:3:1, Long/Short Length=100m-3km/50m-400m, Relief=10-75m, Gentle long axis slope</td>
<td>Variable internal geometry, Carapace of till, Sedimentary but may contain bedrock core</td>
<td>Menzies (1979), Benn and Evans (1996)</td>
<td>Similar relief and slope but not elongate.</td>
</tr>
<tr>
<td><strong>Tuya</strong></td>
<td>ER=1:2:1, Long/Short Axis Length=500m-5km, 500m-5km, Relief=200m-1500m, Symmetric flat-topped and steep-sided</td>
<td>Basal Pillow Lavas, Hyaloclastites, Brecciated lavas forming flat-topped upper surface</td>
<td>Mathews (1947), Gudmundsson (2003), Smellie (2006)</td>
<td>Similar ER but FTM have lower relief and steep slopes not symmetric.</td>
</tr>
<tr>
<td><strong>Tindar</strong></td>
<td>ER=1:5:1, Long Short/Axis Length= up to 5km/up to 1 km, Relief: 200-700m, Elongated Ridge</td>
<td>Basal Pillow Lavas, Hyaloclastites, Brecciated lavas forming flat-topped upper surface</td>
<td>Edwards et al. (2009), Jakobsson and Gudmundsson (2008)</td>
<td>Similar ER but FTM have lower relief and steep slopes are not symmetric</td>
</tr>
<tr>
<td><strong>Mud Volcano</strong></td>
<td>ER=.7:1:1, Long/Short Axis= 500m-4km, Relief=50m-250m, Steep cone, Collapse Structure</td>
<td>Dominant mud breccias, Chimneys, Collapse structures, Chaotic Seismic Character</td>
<td>Samoza et al (2003), Díaz-del-Río et al (2003), Kenyon et al (2003)</td>
<td>Similar relief and ER but not conical and no presence of collapse structure</td>
</tr>
</tbody>
</table>

Continued on pg. 133
<table>
<thead>
<tr>
<th>Table 3 continued from pg 132</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Carbonate Mound</strong></th>
<th><strong>Seafloor Hills of Ross Sea</strong></th>
<th><strong>Flat-Topped Mounds of MCM Sound</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- ER =1.3:1</td>
<td>- ER=1-2.5:1</td>
<td>- ER=1.18:1</td>
</tr>
<tr>
<td>- Long/Short Axis= 1-4km/500m</td>
<td>- Long/Short Axis=1.5-6km/1.5-3km</td>
<td>- Long/Short Axis=1.3 km/700 m</td>
</tr>
<tr>
<td>- Relief=50m-250m</td>
<td>- Relief=40-100m</td>
<td>- Relief=40-100m</td>
</tr>
<tr>
<td>- Steep Slopes/&quot;Moat&quot;/Flow Features</td>
<td>- Asymmetric Steep slopes/Flat tops</td>
<td>- Asymmetric Steep Slopes/Flat-Tops</td>
</tr>
<tr>
<td>- Strong internal layering</td>
<td>- Unknown composition</td>
<td>- Unknown composition</td>
</tr>
<tr>
<td>- Recognition of “mound generations”</td>
<td>- Antiformal distortion of sedimentary layers</td>
<td>- Antiformal distortion of seismic stratigraphy</td>
</tr>
<tr>
<td>- Chaotic circular shape of internal reflectors</td>
<td>- Velocity “pull-ups”</td>
<td>- Variability in seismic character</td>
</tr>
<tr>
<td></td>
<td>- Associated with faulting</td>
<td>- This study</td>
</tr>
<tr>
<td></td>
<td>- Mienis et al., (2006)</td>
<td>- Similar morphology, some seismic similarities and channel separating ridges but not elongate, no “moat” and no sign of flow features formed by current action</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Similar morphology and some seismic similarities. No known faulting but observed in close proximity to known volcanic cones, dikes and fissures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Originated as seafloor volcanic cones, glacially modified then occupied by coral communities forming on hard substrate.</td>
</tr>
</tbody>
</table>
Table 4. Comparison chart for considered landforms in relation to the various lineations observed in this region.

<table>
<thead>
<tr>
<th>Considered Landform</th>
<th>Morphology Description</th>
<th>Subsurface Structure</th>
<th>Useful References</th>
<th>Relation to Linear Ridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mega Scale Glacial Lineations</td>
<td>Length/Width=8-70km/200-1300m&lt;br&gt;Spacing 10s-100s m&lt;br&gt;Height=5-30 m&lt;br&gt;Related to drumlins and occasionally have overprinting iceberg plow marks</td>
<td>Forms in “soft” (&lt;20 kpa shear strength) deforming till&lt;br&gt;Thin acoustically transparent seismic character&lt;br&gt;Overlies smooth sub-bottom reflector</td>
<td>Clark (1993)&lt;br&gt;Shipp et al (1993)&lt;br&gt;Cofaigh et al (2005)</td>
<td>Absence of drumlins, iceberg plow</td>
</tr>
<tr>
<td>Mega Scale Lodgement Lineations</td>
<td>Length/Width=7.4.5 km/?&lt;br&gt;Spacing=?&lt;br&gt;Height= 1 m&lt;br&gt;“Patchy”&lt;br&gt;Absence of other flow indicators</td>
<td>Forms in thin stiff (~100 kpa shear strenght) lodgement till</td>
<td>Shipp et al. (2002)&lt;br&gt;Cofaigh et al., (2007)</td>
<td>Presence of patchy morphology and intense return seismic facies hints at “stiff” sediments</td>
</tr>
<tr>
<td>Bird Basin Linear Ridges</td>
<td>Length/Width=1-20km/200-300m&lt;br&gt;Spacing=342-571m&lt;br&gt;Height=4-6m</td>
<td>Intense, hummocky upper seismic facies&lt;br&gt;No sub-bottom reflector observed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Comparison chart for considered landforms in relation to the linear escarpments and scalloped escarpments in the study region.

<table>
<thead>
<tr>
<th>Considered Landform</th>
<th>Morphology Description</th>
<th>Subsurface Structure</th>
<th>Useful Reference</th>
<th>Comment in relation to Escarpments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shelf Edge Delta</strong></td>
<td>Length/Width=10s-100s km/10s km Relief=10s m Assoc. w Channel forms, slumps and high sediment input</td>
<td>• Seaward dipping clinoforms • Mass wasting downslope of clinoforms • Pro/Aggradation</td>
<td>• Fielding et al 2006 • Mellere et al (2002) • Coleman et al (1981)</td>
<td>Seaward dipping reflectors and slump features are consistent with Escarpments</td>
</tr>
<tr>
<td><strong>Contourites</strong></td>
<td>Length/Width=10s-100s km/10s km Relief=.1-.1 km Forms with AND against Slope Highly Variable Depths Presence of “Moat”</td>
<td>• ~2km thick packages • Built on pre-existing structures • Closely associated with downslope sand waves</td>
<td>Dorrik et al (2002)</td>
<td>No erosional channels (moat) along strike, very low vertical relief</td>
</tr>
<tr>
<td><strong>Grounding Zone Wedge</strong></td>
<td>Length/Width=10s-100s km/5-10 km Downlapping Wedge=.7” Relief ~50m Assoc. with MSGLs, drumlins, gullies and the shelf break</td>
<td>• Seaward dipping clinoforms • Chaotic “till” facies • 75 m sediment package • Overlies Glacial Unconformities “Backstepping Nature”</td>
<td>• Heroy and Anderson (2005) • Cofaigh et al. (2005) • Anderson (2002) • Dowdeswell et al. (2008)</td>
<td>Presence of dipping clinoforms, chaotic “till” facies, slump features on B2K but no presence of MSGLs and no landward dipping topset</td>
</tr>
<tr>
<td><strong>Escarpments</strong></td>
<td>Length/Width=9-45 km/1 km Downlapping Slope=3-5” Relief=20-40 m Cross-cut by channel systems, “splays “into 3 escarpments</td>
<td>• Seaward dipping clinoforms • Chaotic facies beneath clinoforms • Slump features (B2K) • Overlies unconformities</td>
<td>This study</td>
<td></td>
</tr>
</tbody>
</table>
Table 6. Comparison chart for considered landforms in relation to the various channel forms observed in the study area.

<table>
<thead>
<tr>
<th>Considered Channel Type</th>
<th>Morphology</th>
<th>Substrate, submarine location</th>
<th>Key references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proglacial Gullies</td>
<td>• L/W/D= 10km, 1km, 100m, Water depths 600-1200m</td>
<td>Sedimentary, Shelf break, Slope</td>
<td>Shipp et al. (1999), Wellner et al. (2006)</td>
</tr>
<tr>
<td>Subglacial Linear Channels</td>
<td>• L/W/D= 1-10 km, 500-1000m, 200-400m, Water Depths 575-1200</td>
<td>Crystalline Bedrock, inner shelf</td>
<td>Anderson and Shipp (2001) Lowe and Anderson (2003) Domack et al. (2006)</td>
</tr>
<tr>
<td>Turbidite Channels</td>
<td>• L/W/D= 10s-100s km, 100s m, 10s m, Water Depths 1000m+ Highly sinuous</td>
<td>Sedimentary, Continental Shelf and Slope</td>
<td>Oil industry!</td>
</tr>
<tr>
<td>Deep sea channels</td>
<td>• L/W/D= 100s km, 10s m, Water depth 1000s m</td>
<td>Sedimentary, Abyssal Plain</td>
<td>Mammerickx (1980)</td>
</tr>
</tbody>
</table>