Part IV

From the Source to the Sink
Chapter 12

A model for the evolution of magnetic minerals in southern Victoria Land

The following chapter presents a conceptual model for the evolution of magnetic minerals in southern Victoria Land today. The processes of erosion, transportation, and deposition of magnetic minerals in Antarctica are explored with the aim of relating the environmental magnetic records in drill core sediments to terrestrial processes.

12.1 Erosion

12.1.1 Glacial erosion and transport

The thick glaciogene sequences found around the Antarctic margin indicate that glaciers have been the dominant mechanism by which sediments are transported to the ocean system since the mid Eocene times (e.g. Wilson et al., 1998b; Naish et al., 2001b; Florindo et al., 2003a). However, since the assumption of cold, hyper polar conditions glaciers have contributed considerably less material to offshore sedimentary systems probably because the cold based glaciers are less erosive (e.g. Rebesco et al., 2006; Fielding et al., 2008b).

Glaciers typically produce sediments which are poorly sorted and have a wide range of grain sizes (e.g. Benn and Evans, 2010) and the rates of glacial erosion are linked to the availability of liquid water and the removal of debris from beneath the ice (Alley et al., 2003).
Glaciers erode and modify landforms and continents by abrasion or quarrying and can do so rapidly with erosion rates of up 60 mm per year recorded in Alaska (Hallet et al., 1996); even the uplift of the Transantarctic Mountains has been linked to isostatic rebound from lithospheric unloading by glacial erosion (e.g. Kerr and Gilchrist, 1996; Stern et al., 2005). Glacial erosion can also enhance chemical weathering by grinding which destroys crystal lattices thereby increasing their surface area and increasing the rates of chemical reaction. Such chemical reactions may have a more profound effect on the global climate though enhanced erosion and chemical weathering driving enhanced CO$_2$ draw down and climate cooling (Raymo and Ruddiman, 1992).

Quarrying occurs mostly beneath thin, fast flowing glaciers where ice or clasts within the overriding ice exert stresses directly on bedrock and on fractures and weaknesses within bedrock. Morland and Boulton (1975) suggested that a major mechanism of glacial erosion was by ice loading induced failure of bedrock, and Iverson (1991) and Cohen et al. (2006) demonstrated that cycling fluid pressure under advancing ice enhances fracturing and crack propagation in basement rocks, especially in homogenous rock units.

Abrasion of bedrock occurs by clasts entrained within overriding ice and entrained sediment making contact with bedrock (e.g. Hart, 1995; Cuffey and Alley, 1996), because of basal melting and high fluid pressure exerted directly on bedrock (e.g. Hallet, 1981), or because of glacio-fluvial erosion by sediment rich subglacial melt waters (e.g. Swift et al., 2005). The rate of glacial abrasion and the resulting surface also depends on the size of clasts which are in contact with basement rocks, where smaller grain sizes tend to create polished rather than striated surfaces (Hindmarsh, 1996).

Studies of cold based glaciers indicate that they have limited erosive impact on the landscape and may even preserve geomorphic features (e.g. Näslund, 1997; Waller, 2001; Nicola et al., 2009).

**Glacial erosion and magnetic minerals**

Ice loading by a glacier on the interface between entrained clasts, other clasts, and bedrock can easily reduce grain sizes $^1$.

Glacial erosion is probably an effective mechanism of liberating remanence carriers through grinding of rocks and eroded material. Chemical reactions may also occur be-

---

$^1$Pascal’s law indicates that a 1000 metres thick glacier exerts 9.81 MP of pressure at its base. (e.g. $\Delta P = \rho g (\Delta h)$; $\rho =$ density of ice $\sim$1000 kg, $g =$ gravity $\sim$9.81ms, $h =$ thickness of ice)
neath wet based glaciers which may result in oxidation of remanence carriers. However, under normal temperature and pH conditions and in the absence of biological activity Fe compounds have very low solubilities (e.g. Cornell and Schwertmann, 2003).

12.1.2 Mechanical erosion

There are several ways in which rocks can be mechanically disaggregated and most of these are linked to heating and cooling cycles and the expansion of fluids within the rock or expansion of the rock itself. Lichens are also effective at mechanically breaking rocks apart and are discussed in the following section.

Freeze-thaw processes can disaggregate rocks in the following ways:

- Volumetric expansion of water in joints and cracks during freezing.

- Hydrofracturing when expanding water is not expelled quickly enough during freezing.

- Microcrystalline crack growth at grain boundaries during freezing (Walder and Hallet, 1986).

Matsuoka (1995) demonstrated from studies in the Sør Rondane Mountains, Antarctica that freeze thaw processes are enhanced by salt crystallisation.

Thermally induced stress in rock from rapid cooling and warming has also been implicated as an important rock weathering mechanism. Hall (1999) identified rapid surface temperature changes (≥2°C/min) on rock surfaces in Antarctica and suggested that rapid thermally induced surface expansion and contraction can overcome the tensile strength of the rock and lead to surface shattering; this mechanism of surface weathering is especially effective in cold, arid environments. Figure 12.1,D illustrates a possible example of thermally induced fracturing and weathering.

Matsuoka et al. (1996) demonstrated that wind abrasion by saltating sands is also an effective mechanism of mechanical wear on rocks if enough abrasive material is available. The abundance of wind abraded rocks in southern Victoria Land (Figure 12.1 E and F) illustrates that wind erosion is occurring and is probably confined mostly to winter months when the down valley katabatic winds are the strongest (Doran et al., 2002; Nylen and Fountain, 2004).
Mechanical erosion and magnetic minerals

Mechanical weathering processes release magnetic grains from the rock. However, these processes probably have limited effect on the mineralogy or grain size of remanence carries. Wind abrasion is an effective mechanism of reducing magnetic grain size on the microscopic level through grain on grain impact. Studies of surface textures on aeolian grains (e.g. Krinsly and Donalhe, 1968) revealed microscopic (~5 µm) impact structures which indicates that micron to sub micron particles are generated by grain on grain impacts.

12.1.3 Chemical/Biological

Chemical and biological weathering rates typically increase with increased temperature and precipitation (e.g. Bluth and Kump, 1994; White and Blum, 1995; White et al., 1999), and can be strongly driven by biological activity during soil formation, and plant or lichen growth (e.g. Fine et al., 1989; Verosub et al., 1993; Chen et al., 2000). Previous studies on loess and paleosols have demonstrated that magnetite oxidises readily to maghemite during pedogenesis and moisture in the soil is the dominant controller of maghematisation, rather than the age of the soil (Fine et al., 1989; Verosub et al., 1993; Maher and Thompson, 1995; Maher et al., 2002, 2003).

Soil development studies in the upper Wright and Taylor valleys indicate that weathering processes are extremely slow and that these soils may be older than 2.7 Ma (Bockheim, 2002; Bockheim et al., 2008). However, Nezat et al. (2001) and Maurice et al. (2002) demonstrated that chemical weathering in the Dry Valleys can be higher than in temperate regions and that the rate of chemical weathering is controlled almost exclusively by the availability of liquid water.

Nezat et al. (2001) and Maurice et al. (2002) found that high rates of chemical weathering occur in the hyporheic zones 2 in the Dry Valleys, and Prestrud Anderson et al. (1997) concluded that chemical weathering rates beneath glaciers are driven primarily by the availability of melt water. The modern hyporheic zone in the Dry Valleys is limited to a relatively thin layer of sediment between the surface and permafrost. Abiotic weathering of rocks typically occurs when water is acidified to carbonic acid which in turn can dissolve silicate minerals. Carbonic acid is weak though and does not affect Fe rich grains (Ugolini et al., 1991).

Lichens can be effective at chemical and mechanical erosion of rocks. Lichens may

---

2 Hyporheic zone is the water laden sediment beneath and adjacent to streams.
physically disaggregate rocks by growth and freeze/thaw of the lichen and associated salts. Lichens are effective mechanisms of chemically weathering rock by carbonic and organic acid dissolution of silicate minerals (e.g. Chen et al., 2000). Siever and Woodford (1979) showed that organic acids produced by the lichens can dissolve iron from silicate minerals resulting in the production of goethite and Jackson and Keller (1970) demonstrated that lichens growing on basalts in Hawaii resulted in hematite precipitation.

Chemical/Biological erosion and magnetic minerals

Chemical and biological reactions are dependant strongly on the presence of liquid water and magnetic mineralogy can be modified easily by bacteria, acids and through oxidation reactions. Magnetic minerals are easily modified during chemical and biological weathering. Soil formation results in the oxidation of magnetite to maghemite and lichen growth can result in the production of high coercivity minerals such as goethite or hematite. However, biological and chemical reactions all require liquid water which is temporally and geographically limited in the Dry Valleys.

12.2 Transport

Modern sediment transport mechanisms in Antarctica include wind, fluvial, and minor transport by glaciers. In general glacial transport has little effect on the sorting or grain sizes of sediments. However, fluvial and aeolian transport mechanisms do have the ability to modify and concentrate the magnetic minerals on the way to the sedimentary sink.

12.2.1 Fluvial transport

Fluvial transport of sediment is an effective mechanism of sorting sediment and reducing grain sizes. In general sediments become more well sorted with distance from the sediment source (e.g. McLaren and Bowles, 1984).

Some authors have suggested that the fining rate of sediment in fluvial systems depends strictly on the efficiency of sorting and not on parent lithology (e.g. Rice, 1999; Hoey and Bluck, 1999). However, determining how particles become smaller in fluvial systems is difficult because determining whether fining results from selective transport or from direct mechanical abrasion is problematic; these two factors depend
on the geological and/or climate setting (e.g. Hoey and Bluck, 1999).

Physical fining of grain size occurs from impact interactions between particles. Kodama (1994a) suggested that both lithology and the size of interacting particles determines the products of abrasion. Through tumbling experiments with chert and andesite cobbles Kodama (1994b) demonstrated that chert splits into gravel sized particles and andesite is more prone to abrasions thus producing sand and silt sized particles. Similar by experiments by Jones and Humphrey (1997) revealed that weathered clasts are more easily abraded than fresh clasts. They also suggested that fining by abrasion is enhanced during peak flow and that the long periods between peak flow allows for chemical alteration and weathering of clasts to occur thereby enhancing abrasion at a later time. It follows then that the size distribution of sediments in fluvial systems depends on several factors including, particle size, parent lithology, flow rate, and the degree of weathering of particles in the river system.

Modern fluvial systems in the Dry Valleys are active only during peak summer months and are limited to valley floors where water is supplied almost exclusively by glacial and snow melting (Fountain et al., 1999).

**Fluvial transport and magnetic minerals**

As it has been demonstrated by experiments, certain lithologies will be more prone to fining and therefore releasing magnetic minerals to the fine grained sedimentary system.
However, fluvial systems do not cause significant abrasion or fining at the microscopic level (Krinslye and Donahue, 1968) presumably because grains are suspended in a higher density medium when compared with aeolian systems thereby reducing the velocity and forces exerted during grain on grain impacts.

Fluvial transportation is an effective mechanism of concentrating magnetic grains because they have higher densities when compared with silicates and therefore require higher flow velocities to be mobilised. Chemical alteration is less likely in active fluvial systems under normal temperature and pH conditions because Fe compounds have very low solubilities (e.g. Cornell and Schwertmann, 2003).

### 12.2.2 Aeolian transport and magnetic minerals

Atkins and Dunbar (2009) demonstrated from studies in the McMurdo Sound that aeolian sediments comprise the bulk of the sediment making its way to the ocean floor today. They also noted that the finest portion of aeolian sediment does not reach the sea floor which they suggest is carried to the open ocean by currents and may contribute to phytoplankton productivity.

Aeolian transportation of magnetic grains is an excellent rounding and sorting mechanism and grain on grain impacts during saltation can cause abrasion and a reduction of grain size (e.g. Krinslye and Donahue (1968)). Aeolian transport is also an effective mechanism of concentrating magnetic grains because they have higher densities when compared with the lighter silicates which will be preferentially lofted and transported.

Chemical changes are unlikely to occur during aeolian transport because these reactions require the presence of moisture and in general aeolian transport occurs when sediments are dry.

### 12.3 Deposition

Deposition processes can have a profound effect on the concentration, alignment, and chemistry of magnetic grains. Diagenesis can result in the dissolution or chemical alteration of remanence carrying grains thereby preventing further magnetic studies of sediment. However, the affects of currents on magnetic and non magnetic grains in sedimentary systems can yield additional information regarding climate controls on deposition.
Figure 12.2 (previous page): Examples of modern transport processes in southern Victoria Land. A ‘Dirty sea ice’ at the mouth of Taylor Valley. Sediment lying on the sea ice ranged in size from fine silts to pebbles. B. Aeolian pebble ripples in the Salmon Valley. Ripples were between 10 - 30 cm high and sediments were relatively well sorted pebbles with clasts ranging in size from 10 mm to 30 mm. C Fine silt and sand dunes in Commonwealth stream. D Looking down the Salmon Valley with the Salmon Glacier on the left. Note the dark, volcanic rich Ross Sea drift sediments contrasting with the more recent and lighter coloured modern fluvial sediments from the Salmon stream. E Beacon Supergroup boulders (light coloured) scattered over a volcanic debris field at the edge of the Howchin Glacier. Geomorphic features of the previous expansion of the Howchin Glacier were not found (e.g. lateral moraine) which indicates that it was cold based and therefore non-erosive when these light coloured boulders were deposited. F Fluvial transport of sediments from the base of the Commonwealth Glacier in Taylor Valley.

12.3.1 Environmental controls

The depositional environment can cause dilution and/or concentration of magnetic grains in sedimentary deposits.

In the AND-1B succession the lowest concentrations of remanence carriers were in biogenic, diatomite intervals (Wilson et al., 2007b). It is possible that during the deposition of the thick diatomites the delivery of magnetic minerals to the Ross Sea was reduced. Conversely it is also possible that during high productivity periods the delivery rate of magnetic minerals to the Ross Sea remained constant and the rapid deposition or biogenic silica led to a dilution of magnetic minerals.

Diamicts can have wide ranging concentrations that are driven by the presence of basement clasts enclosed within the sediments (e.g. Florindo et al., 2005; Wilson et al., 2007b; Acton et al., 2008). The presence of basement clasts within drill core sediments can result in magnetic records (magnetic intensity and susceptibility) which have a high amount of scatter.

Current processes can lead to concentration increases through winnowing and can align grains with the current direction; this alignment can be measured magnetically and is a reliable proxy for current strength and direction (e.g. Joseph et al., 2002, 2004).

The deposition of till also has an aligning affect on grains and clasts which can
be measured using magnetic instruments (e.g. Fuller, 1962). However, experimental studies of the anisotropy of magnetic susceptibility (AMS) in natural sheared till and of synthetic tills that were sheared under controlled conditions did not reveal a clear relationship between shear strength and the strength of anisotropy (e.g. Principato et al., 2005; Hooyer et al., 2008; Thomason and Iverson, 2009).

12.3.2 Diagenesis of sediments

During sediment burial, reduction diagenesis can adversely affect the magnetisations of sediment. Studies of marine and freshwater successions have revealed that products of sulphate reducing bacteria can over print and even completely erase the magnetisation from sediments by dissolving magnetite (e.g. Berner, 1984; Marnette et al., 1993; Wilkin and Barnes, 1996).

Sulphate reducing conditions in sediments remove magnetite and precipitate pyrite, which is especially problematic because intermediate sulphide phases which carry a remanence (e.g. greigite) may remain; the presence of greigite can indicate that the remanence carried by the sediment is from the time of reduction and not deposition which can prevent environmental magnetic and magnetostratigraphic studies (e.g. Roberts, 1995; Roberts and Weaver, 2005; Rowan and Roberts, 2006; Roberts et al., 2011).

Fluid migration throughs sediments can also result in the dissolution of iron and carbonates and the precipitation of iron rich carbonate minerals such as siderite. Sagnotti et al. (2005) noted that thin alternating polarity intervals at the base of CRP-1 were caused by greigite growth on the surfaces of authigenic siderite. Such geochemical alteration can also make magnetic studies more difficult.
Cold based glaciers may not significantly modify the landscape or leave any trace of their expansion or retreat histories. During the Pliocene the Taylor Glacier (not visible) expanded to at least the Canada Glacier and left sediment drifts on the valley floor and sides. B A view looking to the west, up the Ferrar Glacier. C Looking south across the Taylor Valley with the Commonwealth Glacier to the left and lake Fryxell to the right. The white dotted line indicates the elevation of the glacial Lake Washburn sediments (~300 metres above sea level) D Drop stones and boulders in Lake Washburn sediments which crop out in Commonwealth stream. Note the soft sediment deformation. E Lake Washburn sediments cropping out in the Commonwealth Stream in Taylor Valley. Note the faint bedding in the upper portion of the succession and the people for scale (orange) to the left. F More evidence of soft sediment deformation in Lake Washburn sediments in the Taylor Valley.
12.4 The Source to Sink evolution of magnetic grains today

The modern climate in southern Victoria Land is characterised by extremely cold, dry conditions and minimal summer snow fall in the Transantarctic Mountains (e.g. Doran et al., 2002; Nylen and Fountain, 2004). Most glaciers are cold based and lose mass through sublimation rather than melt (e.g. Lewis et al., 1998). Fluvial systems are active only during the warmest summer months (e.g. McKnight et al., 2007).

Sediments being deposited today onshore in southern Victoria Land are fluvial sands and gravels, aeolian sands, regolith and remobilised remnants from the last glacial maxima. The offshore sedimentary records are characterised by fine grained aeolian (Atkins and Dunbar, 2009) and biogenic sediments with drop stones (McKay et al., 2008b).

The following section aims to develop an environmental magnetic fingerprint for the modern climate setting.

12.4.1 Erosion

Higher snowfall rates during interglacial periods results in expanded, cold based, non-erosive alpine glaciers in the Transantarctic Mountains which do not move significant amounts of sediment (Higgins et al., 2000).

Fluvial erosion is restricted to small melt water streams in valley floors. In the Taylor and Salmon valleys these streams have no interaction with basement rocks. However, melt water streams from the Walcott Glacier have incised and eroded lava flows and scoria. Overall, erosion by fluvial mechanisms is not significant in the Transantarctic Mountains.

Mechanical wind abrasion of rock faces by saltation and mechanical weathering through freeze thaw and thermal expansion of rocks are probably the dominant erosion mechanisms today in the Transantarctic Mountains. Magnetic mineralogy and grain size are not affected during erosion.
Model of modern source to sink evolution of magnetic minerals

Erosion

Freeze thaw, wind abrasion, and thermomechanical erosion are dominant. Erosion rates are extremely slow. Glaciers are cold based and non-erosive.

Transport

Strong katabatic winds move most of the sediment and reduce grains-sizes. Glaciers do not transport significant volumes of sediment. Fluvial transport is confined to melt water streams.

Alteration

Minimal terrestrial chemical alteration of magnetic minerals. Very slow chemical and biological weathering rates. Chemical weathering may be fast in isolated pockets.

Deposition

Aeolian deposition of well mixed magnetic minerals with contribution from all TAM lithologies. High concentration caused by sorting and winnowing. Reduction diagenesis of magnetic minerals may occur.

Basement Geology

- Koettlitz and Skelton Group - Precambrian
  Low concentrations of magnetite, minor maghemite

- Granite Harbour Intrusives - Neoproterozoic and Ordovician
  Low concentrations of magnetite, minor maghemite

- Beacon Super Group Sediments - Devonian to Triassic
  Variable - moderate concentrations of hematite - magnetite

- Ferrar Dolerite - Jurassic
  High concentrations of magnetite, minor maghemite

- McMurdo Volcanics - Eocene - Holocene
  Very high concentrations of magnetite, minor maghemite

Location of cross section through Kukri Hills
V dross section through the Kukri Hills showing the distribution of major basement lithologies and a model for the modern source to sink processes of magnetic minerals. Dominant erosion today is by freeze thaw and thermal expansion and contraction of the rock surface. Abrasion of rock surfaces by mobile aeolian grains may also account for significant erosion and grain on grain impacts during aeolian transport can also decrease grain size. The cold, dry climate prevents significant chemical alteration of magnetic grains during sediment transport which is principally by aeolian means (minor fluvial transport occurs in valley floors). Sediments which are deposited offshore have a mix of magnetic grains and grain sizes from all Transantarctic Mountain lithologies. Aeolian transport may result in the formation of ultra fine magnetic particles which may be responsible for the paramagnetic component in thermomagnetic analyses.

12.4.2 Transport

Fine grained sediments are removed from the mountains and blown offshore to the sedimentary sink by strong katabatic winds. Aeolian transport and abrasion of rock faces are effective mechanism for reducing grain size. It is possible that the paramagnetic component seen in modern cover sediments is driven by the creation of ultra fine grained magnetic particles during abrasion and aeolian transport.

Fluvial transport is confined to melt water streams in valley floors which are active only during the warmest summer months. Even though a sizeable delta has built into New Harbour, flow rates are relatively small (typically less than 5 m$^3$sec$^{-1}$ McKnight et al., 2007), therefore fluvial transport is probably not a dominant sediment transport mechanism.

The modern glaciers in southern Victoria Land are cold based and do not move significant quantities of sediment (e.g. Näslund, 1997; Waller, 2001).

12.4.3 Alteration of magnetic grains

Chemical and biological weathering rates are slow and confined to the valley floors and isolated areas where summer temperatures allow for melt water. Under the modern hyper arid, cold conditions little alteration of the mineralogy of magnetic grains should occur during erosion or transport.
12.4.4 Deposition

Magnetic mineralogy both onshore and offshore is variable because it is sourced from all Transantarctic Mountain lithologies. Some samples with high coercivities may indicate a Beacon Supergroup source because these sediments contain hematite. Magnetic concentrations are high because of preferential sorting and winnowing during aeolian transport. Biogenic activity and organic matter in sediments may result in the diagenetic alteration of remanence carriers.

12.4.5 An environmental magnetic fingerprint of the modern climate

The modern cold, dry interglacial climate is represented in the on and offshore sedimentary systems by high concentrations of unaltered magnetic grains of mixed sizes which are derived from throughout the Transantarctic Mountains. Concentrations are high because of winnowing during aeolian transport. Chemical/biological weathering rates are low and confined to limited areas which allows for the preservation of even the finest magnetic grains resulting in strong paramagnetism and/or superparamagnetism of sediments.
Chapter 13

Late Neogene evolution of the sedimentary system in southern Victoria Land Fiords

The new age models (Chapter 8) allow for a comparison of depositional and erosional events between DVDP-10 and -11 in the lower Taylor Valley and CIROS-2 in Ferrar Fiord (Figure 13.1).

The following chapter divides the drill cores into discrete time intervals based on changes in lithology, common temporal breaks in the records and on key climatic changes which are interpreted from the environmental magnetic records. Prominent shifts or events in the environmental magnetic records and their significance are discussed in detailed sections.

The latest Miocene - earliest Pliocene (Section 13.1) is represented only in DVDP-11 and contains a record of expanded glaciers and orbitally paced advance and retreat cycles. The early Pliocene (Section 13.2) is represented in DVDP-10 and -11 and contains a record of warmth with retreated glaciers, open marine conditions and low input of magnetic minerals. The mid Pliocene - early Pleistocene (Section 13.3) contains a record of glacial expansion and cooling. At the Plio-Pleistocene boundary (Section 13.4), the appearance of paramagnetic behaviour in sediments may indicate initiation of katabatic winds and the shift to modern, hyper polar conditions. The Pleistocene (Section 13.5) is represented in all three drill cores and contains a record of sediment deposition in fresh water lakes and shallow fiords.

The environmental magnetic records (Chapter 9) provide an insight into the terrestrial erosional setting and climate in Southern Victoria Land. The three fundamental
magnetic parameters (concentration, coercivity, and grain size) are discussed (the raw data are presented in chapter 9) in terms of their environmental and climatic significance. The lower portion of CIROS-2 (older than $\sim1.2$ Ma) is not used for environmental magnetic studies because of diagenetic alteration and in DVDP-10 the age model is too poorly constrained to allow for high resolution studies of the environmental magnetic record. The DVDP-11 record is the main focus because it has the highest sample density, fewest core breaks, and a well constrained age model.

Concentration estimates were made from MS and ARM intensity records because these data have the highest resolution and because they give a broad indicator of the contributions of magnetic behaviour (MS) and of the remanence carrying portion (ARM) of the sediment. NRM intensity was not used because it is not truly representative of the remanence carrying capability of the sediment (multiple magnetic overprints are present which were imparted since the sediment was recovered, see chapter 6). Mr and Ms were not used because these are available only with a relatively low resolution.

Coercivity of magnetic minerals in sediment is estimated using $H_c$ because it is the most sensitive data set available in this study. $H_c$, $H_{cr}$ and MDF of ARM all provide estimates of the coercivities of grains within the sediment and similar behaviours are observed in each drill core (see chapter 9). Grain-size trends were identified using the Mr/Ms and $H_{cr}/H_c$ ratios. In most cases these two parameters had similar behaviours and trends.

The records are divided into four intervals which span the transition from a more dynamic sub-polar Antarctic ice-sheet to today’s polar ice sheet. Ultimately the sedimentary records and their environmental magnetic properties are correlated with terrestrial deposits upstream of the drill sites and with the wider Southern Ocean events in figure 13.1.

A model for the temporal and spatial evolution of magnetic minerals is presented in chapter 14.
Figure 13.1 (previous page): Correlation of CIROS-2, DVDP-10, -11 drill cores based on age models and climate interpretations. The modelled ice volume is from Pollard and DeConto (2009), benthic $\delta^{18}$O stack is from Lisiecki and Raymo (2005), $\delta^{18}$O to sea-level calibration from Naish and Wilson (2009), and the obliquity from (Laskar et al., 2004), mean daily insolation at 73°S on December 21, and GPTS (Lourens et al., 2004). Terrestrial Records column: Wright Valley (W) records where O = Onyx drift, W = Wright drift, AIII = Alpine III drift, AIV= Alpine IV drift from (Hall et al., 1993; Hall and Denton, 2005), Red star is hart ash (Hall et al., 1993) and PM = Prospect Mesa (Prentice et al., 1993). Taylor Valley (T) records where black lines indicate deposition of alpine drifts (Wilch et al., 1993b,a; Bockheim et al., 2008) and blue line indicates deposition of lake sediments (Hall et al., 2000). Ferrar Fiord (F) records where black stars indicate deposition of alpine drifts (Staiger et al., 2006) and the green star indicates deposition of wet-based Mt Feather Diamicton (Wilson et al., 2002a). Offshore Records column where the green bar indicates ice free Ross Sea (Naish et al., 2009; Winter et al., 2011) red, orange, and green bars indicate significantly elevated SSTs from Escutia et al. (2009), Whitehead and Bohaty (2003), and Villa et al. (2008) respectively. Blue hexagons are Ice Berg Rafted Debris (IBRD) armada events identified by Williams et al. (2010).
13.1 Expanded glaciers during latest Miocene - earliest Pliocene (Figure 13.2)

The lower portion of DVDP-11 (below 263 m) spans between 4.58 Ma and 5.35 Ma, an interval which is dominated by thick, massive to moderately stratified diamictites that were deposited beneath an advanced Taylor Glacier (Porter and Beget, 1981). Sharp contacts and ice loading features such as soft sediment deformation and fracturing at 314.55 m and numerous smaller fractures and shears between 285 m and ~280 m (McKelvey, 1981; Wilson, 1993) indicate that the Taylor Glacier was over the drill site. In the adjacent Ferrar Fiord, erosion of basement rocks was probably taking place under an advanced Ferrar Glacier.

Thin, diatomaceous mudstone intervals within the diamict (e.g. 303 - 307 m, figure 13.2) represent short periods of glacial retreat and ice distal conditions.

In DVDP-11 a transition from diamict to mud dominated sediments between 260 m and 240 m is interpreted as a retreat of Taylor Glacier after 4.68 Ma and a shift to more open marine dominated conditions with minimal ice-influence. The Ferrar Glacier probably also retreated around this time because the oldest sediments (ca. 4.4 Ma) deposited on granite-gneiss basement appear in the CIROS-2 core (Figure 13.1).

13.1.1 Latest Miocene - Earliest Pliocene environmental magnetic record

Magnetic concentrations are low overall compared with the upper portion of the drill core (Figure 13.2). From the base of the drill core to ~ 280 metres the environmental magnetic record is reasonably bland with no significant changes in concentration, coercivity, or grain size. Between 280 m and 240 m the record becomes cyclic with changes in concentration, coercivity and grains-size which coincide with glacial advance and retreat cycles. Cycles are numbered 1 through 4 (Figure 13.2).

Correlation with the oxygen isotope super cycle

A super cycle in the δ<sup>18</sup>O record (Lisiecki and Raymo, 2005) spans between ~5.13 Ma and ~4.6 Ma with maximum δ<sup>18</sup>O values at ~4.9 Ma (grey shaded area, figure 13.2). Magnetic concentrations and sediments broadly mirror the decline in δ<sup>18</sup>O between ~5.13 and 4.9 Ma with decreasing concentrations in concert with thickening diamictites; coercivities are relatively high throughout this interval and grain sizes are
small. The ice-volume model of Pollard and DeConto (2009) indicates a period of extremely low ice volume between 5.0 and 4.9 Ma. However because this interval spans the very earliest portion of the model and because in the AND-1B drill record it spans a volcanogenic unit, the accuracy of the ice-volume model cannot be verified.

After 4.9 Ma a warming trend in the $\delta^{18}$O and ice volume records correlates with the appearance of cyclic behaviour of environmental magnetic parameters in DVDP-11 (Figure 13.2).

**Correlation with the oxygen isotope and ice volume records**

Coercivity and grains-size estimates are variable and do not correlate well with changes in lithology. However, in some instances (Cycles 2 and 3, figure 13.2) they do correlate with unconformities. Concentrations are high in ice-distal, marine mudstone units and low in diamicritites with grain sizes exhibiting an anti-phase relationship with concentration. Possible sources of error in such a correlation are imprecise positioning of samples or of sedimentary units in lithologic logs.

At least two cycles (2 and 3) of decreasing concentration/coercivity and increasing grain size are demonstrated in figure 13.2.

A tentative correlation is made with the $\delta^{18}$O record (Lisiecki and Raymo, 2005) ($\delta^{18}$O I and II) which spans 2 obliquity cycles. The boundary between cycles 2 and 3 corresponds to a transition to an extended period of reduced ice-volume which continues until $\sim$4 Ma. It is possible that the cycles span only one obliquity cycle, this is difficult to test however because chronostratigraphic constraints at obliquity timescales are not available.

**13.1.2 Correlation with regional events**

The strengthening Antarctic Circumpolar Current (ACC) between 10 and 5 Ma (e.g. Carter et al., 2004; Barker et al., 2007; Carter et al., 2008b) is associated with thermal isolation and cooling of the Antarctica continent and geomorphic evidence from the Dry Valleys region (e.g. Marchant and Denton, 1996; Marchant et al., 1996; Lewis et al., 2010) have been interpreted to reflect limited ice-volume fluctuations in the EAIS since this time.

However, recent works indicate episodes of ocean warming (e.g. Whitehead and Bohaty, 2003; Escutia et al., 2009) and ice-sheet instability (e.g. Naish et al., 2009; Williams et al., 2010) that persisted into the late Pliocene; a time when atmospheric
$p$CO$_2$ levels were probably at about 400 ppm (e.g. Seki et al., 2010).

Numerical ice sheet models (Pollard and DeConto, 2009) show prolonged reduced ice volume between 4.7 Ma and 4.55 Ma and Williams et al. (2010) recognised a spike in Iceberg Rafted Debris (IBRD) at ODP site 1165 at 4.8 Ma which they attribute to armadas of icebergs during continent wide ice stream break-up under a retreating EAIS.

Whitehead and Bohaty (2003) reported Sea Surface Temperatures (SST) up to 5°C higher than today between 4.55 - 4.80 Ma in Prydz Bay. Thick diatomite beds in the AND-1B drill-core (Figure 13.2) indicate ice-free conditions, minimal summer sea-ice and withdrawn glaciers in the Ross Sea (Naish et al., 2009; Winter et al., 2011) at ~4.5 Ma with limited sediment input from the glaciers draining the EAIS (Talarico and Sandroni, 2009; Talarico et al., 2011).

In the Transantarctic Mountains Wilson et al. (2002a) reported a latest Miocene age for the Mount Feather Diamicton (green star, figure 13.2); a wet-based glacial deposit which originated from a large ice sheet behind the Transantarctic Mountains at head of the Ferrar Glacier.

In the Wright Valley the shallow marine Prospect Mesa Gravels (grey line, figure 13.2) were deposited at 5.5 ±0.4 Ma, which were later buried beneath the wet-based glacigene Peleus Till (Prentice and Krusic, 2005). The Peleus Till has been interpreted to represent a major expansion of the EAIS into the Wright Valley and has an estimated age of between 5.5 ±0.4 Ma and 3.7 ±0.1 Ma (Prentice and Krusic, 2005).

It is likely that the Mount Feather Diamicton and the Peleus Till were deposited at the same time as the late Miocene - Early Pliocene sediments at the base of DVDP-11 which were deposited under an expanded Taylor Glacier.

The retreat of the Taylor Glacier after 4.8 Ma agrees well with other evidence from around the Antarctic margin of unstable ice streams and warm SSTs. In DVDP-11 a thin mudstone interval (303 - 307 m) represents ice distal conditions at ~5.15 Ma which coincides with two ~0.8‰ negative inflections (T5/T7) of the δ$^{18}$O record (Lisiecki and Raymo, 2005) and may be the Prospect Mesa Gravels equivalent in Taylor Fiord.

13.1.3 Suggested drivers of environmental magnetic cycles

The higher concentrations of maghemite/oxidised magnetite in ice distal, mudstone units may be driven by higher chemical weathering rates and soil development on land during warm periods.

High resolution thermomagnetic measurements in cycle 2 (Figure 13.3) revealed
Environmental magnetic data and lithology are correlated with the modelled Antarctic ice-volume (Pollard and DeConto, 2009), benthic δ¹⁸O stack (Lisiecki and Raymo, 2005) and sea-level calibration (Naish and Wilson, 2009) where selected isotope events are named, obliquity (Laskar et al., 2004), mean daily insolation at 73°S on December 21, and GPTS (Lourens et al., 2004). Correlated events include the Prospect Mesa (PM) gravels (Prentice et al., 1993) and the Mt Feather Diamicton (green star) (Wilson et al., 2002a). The green bar indicates ice free Ross Sea (Naish et al., 2009; Winter et al., 2011), the orange bar indicates significantly elevated SSTs (Whitehead and Bohaty, 2003). Blue hexagon is IBRD armada events identified by (Williams et al., 2010) indicating a destabilised Antarctic Ice-sheet or ice margin. Firm correlations with the GPTS are drawn in black. A dashed line is used where correlations occur at an unconformity, core-break, in an ambiguous polarity interval or between widely spaced samples. Correlations between unconformities, lithological units and the ice-volume or δ¹⁸O records are shown in red.

Higher concentrations of maghemite and oxidised magnetite in mud rich, ice distal units when compared with diamictites. Diamictites typically are dominated by fresh, unaltered magnetite and smaller quantities of maghemite and oxidised magnetite. Concentrations are also lower when compared with mud rich units which may result from greater input of glacially eroded, fresh siliciclastic sediments which dilute the magnetic minerals.

Studies of modern Antarctic stream and hyporheic systems have demonstrated that chemical weathering depends critically on the availability of liquid water (Nezat et al., 2001; Maurice et al., 2002). The modern, interglacial climate in Taylor Valley is extremely cold and dry (mean annual precipitation of <100 mm and average soil temperatures of ∼20°C, Doran et al., 2002) and liquid water is confined principally to melt water streams in limited areas where temperatures rise above freezing in summer.

Studies of Chinese, Russian and Californian loess and paleosols have demonstrated that magnetite oxidises readily to maghemite during pedogenesis. These studies identified that the state of climate, particularly rainfall and moisture are the dominant controllers of maghematisation, rather than the age of the soil (Fine et al., 1989; Verosub et al., 1993; Maher and Thompson, 1995; Maher et al., 2002, 2003).

In this study the only examples of maghemite in modern terrestrial sediments were
Figure 13.3: Lithology, glacial proximity, thermomagnetic behaviour, ARM and Anisotropy of Magnetic Susceptibility (AMS) of cycle 2 from figure 13.2. ARM indicate decreasing concentration during cooling and AMS lineation increase up core suggesting greater influence of glacial flow on magnetic fabrics. Thermomagnetic behaviour indicates an up core decrease of mixed oxidised magnetite and maghemite and increased contributions of fresh, unaltered magnetite. During glacial retreat between ~262 and ~261 metres larger quantities of oxidised magnetite and maghemite dominate the thermomagnetic behaviour. Intervals with high concentrations of oxidised magnetite and maghemite indicate that paleosols may have developed in the Taylor Valley during glacial minima under warm and humid conditions. During glacial maxima greater quantities of fresh magnetite were delivered to Taylor Fiord along with more siliciclastic material.
found in the Salmon and Walcott streams and in a single high alpine (>1000 msl) paleosol in the Salmon Valley (T044, see chapter 11)\(^1\). All other analyses of modern aeolian sediments and colluvium revealed a dominance of pure magnetite/titanomagnetite indicating that oxidation processes under modern, hyper-arid conditions are very slow or that they do not occur at all.

It is possible that the cycles observed in DVDP-11 before \(\sim 4.7\) Ma represent oscillations between colder polar conditions and warmer, wetter conditions. Prolonged ice-distal conditions are not observed in DVDP-11 until 4.6 Ma. However, thin muddy intervals within diamicrites (e.g. 257.63 m and 275.95) have rich foraminiferal assemblages (Webb and Wrenn, 1982) indicating deposition in a deep water fiord under ice free conditions and Ishman and Rieck (1992) suggested greater terrestrial rather than glacial input in ice-distal deep water facies. Analyses conducted here indicate that the mudstone units contain high concentrations of oxidised magnetite/maghemite which may be sourced from soils which developed during warm, humid conditions in the Taylor Valley.

Alternatively the higher coercivities may be attributed to higher production rates from maghemite or possibly hematite bearing rocks. Analyses of basement rocks (see chapter 11) did not reveal a unique source of maghemite. Beacon Super Group sediments are dominated by hematite, and Granite Harbour Intrusives typically had mixtures of magnetite and maghemite especially in weathered outcrops. Oxidised McMurdo Volcanic Group rocks also contained high coercivity phases.

Hysteresis and thermomagnetic analyses did not reveal significant quantities of hematite in glacigenic sediments which are sourced from Taylor Valley hinterland. It follows then that glacial advances resulted in increased erosion of fresh basement rocks and magnetite by the Taylor Glacier and therefore higher concentrations of unaltered magnetite.

Post depositional oxidation of magnetite is also an alternative explanation for the presence of oxidised magnetite. Studies from marine successions have revealed that oxidation of magnetite through pore water interactions during dewatering can occur in some instances (Robinson, 2001; Passier and Dekkers, 2002). However, the presence of a mix of pristine magnetite grains and variably oxidised grains rather than a dominantly oxidised mineralogy suggests that the grains are detrital rather than authigenic.

An argument for warm, wet-based glaciations and significantly warmer than present conditions between 5.35 Ma and 4.6 Ma is also supported by:

\(^1\)Salmon Valley is a poorly studied area; T044 may represent an older climate state.
• The presence of the Mount Feather Diamicton (Wilson et al., 2002a) which was deposited during the latest Miocene by a wet-based Ferrar Glacier.

• The Wright Valley Prospect Mesa Gravels, which comprise a diamictite overlain by fossiliferous gravels (e.g. Webb, 1974; Prentice et al., 1993) indicating that during the latest Miocene - early Pliocene the Wright Valley was a <100 m deep fiord with bottom water temperatures of up to 10°C (Webb, 1974).

• The AND-1B drill core, correlative diatom units (DU-XIII, -XII, Winter et al., 2010) indicate periodic open marine, ice free conditions in the Ross Sea between glacial advances across the drill site.

• Equilibrium-line altitude reconstructions indicate that a warmer and wetter climate is needed to support the larger early Pliocene Glaciers in Taylor and Wright Valleys (Krusic et al., 2009).

13.2 Early Pliocene warmth (Figure 13.5)

The early Pliocene interval is represented in DVDP-10, and -11, and occurs at the base of CIROS-2. In DVDP-11 an interval between 200 and 240 metres is dominated by mudstones and ice-distal to open marine facies which represents the early Pliocene period between ~4.25 Ma and ~4.1 Ma.

In DVDP-10 a slightly older interval of diamictites, sandstones, and mudstones represents the interval between ~4.4 Ma and ~4.2 Ma. However, the age model in DVDP-10 is not well constrained because of core breaks and wide sample spacing.

In DVDP-11 the ~40 metre thick mud dominated interval represents the most continuous ice-distal to marine facies in the drill record. It coincides with a period of very low ice volume, a very light portion of the $\delta^{18}O$ record, and high sea-level. A break in the sedimentary records (CIROS-2, and DVDP-10, -11) between 4.1 Ma and 3.6 Ma coincides with a major unconformity in the AND-1B drill core (438.61 mbsf) and a relatively well developed regional unconformity that is recognised in seismic reflection data as the Ri reflector (Levy et al., 2012).

In-situ paleoecological studies in both DVDP-10 and -11 (Webb and Wrenn, 1982; McKelvey, 1991) indicate that the Taylor Valley was occupied by a deep fiord with water depths estimated between 600 and 900 metres (Figure 13.4). However, Fielding

---

2The most commonly agreed upon age for this unit is 5.5±0.4 Ma from a Sr-isotope age on a scallop. However, Prentice et al. (1993) suggested that the gravels may be as young as middle Pliocene.
et al. (2011) suggested that worm burrows recorded in the lower portion of DVDP-10 (e.g. McKelvey, 1981, 1991) are in fact the remains of plant rootlets and consequently argued for subaerial exposure which is at odds with the interpretation of deep fiordal environment. McKelvey (1981) also reported multiple bioturbated intervals in the correlative unit in DVDP-11.

In DVDP-11, Winter (1995) and Winter and Harwood (1997) reported a diverse, open marine diatom assemblage between 199 m and 211 m and Ishman and Rieck (1992) reported a diverse foraminiferal assemblage between 202 and 242 m which they attribute to unstable environmental conditions. $\delta^{18}$O data from this interval indicate a large up to $\sim$20% excursion between $\sim$220 and $\sim$210 metres which may indicate a large melt water pulse entered the Taylor Fiord (Ishman pers. comms). Conversely, Marchant et al. (1993) suggested hyper arid and extreme polar conditions in the Arena Valley ($\sim$60 km inland from the DVDP drill sites), from an ash (4.34 ±0.025 Ma, see figure 13.5) which was deposited on a desert pavement.

Figure 13.4: Pliocene shoreline reconstructions based on paleodepth estimates from DVDP drill cores (Webb and Wrenn, 1982; McKelvey, 1991). Dark blue is the shoreline based on minimum depth estimate (600 m), light blue is maximum (900 m).
In the AND-1B drill core, the correlative diatom units are DU-XII, -Xlc, and -XIib (Winter et al., 2010) which indicate prolonged open marine, ice free conditions with minimal summer sea ice, air temperatures above freezing (Naish et al., 2009), and ocean temperatures of 3-5°C (Winter and Sjønneskog, 2010). Whitehead and Bohaty (2003) reported significantly warmer SST’s than today in Prydz Bay between 4.4 Ma and 4.3 Ma, and around 3.7 Ma. Moreover, Hillenbrand and Fütterer (2001) reported significantly less sea-ice coverage in the Bellingshausen Sea during the early Pliocene. Escutia et al. (2009) reported SSTs up to 5.8°C above present between 3.7 Ma and 3.5 Ma (Gi5, Gi1, MG11 and MG7) at ODP sites at the Antarctic Peninsula and at Prydz Bay (ODP sites 1095, 1096, and 1165).

An unconformity at ~200 m in the DVDP-11 accounts for ~500 kyr. The unconformity is tentatively correlated with the Gi2 and/or Gi4 isotope events which represent a ~40 lowering of sea-level. In the Wright Valley the Peleus till was emplaced during this interval indicating expansion of wet-based East-Antarctic derived glaciers in the Early Pliocene (Hall et al., 1993). Conversely, the air-fall Hart ash was also deposited during this time (3.9 ± 0.3 Ma; Hall et al., 1993) on a cryoturbated desert pavement. However, there are concerns regarding the accuracy of the K/Ar age and its relationship with surrounding units.

Between 200 m and 195 m is a ~70 kyr interval of diamicrite overlain by mudstone which represents glacial retreat. This ice retreat period correlates with a period of extended open marine conditions in the Ross Sea (Naish and Wilson, 2009), elevated sea surface temperatures (Escutia et al., 2009), low ice volume (Pollard and DeConto, 2009), and retreating EAIS glaciers (Williams et al., 2010).

13.2.1 Early Pliocene environmental magnetic record (Figure 13.5)

Diagenesis in CIROS-2 prevents the construction of an environmental magnetic event stratigraphy and low sample resolution and core breaks in DVDP-10 means that trends are not clear. Overall magnetic concentrations are low, and coercivity and grain size estimates show considerable variability in DVDP-10.

In DVDP-11 the lower diamicrite has a fairly uniform magnetic expression with little scatter in the data; it is tentatively correlated with Marine Isotope Stage Co2. The overlying mud succession contains complex cycles and trends.

Magnetic concentration is uniform between 227 and 205 metres with a rapid increase
Figure 13.5 (previous page): Early Pliocene portion of DVDP-11. Environmental magnetic data and lithologic logs are correlated with the modelled Antarctic ice volume (Pollard and DeConto, 2009), benthic δ¹⁸O stack (Lisiecki and Raymo, 2005) and sealevel calibration (Naish and Wilson, 2009) where selected isotope events are named, obliquity (Laskar et al., 2004), mean daily insolation at 73°S on December 21, and GPTS (Lourens et al., 2004). The green bar indicates ice free Ross Sea (Naish et al., 2009; Winter et al., 2011), the orange and red bars indicate significantly elevated SSTs around the Antarctic margin (Whitehead and Bohaty, 2003; Escutia et al., 2009). Orange star indicates the age of the Arena Valley ash (Marchant et al., 1993) and the red star indicates the age of the Hart Ash (Hall et al., 1993). The grey line indicates the youngest possible age of the wet-based glacigene Peleus till (Prentice and Krusic, 2005). Blue hexagon is IBRD armada events identified by Williams et al. (2010) indicating a destabilised Antarctic ice-sheet or ice margin. Firm correlations with the GPTS are drawn in black, where correlations occur at an unconformity, at a core-break, in an ambiguous polarity interval or between widely spaced samples a correlation is made using a dashed line. Correlations between unconformities, lithological units and the ice-volume or δ¹⁸O are shown in red.
between 205 and 200 metres towards a major unconformity. Coercivities between 225 and 200 metres contain three high to low cycles superimposed on an up-core increase in coercivity and decrease in grain size.

**Suggested drivers of environmental magnetic cycles**

Coercivities and concentrations are the lowest and grain size the largest in the lower diamict in DVDP-11. It is possible that this behaviour is driven by the steady state delivery of fresh, unaltered magnetite into the fiord by an expanded Taylor Glacier between 4.27 Ma and 4.23 Ma. After this expanded phase, a \( \sim 2 \times 10^6 \) km\(^3\) decrease in ice-volume (Pollard and DeConto, 2009) may correlate with the retreat of the Taylor Glacier and a reduction in Antarctic ice volume.

In the overlying mud successions, which represent warm, ice free conditions the stepwise (cycles 1 and 2, figure 13.5), up-core increase in coercivity and decrease in grain size may be driven by an increased input of oxidised magnetite or maghemite. Much like the discussion presented in the preceding section during this time of low ice volume and warm water temperature in the Taylor Fiord it is possible that significant soils formed at the edges of the Taylor Valley. Concentrations do not vary significantly in this unit indicating that there were no major changes in the production rate of magnetic minerals between 226 m and 206 m.

Between 206 m and 200 m (cycle 3, 13.5) Winter and Harwood (1997) reported a diverse *in-situ* open marine diatom flora and Ishman and Rieck (1992) reported the most diverse foram assemblage in DVDP-11. An increase in magnetic concentrations indicates that a significant pulse of magnetic material entered the Taylor Fiord which may have been delivered by rivers during a period of extreme warmth. Alternatively this increase in concentration may signal the advance of the Taylor Glacier grounding line leading up a major unconformity at 200 metres.

**Correlation with the oxygen isotope and ice volume records**

A tentative correlation is made between the coercivity cycles (226 - 200 m) and the oxygen isotope record. The correlation of coercivity peaks is constrained by the C3n.1n-C2Ar reversal which places the peak (2) within Gi27; consequently the underlying (1) and overlying (3) peaks are correlated with the Co1 and Gi25 excursions respectively. The correlation may indicate that 41 kyr warming and cooling events controlled the region wide precipitation, temperature, and soil formation.
13.3 mid Pliocene - early Pleistocene glacial expansion and cooling

A significant expansion of the Taylor and Ferrar Glaciers is recognised which is followed by a cooling from the mid Pliocene to the early-mid Pleistocene.

13.3.1 mid Pliocene

The three successions studied here are discontinuous between $\sim 3.5 \text{ Ma}$ and $\sim 2.6 \text{ Ma}$ which prevents a robust correlation between drill cores. Sediments indicate a dynamic system with alternating massive and stratified diamicrites and current washed sands and gravel. In CIROS-2 sediments are dominated by massive and stratified diamicits that were deposited beneath an expanded Ferrar Glacier which repeatedly grounded over the drill site. In DVDP-10 sediments are also dominated by massive and stratified diamicits and in DVDP-11 only a thin interval of pebble conglomerate and stratified diamicit is preserved which indicates an expanded Taylor Glacier.

13.3.2 Early Pleistocene

In the DVDP-11 between $\sim 190 \text{ m}$ and $\sim 160 \text{ m}$ and above $\sim 138 \text{ m}$ in DVDP-10 a significant provenance shift (Porter and Beget, 1981) and thick sequences of winnowed gravels and sands after $\sim 2.6 \text{ Ma}$ signals the first grounding of eastern sourced ice in New Harbour and the expansion of the West Antarctic and Ross Sea Ice Sheets. After this first grounding event open marine and ice distal conditions are no longer seen in the CIROS-2 or DVDP drill cores.

The New Harbour ice grounding event coincides with increased glacio-eustatic variations (Naish, 1997; Naish et al., 2009) and a significantly greater ice-volume than at anytime during the Pliocene warm period (Pollard and DeConto, 2009). The coarsening of facies in the DVDP cores is probably due to shallowing water depths.

Correlation with regional events

The terrestrial sedimentary records indicate expansion of the Dry Valleys glaciers after 3.5 Ma.

In the Wright Valley, glacial deposits indicate an expanded and dynamic upper Wright Glacier (Hall et al., 1993; Hall and Denton, 2005). Hall et al. (1993) and Hall and Denton (2005) used entrained basalt clasts within the Onyx, Wright, and Alpine...
III drifts to constrain their ages to 3.3, 3.4, and 3.5 Ma respectively. However, these ages do not reflect the emplacement age of each drift and are used as a maximum age only.

In the Taylor Valley the highest and oldest glacial drifts (Alpine drifts III, IVb, and IV) indicate that the Taylor Glacier expanded to at least the Canada Glacier between ~3.5 and 2.7 Ma (Wilch et al., 1993b,a; Bockheim et al., 2008).

In the Ferrar Valley the oldest and highest glacial drifts occur at this time also (Staiger et al., 2006). Krusic et al. (2009) inferred from equilibrium-line altitude calculations, that during the early-mid Pliocene period the climate in the Wright and Taylor Valleys must have been warmer and wetter in order to support the expanded glaciers.

Williams et al. (2010) suggested that the EAIS underwent a period of rapid retreat at ~3.5 Ma from IBRD at ODP site 1165 and in the Ross Sea uninterrupted open-marine conditions persisted for at least 250 kyr (3.4 Ma - 3.65 Ma, Winter et al., 2011). Numerous short duration episodes of open marine conditions with minimal summer sea-ice are recorded between 3.5 Ma and 1.2 Ma in the AND-1B core, however, these become thinner and less frequent in younger sediments.

Sea-level records from New Zealand’s West Coast (Naish and Wilson, 2009) and from the United States Atlantic Coastal plain (Dowsett and Cronin, 1990) indicate that sea-level was between 10 m and 35 m higher than present and ice-sheet models (Pollard and DeConto, 2009) indicate frequent deglaciations and relatively low ice-volume until MIS stage M2.

After ~2.8 Ma and into the early Pleistocene the Antarctic ice-sheets cooled and changed in character. The oxygen isotope stack of Lisiecki and Raymo (2005) indicates a shift from low amplitude, obliquity paced fluctuations to higher amplitude variations and a general baseline shift to modern interglacial $\delta^{18}O$ values in response to the growth of large Northern hemisphere ice sheets (Laurentide and Fennoscandian ice sheets, Raymo, 1994). Seki et al. (2010) reported a rapid decline in atmospheric $CO_2$ from ~400 ppm to pre-industrial levels between 3.2 Ma and 2.8 Ma which they associated with NH ice-sheet growth.

Around this time the ice sheet model indicates an expanding ice sheet and a baseline shift to modern day interglacial ice volume with occasional, short-lived deglaciations (Pollard and DeConto, 2009). Seismic reflection data indicate expansion of the WAIS into the Ross Sea (Bart, 2004) and from DSDP-ODP drill sites at the Antarctic Peninsula Rebescos et al. (2006) suggested that the Antarctic ice-sheet transitioned from a warm wet-based to a cold dry-based ice sheet.

335
In the AND-1B core diatomite beds become thinner and less frequent (Naish et al., 2009) and McKay et al. (2009) suggested a switch to a cooler style ice-sheet with less meltwater influence. Talarico et al. (2011) reported a sharp increase in metamorphic clasts at ~2.55 Ma which they attributed to expansion of the southern Mulock and Skelton glaciers.

Fitzgerald (1992) reported accelerated uplift of the Transantarctic Mountains after the Miocene and Stern et al. (2005) suggested that the acceleration may have been driven by increased erosion by large scale wet-based glaciers and isostatic rebound of the Transantarctic Mountains.

13.3.3 Late Pliocene - early Pleistocene environmental magnetic records (Figure 13.7)

Because the age models are less well constrained in the upper portions of the drill cores, correlations with other records are more difficult. However, several broad trends and some discrete events are identified.

In DVPD-10, and -11 after ~2.6 Ma a significant increase in magnetic concentration and an average decrease in magnetic grain size differentiates the upper portion of the drill cores from the underlying sediments. The change in concentration is probably driven by the change in ice source from westerly sourced ice where rocks are dominated by granites, metamorphic, and sedimentary units to eastern sourced ice where rocks are dominated by the McMurdo Volcanic Group.

DVPD-10 sediments are the oldest in this time bracket and record a significant baseline shift at a core break between 148 and 143 metres from low average concentrations to high concentrations. The core break has an age of ~3.3 Ma which coincides with M2 isotope stage; an abrupt 0.5‰ excursion in the δ¹⁸O record (Lisiecki and Raymo, 2005) and a ~40 metre fall in sea-level.

In DVPD-10, and -11 sediments which were deposited after 3.3 Ma have higher concentrations and a considerably higher noise level in the grain size and coercivity records.

In DVPD-11 the C2r.1r - C2n reversal (151.22 ±0.83m) occurs in the middle of a ~20 metre thick, massive to weakly stratified diamict which is correlated with Marine Isotope Stage 72. The diamictite can be divided into two portions with a break at ~155 metres which separates an interval with noisy, high concentrations from an overlying magnetically quiet interval. The break is characterised by high coercivities but there
is no significant change in facies associated with the changes in magnetic mineralogy.

The portion of the DVDP-10 record between 133 m and 85 m contains a relatively high sample density but has poor age control. A correlation with the GPTS is made at 117.5 metres. However, because it occurs at an unconformity it serves only as a guide. Three thin, fine grained intervals indicate a retreat of the ice front or ice lift off but with so few chronostratigraphic constraints a correlation with the $\delta^{18}$O record is difficult. The environmental magnetic record does not reveal any particular trends and the fine grained intervals do not have a unique expression when compared with coarser grained intervals.

- Magnetic concentrations and noise level in the environmental magnetic parameters is substantially higher after $\sim$ 3.3 Ma.
- Trends in concentration, coercivity and grain size dependent parameters are visible, however, because of poor age control, correlations with the ice-volume or $\delta^{18}$O records are difficult.
- Environmental parameters do not correlate with lithological units, changes in lithology or with unconformities.

Suggested drivers of environmental magnetic record

The influx of predominantly McMurdo Volcanics sourced sediments resulted in higher magnetic concentrations because the McMurdo volcanics have the highest concentrations of magnetic minerals in southern Victoria Land (see chapter 11) and are easily eroded.

Unstable depositional and environment conditions are probably reflected by the higher noise level in environmental magnetic parameters.

Eustatic sea-level fluctuations increased significantly between 3.3 and 2 Ma in response to the growth of major northern hemisphere ice-sheets at around 2.6 Ma (Shackleton et al., 1984). Naish and Wilson (2009) suggested eustatic sea-level fluctuations of 10 to 30 metres between 3.6 and 2.58 Ma which increased further to between 110±20 m and 25±10 m after 2.6 Ma (Naish, 1997).

In the AND-1B record after 2.6 Ma diatomite intervals become rarer and thinner and thicker diamicties and more frequent ice grounding events indicate more frequent and larger glaciations (Naish et al., 2009).

The shift to more vigorous glaciations and higher amplitude eustacy coupled with continued and accelerating uplift (e.g. Fitzgerald, 1992; Stern et al., 2005) resulted
in overall reduced accommodation space, more erosion, ice-contact, and current winnowing of sediments. The unstable depositional environment probably caused the shift from continuous and cyclic environmental magnetic behaviour of the Miocene and early Pliocene sediments to the discontinuous, noisy, and more variable record of the late Pliocene and early Pleistocene.

13.4 The appearance of paramagnetic behaviour at the Plio-Pleistocene boundary

Thermomagnetic analyses revealed a significant (sometimes >50% of susceptibility), thermally stable paramagnetic component in magnetic susceptibility in the top portion of drill cores (Figure 13.6). Hysteresis analyses also indicate that a greater paramagnetic slope correction is needed to correct these data. Thermomagnetic analyses of modern aeolian sediments of southern Victoria Land revealed strong paramagnetic behaviour in all samples. The oldest definitive occurrence of this paramagnetic component in drill core sediments occurs at \( \sim 2.2 \) Ma in DVDP-11 (it may extend to 3.3 Ma in DVDP-10).

13.4.1 Drivers of paramagnetism

Mineralogical driver of paramagnetism

The appearance of paramagnetism in drill core sediments coincides with the environmental shift and change in ice/sediment source after \( \sim 3 \) Ma. This may indicate that paramagnetic behaviour observed in sediments is controlled by the influx of volcanic rich sediment from the east or by a change in the climate.

Thermomagnetic analyses of 134 specimens of various basement lithologies (see chapter 11) revealed that only McMurdo Volcanic Group rocks have paramagnetic behaviour. Therefore it is possible that iron rich minerals or titanomagnetite in rapidly cooled volcanic rocks are the driver of the paramagnetic component and that sediments eroded from these volcanics retain this component. Quenched volcanic rocks can contain a wide range of titanomagnetite compositions because there is insufficient time to form discrete Ti and Fe lamellae.\(^3\)

\(^3\)Pure titanomagnetite (Fe\(_2.5\)Ti\(_{0.6}\)O\(_4\)) has a Curie temperature of 150°C (Dunlop and Özdemir, 1997).
Figure 13.6: Distribution of paramagnetism in CIROS-2, DVDP-10, and -11. Green intervals indicate the presence of paramagnetic behaviour, grey intervals intervals indicate no paramagnetic behaviour, and red intervals are without data. Paramagnetism is ubiquitous after \( \sim 1 \) Ma. The oldest occurrence of paramagnetic behaviour is in DVDP-11 after \( \sim 2.2 \) Ma. However, the absence of samples between 166 m and 192 metres (2.2 - 2.8 Ma) in DVDP-11, and 124 m and 138 m (1.8 - 3.3 Ma) in DVDP-10 means the transition to paramagnetic behaviour may have occurred earlier.
Atkins and Dunbar (2009) demonstrated that Transantarctic Mountain and McMurdo Volcanics lithologies dominate the aeolian sediments deposited into Southern McMurdo Sound today. Thermomagnetic analyses of aeolian sediments from Taylor Valley, from the sea ice surface, and of sediments from the McMurdo Sound sea floor all display paramagnetic behaviour. In Taylor Valley down valley winds are strongest and most frequent during winter. During summer winds are weaker and directed up valley (Doran et al., 2002; Nylen and Fountain, 2004). It is reasonable to assume then that aeolian sediments found in Taylor Valley and on sea ice in front of Taylor Valley should be dominated by up-valley lithologies which include outcrops of McMurdo Group Volcanics.

However, in drill core sediments paramagnetic behaviour appears only after $\sim$2.2 Ma which post-dates the oldest suggested eruptions of McMurdo Volcanic group in Taylor Valley by at least by 1.7 Ma (Wilch et al., 1993a,b), possibly by up to 2.5 Ma (Armstrong, 1978).

It is possible that a provenance shift associated with the first ice-grounding events from eastern sourced ice and the formation of proglacial lakes in New Harbour are the driver of paramagnetic components in sediments deposited after $\sim$3 Ma, however, other factors may also be responsible.

**Diagenetic driver of paramagnetism**

The appearance of paramagnetism may be driven by diagenetic alteration of sediments. In CIROS-2 the appearance of paramagnetic behaviour occurs only above a zone of diagenetic alteration and in DVDP cores it occurs above a major unconformity indicating that sediments without paramagnetic behaviour may be altered. Diagenetic alteration of drill core sediments has been discussed and is confined to CIROS-2 only (see chapter 6).

However, diagenetic alteration of the paramagnetic minerals is a possibility. Diagenesis may be caused by the scavenging of available iron from iron bearing minerals such a biotite. EPMA analyses did not reveal unusual mineralogical or morphological changes with depth in either of these drill cores. Additionally, iron bearing minerals such as magnetite and hematite are several order of magnitude more reactive than other iron bearing minerals such as ilmenite, garnet, augite, or amphiboles (Canfield et al., 1992) it follows then that magnetite or hematite should be more adversely affected by diagenesis before other paramagnetic minerals.

The thermal alteration indices can give an indication of whether sediments have
undergone diagenesis (e.g. authigenic greigite will break down to magnetite on heating thus increasing the magnetic susceptibility). However, in DVDP-10, and -11 greater alteration occurs in sediments which display paramagnetic behaviour yet the shape of the cooling curve remains unchanged. This indicates that both the remanence carriers and paramagnetic components are stable to at least 700°C. A good example of this type of alteration is in modern sediments from southern Victoria Land (see chapter 11).

Diagenetic alteration of minerals may have occurred in streams or in paleosols before the sediments were deposited, this may in turn be a climate controlled diagenetic signal.

Climate driver of paramagnetism

An alternative driver for paramagnetism is climatic control on the production and/or preservation of paramagnetic minerals. In the lower portions of the DVDP-10, and -11 drill cores, finer magnetic grain sizes are associated with sedimentary units which represent colder climatic conditions. The appearance of paramagnetic behaviour in drill cores coincides with the development of the cold, hyper arid cryosphere and may be driven by the appearance of strong katabatic winds.

Little direct evidence exists about the timing of the onset of strong katabatic winds in Antarctica. However, evidence from the evolution of deep sea circulation may give indications about their onset. Modelling studies by DeConto et al. (2007) demonstrated that the strength of katabatic winds and subsequent growth of sea ice depends critically on the presence and size of the Antarctic Ice sheets. Significant cooling, expansion of sea-ice, and a change in the style of the Antarctic ice sheets occurred between 3 Ma and 2.4 Ma (e.g. Kennett and Hodell, 1993) and Hall et al. (2001) reported increased ventilation of the Deep Pacific Ocean during glacial times over the past 1.2 Ma which they attributed to increased sea ice production in Antarctica.

Petrelli et al. (2008) and Van Woert (1999) demonstrated from modelling studies and observations that winter katabatic winds are the principal driver of sea-ice production and polynya in the Ross Sea. Antarctic bottom waters (AABW)\(^4\) probably play a dominant role in driving global deep ocean circulation (Carter et al., 2008b) and sea-ice growth and polynya have been implicated as key bottom water production mechanisms (e.g. Gordon, 1982; Weingartner et al., 1998b; Huhn et al., 2008)\(^5\).

\(^4\)AABW are sourced from the Weddell Sea (~50%), Wilkes Land Margins (~30%), and the Ross Sea (~20%) (Carter et al., 2008b).

\(^5\)Some other mechanism of bottom water formation include freezing and melting beneath ice shelves.
It is possible that the paramagnetic component is driven by the initiation of strong katabatic winds and hyper-arid conditions. Aeolian transport is also an effective mechanism for reducing grain size and creating ultra fine (∼5 µm) particles through grain on grain impact either during erosion or transport (see chapter 12). It may be that the mineral responsible for paramagnetic behaviour does not survive chemical weathering and that by inference the Pliocene climate in southern Victoria Land, or at least in the Taylor Valley was generally wetter and warmer than it is today. The absence of maghemite and oxidised magnetite in these younger sediments also seems to indicate that wide spread chemical weathering and oxidation of magnetite ceased after at least 2.2 Ma.

All modern sediments collected for this study display paramagnetic behaviour. The only terrestrial sediments (other than those found in the drill cores) which did not display paramagnetic behaviour are from well cemented sediments from beneath the Walcott Glacier (see chapter 11). However, these sediments may be significantly older than surrounding surficial cover (one specimen has a reversed polarity magnetisation indicating that it predates 781 kyr) therefore they may represent marine sedimentation at Walcott Bay during the Pliocene or even Miocene. Biostratigraphic or other age controls were unavailable at the time of writing.

It is possible then that the initiation of katabatic winds allowed for creation of significant quantities of paramagnetic particles and that the cold, hyper arid climate allowed these particles to survive alteration.

(Baines and Condie, 1998) and mixing of different water masses (Jacobs, 2004).
Figure 13.7 (previous page): Latest Pliocene - early Pleistocene portion of DVDP-10 and -11. Environmental magnetic data and lithologic records are correlated with the modelled Antarctic ice volume (Pollard and DeConto, 2009), benthic $\delta^{18}$O stack (Lisiecki and Raymo, 2005) and sea-level calibration (Naish and Wilson, 2009) where selected isotope events are named, obliquity (Laskar et al., 2004), mean daily insolation at $73^\circ$S on December 21, and GPTS (Lourens et al., 2004). The green bar indicates ice free conditions in the Ross Sea (Naish et al., 2009; Winter et al., 2011). Correlated terrestrial events include the Taylor Valley alpine drifts (black line) (Bockheim et al., 2008), grey lines indicate Wright Valley alpine drifts (Hall et al., 1993; Hall and Denton, 2005) black stars indicate deposition of Ferrar Glacier alpine drifts (Staiger et al., 2006). Blue hexagon is IBRD armada events identified by (Williams et al., 2010) indicating a destabilised Antarctic Ice-sheet or ice margin. Firm correlations with the GPTS are drawn in black. Where correlations occur at an unconformity, core-break, in an ambiguous polarity interval or between widely spaced samples a correlation is made using a dashed line. Correlations between unconformities, lithological units and the ice-volume or $\delta^{18}$O are shown in red.
13.5 mid Pleistocene to Holocene

The upper most portions of the DVDP and CIROS-2 successions span the last 1.2 Myr and contain the mid-Pleistocene transition (MPT) where the Antarctic ice-sheets transition from a 41 kyr to 100 kyr cyclicity. Accommodation space in the Taylor Valley was almost exhausted with the DVDP-10 record now within 60 metres of modern sea level and the DVDP-11 deposited above modern sea-level after ∼900 kyr. CIROS-2 is still below sea-level today, however after ∼1 Ma the succession is dominated by freshwater sediments.

The successions contain numerous ice-grounding events and comprise sandy and gravelly sediments with rare diamictons especially in DVDP-11 and CIROS-2. In DVDP-10, Porter and Beget (1981) reported a sharp increase of McMurdo Volcanic sourced sediments (up to 40%) above 50 metres. In CIROS-2, Barrett and Hambrey (1992) also reported a sharp increase of McMurdo Volcanic sourced sediments (up to 47%) between 60 and 70 metres and provenance studies of clasts indicate mixed local (down valley) and distal (from the south) sources (Sandroni and Talarico, 2006) above 100 metres. Talarico et al. (2011) noted that in the AND-1B core at 82.7 mbsf (∼0.9 Ma) a large increase in Skelton-Mulock sourced clasts occurs which they attributed to the expansion of larger EAIS glaciers and a shift to hyper polar conditions.

In DVDP-11 a switch from marine to terrestrial sedimentation occurs between 1.7 Ma and 1.2 Ma and Winter and Harwood (1997) reported a diverse freshwater diatom assemblage above 91 m. In CIROS-2 Winter and Harwood (1997) also reported a dominance of freshwater diatoms above ∼80m (<1.2 Ma).

It is likely, that during glacial maxima, sedimentation occurred in an ice-dammed lake behind an expanded Ross Ice Shelf in the Taylor Valley and Ferrar Fiord. Marine diatoms are absent in DVDP-10 and CIROS-2 after ∼1.2 Ma indicating unfavourable conditions for diatoms during interglacial high stands when marine sediments accumulated.

MIS-31

The age models indicate that the super-interglacial, Marine Isotope Stage 31 (MIS-31, e.g. Scherer et al., 2008) may be recorded in DVDP-10 and -11. During super interglacial, Marine Isotope Stage 31 (∼1.07 Ma) sea surface temperatures warmed significantly, polar fronts migrated southwards and expanded, and the WAIS was probably significantly smaller (e.g. Flores and Siero, 2007; Scherer et al., 2008; Villa et al., 2008;
Maieron et al., 2009). In the AND-1B succession MIS-31 is recognised by a diatom bearing interval between 86.90 and 92.24 metres (DU-II) which indicates open-marine productivity and reduced sea-ice cover (Villa et al., 2010; Winter et al., 2010) and in CRP-1, MIS-31 is recognised by a thin carbonate (Scherer et al., 2008) interval which Taviani and Claps (1998) interpreted to represent a period of optimal climate under glacial retreat. Sea-level was probably also higher therefore allowing a transgression into Taylor Valley and allowing for the deposition of a thin mudstone interval at ~130 metres in DVDP-11 and a thin fine sand interval at ~71 metres in DVDP-10. Hendy (2000) reported from studies of DVDP-12 sediments that the oldest lakes in the Dry Valleys area occur in the Taylor Valley and have ages as old as 295 kyr. However, it is likely that sedimentation was dominantly in ice-dammed lakes after 1.2 Ma in Taylor Valley and that in Ferrar Fiord fresh water sediments accumulated during glacial maxima with marine sedimentation during interglacial periods.

13.5.1 Global and regional events during the mid Pleistocene to Holocene period

During the mid Pleistocene, large Northern Hemisphere ice sheets were well established at glacial maxima (e.g. Raymo, 1994) and large glacioeustatic sea-level fluctuations of up to 120 metres resulted from the growth and decay of these large ice sheets (Veeh and Chappell, 1970; Fairbanks, 1989; Chappell and Shackleton, 1986; Pillans et al., 1998). The ice volume model of Pollard and DeConto (2009) indicates large, up to $13 \times 10^6$ km$^3$ fluctuations. Numerous ice grounding events are recognised in seismic reflection data which indicate that the WAIS extended to the edge of the continental margin in the Ross embayment. The behaviour of the EAIS seems more conservative with some portions of the ice sheet remaining in stasis while the WAIS expanded (e.g. Alonso et al., 1992; Bart and Anderson, 2000; Anderson et al., 2002).

However, significant warming events still occurred during this cool period. Ice volume models indicate that the WAIS collapsed at least four times in the last 1.2 Myr (Pollard and DeConto, 2009) and sea-level records indicate that between 390 ka and 550 ka sea-level may have been 22 metres above present (Hearty et al., 1999) indicating that some of the EAIS may have been lost too.

The mid-Pleistocene transition (MPT) between ~900 kyr and ~400 kyr marks a shift from low amplitude 41 kyr ice volume fluctuations to larger ~100 kyr fluctuations. The MPT is recognised in the deep ocean as an unstable period with both 41 kyr and
100 kyr periodicities, and mixed warm and cool conditions followed by abrupt cooling at ∼400 kyr and a transitions to 100 kyr climate cycles (e.g. Hall et al., 2001; Venuti et al., 2007; Crundwell et al., 2008). Declining CO₂, complex ice volume dependent and/or silicate weathering feedback mechanisms, amplification of weak orbital parameters, and the removal of a deforming soft sediment layer beneath ice sheets (e.g. Imbrie et al., 1993; Clark and Pollard, 1998; Berger et al., 1999; Shackleton, 2000; Huybers, 2006; Clark et al., 2006) have all been invoked as drivers of the MPT.

13.5.2 Pleistocene environmental magnetic records (Figures 13.8, 13.9, 13.10)

Interpretation of these youngest records is difficult because age control is poor and sample density is low. Several contemporaneous behavioural changes occur across all three drill cores.

Overall these youngest sediments have the highest concentrations and are dominated by magnetite. Magnetic grain sizes are coarser in all three drill cores when compared with older sediments. Thermomagnetic analyses indicate that the paramagnetic component is ubiquitous and reaffirms that magnetite is dominant in all three drill cores at ∼1 Ma indicating continuation of hyper arid conditions since the early Pleistocene.

An increase in magnetic concentration occurs after ∼1 Ma in all three drill cores across all lithologies, which coincides with the increased proportion of McMurdo Volcanic sourced sediments in DVDP-10 and CIROS-2.

Overall the magnetic behaviour of sediments from drill cores after 1 Ma is indistinguishable from the behaviour of most modern, marine, aeolian, and lake sediments. Glacial-interglacial cycles are not recognised in any of the successions after 1.2 Ma because sample resolution is too low and probably because limited accommodation space prevented the depositions of complete glacial-interglacial cycles.
Environmental magnetic data and lithologic records are correlated with the modelled Antarctic ice volume (Pollard and DeConto, 2009), benthic δ¹⁸O stack (Lisiecki and Raymo, 2005) and sea-level calibration (Naish and Wilson, 2009) where selected isotope events are named, obliquity (Laskar et al., 2004), mean daily insolation at 73°S on December 21, and GPTS (Lourens et al., 2004). The green bar indicates ice free Ross Sea (Naish et al., 2009; Winter et al., 2011), the green line indicates significantly elevated SSTs (Villa et al., 2008) during Marine Isotope Stage 31. Black lines indicate deposition of alpine drifts (Bockheim et al., 2008), blue line indicates deposition of lake sediments (Hendy, 2000) and black stars indicate deposition of Ferrar Glacier alpine drifts (Staiger et al., 2006). Firm correlations with the GPTS are drawn in black, where correlations occur at an unconformity, core-break, in an ambiguous polarity interval or between widely spaced samples a correlation is made using a dashed line. Correlations between unconformities, lithological units and the ice-volume or δ¹⁸O are shown in red.
Figure 13.9 *(previous page)*: Late Pleistocene to Holocene portion of DVDP-10. Environmental magnetic data and lithologic records are correlated with the modelled Antarctic ice volume (Pollard and DeConto, 2009), benthic δ¹⁸O stack (Lisiecki and Raymo, 2005) and sea-level calibration (Naish and Wilson, 2009) where selected isotope events are named, obliquity (Laskar et al., 2004), mean daily insolation at 73°S on December 21, and GPTS (Lourens et al., 2004). The green bar indicates ice free Ross Sea (Naish et al., 2009; Winter et al., 2011), the green line indicates significantly elevated SSTs (Villa et al., 2008) during Marine Isotope Stage 31. Black lines indicate deposition of alpine drifts (Bockheim et al., 2008), blue line indicates deposition of lake sediments (Hendy, 2000) and black stars indicate deposition of Ferrar Glacier alpine drifts (Staiger et al., 2006). Firm correlations with the GPTS are drawn in black, where correlations occur at an unconformity, core-break, in an ambiguous polarity interval or between widely spaced samples a correlation is made using a dashed line. Correlations between unconformities, lithological units and the ice-volume or δ¹⁸O are shown in red.
Figure 13.10 (previous page): Late Pleistocene to Holocene portion of DVDP-11. Environmental magnetic data and lithologic records are correlated with the modelled Antarctic ice volume (Pollard and DeConto, 2009), benthic δ¹⁸O stack (Lisiecki and Raymo, 2005) and sea-level calibration (Naish and Wilson, 2009) where selected isotope events are named, obliquity (Laskar et al., 2004), mean daily insolation at 73°S on December 21, and GPTS (Lourens et al., 2004). The green bar indicates ice free Ross Sea (Naish et al., 2009; Winter et al., 2011), the green line indicates significantly elevated SSTs (Villa et al., 2008) during Marine Isotope Stage 31. Black lines indicate deposition of alpine drifts (Bockheim et al., 2008), blue line indicates deposition of lake sediments (Hendy, 2000) and black stars indicate deposition of Ferrar Glacier alpine drifts (Staiger et al., 2006). Firm correlations with the GPTS are drawn in black, where correlations occur at an unconformity, core-break, in an ambiguous polarity interval or between widely spaced samples a correlation is made using a dashed line. Correlations between unconformities, lithological units and the ice-volume or δ¹⁸O are shown in red.
Chapter 14

A model of the evolution of southern Victoria Land climate

Chapter 12 presented a conceptual model for the evolution of magnetic minerals in southern Victoria Land today. Here the conceptual model is expanded to look back in time at how the erosion, transport, and depositional systems behaved during Pliocene glacial minima and maxima and the recent glacial maxima. The climate reconstructions are constrained by paleoecological records from other studies and by the sedimentologic and environmental magnetic records presented during this study (Chapter 13). In the modern climate setting all weathering mechanism are active. However the dominant and most wide spread weathering mechanism will be most easily recognised in the magnetic and sedimentary records.

14.0.3 Pliocene Glacial Minima

During the Pliocene warm period glaciers retreated up valley and the Ross Sea had limited sea ice cover. Sediments deposited during this climate regime can comprise alluvial sands and gravels in the hinterland, organic rich muds and silts in the fiords which originated from meltwater plumes and river systems, and biogenic sediments in the open Ross Sea from diatom blooms. Rare drop stones and ice rafted debris can be found in all of these sediments (Figure 14.1).

Under warmer, wetter conditions chemical and biological weathering rates of magnetic minerals are higher and more widespread. The higher temperatures resulted in greater precipitation and increased melt rates from snow, and alpine glaciers. The warm, wet conditions would have encouraged soil formation at the edges of fiords and on mountain slopes. Chemical weathering rates in streams and ground water systems
Figure 14.1: Cross section through the Taylor Valley during Pliocene Glacial Minima showing the distribution of lithologies (modified after McKay et al., 2009) and the environmental magnetic facies. Water depths are constrained by microfossil paleoecology (e.g. Webb and Wrenn, 1982; McKelvey, 1991).

were also higher because of a deeper permafrost boundary or absence of permafrost, and because of expanded hyporheic zones and groundwater systems. Mechanical weathering processes were probably still operating. However, under warm conditions the products of mechanical weathering would have been incorporated into soils and subsequently undergone chemical alteration.

Magnetic concentrations and grain-sizes decrease with distance from the coast as most terrigenous sediment is supplied by melt water streams and rivers into deep mountain fiords; sea-level reconstructions indicate that fiords extended 30 km inland from the modern coast line. In the DVDP drill cores the lowest magnetisations are observed in the most ice-distal facies at a time when the Taylor Glacier was probably some 30 km upvalley from the drill site.

The lack of sea-ice and warm sea-surface conditions in the Ross Sea suggests that katabatic winds may have been weaker and confined to inland areas resulting in reduced or no aeolian sediment transport into the fiords and Ross Sea.

Diagenetic alteration of magnetic mineralogy through anoxic, bacterial reducing conditions is favoured in deep fiords and offshore records because of high biogenic productivity and deposition rates. The detrital magnetic mineralogy is dominated by
altered, oxidised magnetic minerals from soils and alluvium. Magnetic minerals are derived mostly from confined catchments and ice drainage systems with little input from adjacent catchments and mountain ranges. An idealised environmental magnetic sequence motif of Pliocene glacial-interglacial, ice proximal cycles during the latest Miocene and early Pliocene is presented in figure 14.3.

### 14.0.4 Pliocene Glacial Maxima

During Pliocene glacial maxima large EAIS outlet glaciers expanded to at least the mouth of the Taylor Fiord and alpine glaciers were also expanded because of higher snow fall rates. In DVDP-11 massive and stratified diamicts indicate oscillations of the grounding line of the expanded Taylor Glacier. Geomorphic records up-valley confirm the expansion of the Taylor Glacier and indicate that at 3.5 Ma the Taylor Glacier was over 1000 metres thick and advanced to at least the Canada Glacier (Figure 14.2).

Magnetic concentrations and grain-sizes are variable with the presence of small, strongly magnetised clasts in diamicts resulting in magnetic records which have scattered data.

![Diagram](image)

Figure 14.2: Cross section through the Taylor Valley during Pliocene Glacial Maxima showing the distribution of lithologies (modified after McKay et al., 2009) and the environmental magnetic facies. Water depth estimates are constrained by microfossil paleoecology (e.g. Webb and Wrenn, 1982; McKelvey, 1991) and Taylor Glacier thicknesses are constrained by drifts (Bockheim et al., 2008).
The advancing and expanding glaciers deposited an evolving magnetic mineralogy. As the glaciers gradually expand, soils and alluvium are progressively eroded as the valley floor and slopes are cleaned of surface cover. The earliest diamicts from the initial expansion of the glacier contain altered and oxidised magnetic minerals derived from soils and alluvium. As the glacier thickens, soils and alluvium are eroded to expose basement rocks to erosion. The resulting late stage diamicts which are derived from basement lithologies contain fresh, unaltered magnetic minerals with variable grain-sizes. An idealised environmental magnetic sequence motif of Pliocene glacial-interglacial cycles is presented in figure 14.3.

Soil development during Pliocene glacial maxima was confined to small, ice-free areas at low altitude where temperatures were warm enough to allow liquid water. Aeolian input may have been higher because of greater ice volume. However, environmental magnetic indicators of aeolian sediments may be overcome by the magnetic signature of diamicts.

Figure 14.3: Idealised environmental magnetic sequence motif of Taylor and Ferrar Fiord successions during the latest Miocene-early Pliocene dynamic period. Ice distal facies are characterised by oxidised magnetic minerals derived from soils and alluvium. Ice proximal/immediate facies are characterised by freshly eroded, unaltered magnetic minerals.
14.0.5 Modern Glacial Maxima (~10 ka)

Continued uplift of the Taylor and Ferrar fiords led to an evolving sedimentation style of massive diamicts and very ice proximal glaciomarine sedimentation to lacustrine sedimentation. The dominant ice source during modern glacial maxima is from the Ross Sea resulting in the formation of ice dammed lakes in the Taylor Valley and Ferrar Fiord (Figure 14.4).

Modern glacial maxima are characterised by very ice proximal massive diamicts, glaciomarine diamicts, and current winnowed gravels at the grounding line near the coast as seen in DVDP-10. Sediments have high concentrations of volcanogenic debris and widely varying grain-sizes.

Figure 14.4: Cross section through the Taylor Valley during Modern Glacial Maxima showing the distribution of lithologies (modified after McKay et al., 2009) and the environmental magnetic facies. Water depth of lake Washburn (modern lake Fryxell) constrained by the highest occurrence lake shore geomorphology (e.g. Hall and Denton, 2000).

Further inland from the grounding line, at the DVDP-11 drill site, modern glacial maxima result in lacustrine sedimentation in a fresh water lake setting. Sediments are finer and comprise bedded sands, silts and occasional pebbles and drop stones, which are derived from aeolian sources, ice rafted debris, melt water plumes, and possibly from melt water streams.

Magnetic concentrations are high and dominated by magnetite in glaciomarine sedi-
ments (DVDP-10) because of the presence of volcanic rich debris. Lacustrine sediments of DVDP-11 have high concentrations of magnetite and a minor high coercivity phase. Aeolian sediments are derived from Transantarctic mountain lithologies which include a portion of the hematite rich Beacon Supergroup Sediments.

Very low chemical/biological erosion and weathering rates mean that fine grains are not altered resulting in strong paramagnetism and superparamagnetism in sediments.

14.0.6 Modern Glacial Minima (today)

Modern sediments are characterised by onshore alluvial and aeolian sands, regolith and remnants from the last glacial maxima in the form of volcanic rich Ross Sea drift sediments. The offshore sedimentary records are characterised by fine grained aeolian and biogenic sediments with rare drop stones.

Erosion and sediment removal rates are extremely slow. Mechanical weathering through freeze thaw and thermal processes are the dominant erosion mechanism. Expanded, cold based, non-erosive alpine glaciers in the Transantarctic Mountains move little sediment. Strong katabatic winds are responsible for the majority of sediment transport to the sink and fluvial erosion and transport is confined to small melt water streams.

Figure 14.5: Cross section through the Taylor Valley during Modern Glacial Minima showing the distribution of lithologies (modified after McKay et al., 2009) and the environmental magnetic facies.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Fluvial/Aeolian sands, gravel</th>
<th>Fluvial/Aeolian sands, gravel</th>
<th>Aeolian sands, minor biogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration</td>
<td>Variable high</td>
<td>Variable high/low in diatomite</td>
<td></td>
</tr>
<tr>
<td>Grainsize</td>
<td>Variable mixed SP/SD/PSD/MD</td>
<td>Variable mixed SP/SD/PSD/MD</td>
<td></td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Mixed mineralogy of up-valley lithologies and distal aeolian</td>
<td>Post depositional diagenesis unlikely</td>
<td>Mixed mineralogy from all TAM rocks</td>
</tr>
</tbody>
</table>
Chemical and biological weathering occurs only during the summer months in water saturated sediments on valley floors and in isolated pockets. Magnetic mineralogy both onshore and offshore is variable and represents a mix of all Transantarctic Mountain lithologies. Most grains will be chemically unaltered after erosion and transport because of the extremely low chemical weathering rates. Sorting and winnowing of sediment during aeolian transport results in high concentrations. Diagenetic alteration of remanence carries may occur once magnetic grains reach the sink.
Chapter 15

Conclusions

The new chronologies from DVDP-10, -11 and CIROS-2 provide an important temporal framework for interpreting the climate evolution in the Taylor Valley and the Ferrar Fiord and have allowed, a more precise correlation of these records with other on-shore and offshore geological records. The environmental magnetic records reveal a climate driven modulation of magnetic minerals in drill core sediments. During the warmest times of the Pliocene, magnetic minerals are oxidised which indicates terrestrial soil formation under warmer and wetter conditions than today. The appearance of paramagnetic minerals at the Plio-Pleistocene boundary indicates the onset of strong katabatic winds and the establishment of modern hyper arid conditions. Future environmental magnetic studies of drill core sediments may be able to use paramagnetic behaviour in sediments as a tracer for the waxing and waning of the katabatic winds.

The source to sink model of magnetic minerals indicates that under modern, hyperpolar conditions magnetic minerals remain chemically unchanged from source to sink but are reduced in size through aeolian transport process resulting in paramagnetism in sediments. During warmer Pliocene times, the model calls for chemical weathering and oxidation of magnetic minerals which requires the presence of liquid water and substantially different climate conditions from today.

The drill core sediments contain a record of an expanded and dynamic Taylor Glacier during latest Miocene with a retreat and shift to open marine, ice-free conditions during the warm Pliocene. Eastern sourced glaciers returned to the Ferrar and Taylor fiords during the late Pliocene under cooling conditions with a further cooling at ~2.6 Ma resulting in the grounding of the WAIS in New Harbour. Finally reduced accommodation space in the Taylor Valley and Ferrar Fiords during the late Pleistocene resulted in the deposition of shallow marine and fresh water sediments.
15.1 Revised event stratigraphy for New Harbour Drill cores

New magnetostratigraphies were constructed of New Harbour successions based on complete AF and/or thermal demagnetisation of discrete specimens from drill cores. The magnetostratigraphies were correlated with the GPTS using biostratigraphic and radiometric constraints to reveal advance and retreat histories of the Taylor and Ferrar Glaciers and to allow for correlations with the onshore and offshore records.

15.1.1 Paleomagnetism of New Harbour drill cores

A suite of paleomagnetic samples from DVDP-10, -11 and CIROS-2 were subjected to stepwise AF and thermal demagnetisation. Demagnetisation data resulted in the identification of six behavioural groups. Group A specimens are the most well behaved with very low scatter in demagnetisation data. Group B specimens are less well behaved and have greater scatter of demagnetisation data; the majority of samples (45%) had group B type behaviour. Group C specimens have considerable scatter in demagnetisation data and MAD values are high. Only groups A, B, and C samples were used to develop the magnetostratigraphy. Groups D, E and F samples had weak and unstable magnetisations which produced scattered demagnetisation vectors. Rock magnetic analyses revealed that magnetite and minor quantities of maghemite were the dominant remanence carriers in the EW gestures. In CIROS-2 magnetite is the dominant magnetic mineral above ~90 m and pervasive diagenetic alteration has removed the remanence below ~90 m leaving only iron rich siderite cement.

15.1.2 Revised magnetostratigraphies for New Harbour drill cores

By using modern demagnetisation techniques and instruments the detrital magnetisation of DVDP-10, -11, and CIROS-2 has been more accurately revealed. In DVDP-10, and -11 the sampling density is lower than in older studies. However, stepwise demagnetisation of specimens revealed that the detrital remanence was not fully identified during previous studies, therefore the magnetostratigraphies from this study are more well tested and robust.

In CIROS-2 four magnetozones are recognised above 92.6 m. In DVDP-10, eight magnetozones are identified but because of widely spaced samples only four magnetic
reversals are used in the correlation with the GPTS. Magnetozones which do not end at a reversal ended in an ambiguous polarity zone. In DVDP-11 14 magnetozones are identified. Sample resolution is high below \(\sim 200\) m which resulted in precisely located (\(\pm 1\) m) magnetic reversals within the drill core.

### 15.1.3 Revised age models for New Harbour drill cores

Correlation with the GPTS was guided by the biostratigraphies of Winter and Harwood (1997) and by revised FAD and LAD ages for diatom taxa by Cody et al. (2008). Two \(^{40}\)Ar/\(^{39}\)Ar ages (one in DVDP-11 (Prentice et al., 1999) and one in CIROS-2 (Barrett et al., 1992)) and additional \(^{10}\)Be ages in DVDP-11 (Wilson, 1993) were also used to constrain the correlations. Summary stratigraphic correlation of New Harbour drill cores is presented in figure 15.1.

In CIROS-2 the four magnetozones in the upper 90 m of the drill core are correlated one for one with youngest chronozones of the GPTS. The remainder of the age model is constructed from the biostratigraphy and an \(^{40}\)Ar/\(^{39}\)Ar age of 2.91±0.11 Ma at 125 m which resulted in an extrapolated basal age of \(\sim 4.35\) Ma. Two unconformities are recognised in the succession; one at 99 m which spans between \(>1.08\) Ma and \(<2.78\) Ma and one at 139 m which spans between \(>2.82\) and \(<4.23\) Ma.

In DVDP-10 the age model is not well constrained because of widely spaced samples. The C1n - C1r.1r reversal (0.781 Ma) is recognised at 48.24±6.85 m and the C1r.1r - C1r.1n reversal (0.988 Ma) is recognised at 57.18±1.71 m. Two significant unconformities are recognised; one at 133.5 m which spans between \(>1.91\) Ma and \(<3.14\) Ma and one at 155 m which spans between \(>3.50\) Ma and \(<4.20\) Ma. The C3n.1n - C3n.1r reversal (4.300 Ma) is recognised at 165.07±5.61 m and the successions has an extrapolated basal age of \(\sim 4.65\) Ma.

The age model for DVDP-11 is the most well constrained because the sample density is highest in this core. A one to one correlation with the youngest chronozones of GPTS is suggested for the upper four magnetozones above 137.50 m where an unconformity is recognised which spans between \(>1.21\) Ma and \(<1.78\) Ma. The C2n-C2r.1r reversal is recognised at 151.22 ±0.83 m and an unconformity at 201.00 m spans between \(>3.61\) Ma and \(<4.12\) Ma. A thick normal polarity interval between 211.67 m and 248.56 m is correlated with the normal polarity chron C3n.1n and C3n.2n with an unconformity at 239.60 which spans between \(>4.24\) Ma and \(<4.58\) Ma. Magnetozones below 248.56 m are correlated one for one with the GPTS resulting in an extrapolated basal age of \(\sim 5.35\) Ma.

365
Figure 15.1: Stratigraphic correlation of CIROS-2, DVDP-10, and -11. Blue interval indicates Pleistocene sediments. Green indicates Pliocene sediments.
15.2 Environmental magnetic records from New Harbour drill cores

Environmental magnetic studies were conducted of DVDP-10, -11 and CIROS-2 successions. The records were divided into sections based on concentration, mineralogy, and grain size variations.

CIROS-2 was divided into three intervals. The upper 80 m (section I) have high concentrations of PSD magnetite with considerable variation in the data. Paramagnetic behaviour was ubiquitous in thermomagnetic analyses of sediments from section I. Between 80 and 100 m is section II which has lower concentrations of PSD magnetite. Coercivities are slightly higher indicating that some hematite or maghemite may be present. From 100 m to the base of the drill core is section III where severe diagenesis has removed magnetic grains from the sediment.

DVDP-10 was divided into two sections based mostly on a change in concentration at 142 m. The upper portion (section I) has high concentrations of PSD magnetite and a paramagnetic component between 55 m and 40 m and between 85 m and 124 m. In section II concentrations are lower and coercivities are slightly higher. Sediments in section II contain magnetite and variably oxidised magnetite/maghemite. Hysteresis data indicate that PSD magnetite is still the dominant magnetic mineral.

DVDP-11 is divided into five sections with a major change at 189 m from high concentrations to lower concentrations. Magnetite is the dominant magnetic mineral in the upper three sections, however higher curie temperatures, coercivities, and wasp waisted behaviour in hysteresis data indicate that the upper 118 m of DVDP-11 may contain hematite. Below 189 m (section IV and V) concentrations decrease and sediments contain mixtures of magnetite and oxidised magnetite/maghemite. A significant paramagnetic component in magnetic susceptibility occurs above ~166 m. Hysteresis analyses reveal a coarsening of magnetic grain size with depth.

15.3 Magnetic mineralogy of basement and cover rocks from southern Victoria Land

Analyses of basement rocks revealed that the Koettlitz and Skelton Group rocks contain very low concentrations of magnetite and minor maghemite. Granite Harbour Intrusives rocks also have low concentrations of magnetite and/or maghemite. Even
though the concentrations are low in these rocks, they occupy large areas of the hinterland, and therefore by volume may contribute significant quantities of magnetite and maghemite to the sedimentary sink.

Beacon Supergroup sediments have the highest coercivity minerals but have concentrations which can vary by an order of magnitude from formation to formation. The Ferrar Dolerite has high concentrations of magnetite and maghemite. Thermomagnetic analyses revealed that most Ferrar Dolerite specimens contained specific phases of titanomagnetite which are thermally unstable and may be a useful provenance tracer.

McMurdo Volcanics have the highest concentrations of magnetic minerals which are dominated by magnetite with minor quantities of oxidised magnetite or maghemite.

Magnetic analyses of cover rocks revealed that all surficial, lacustrine and seafloor rocks have high concentrations of magnetite and minor quantities of maghemite, oxidised magnetite and/or hematite. Basement lithologies immediately beneath or surrounding the cover sediments did not relate to the concentration or type of magnetic mineral within the overlying sediment. A paramagnetic component was ubiquitous in aeolian, lacustrine and sea-floor samples but rarer in fluvial sediments.

15.4 Modern source to sink evolution of magnetic minerals

Modern erosion of basement rocks in the Transantarctic Mountains occurs by freeze thaw action, thermal expansion and cracking of rocks from rapid sunlight driven heating and cooling cycles and by wind abrasion of rock faces by aeolian grains. Magnetic grain size remains unchanged during erosion and because chemical and biological weathering rates are extremely slow, or not occurring at all, the chemical composition of magnetic minerals does not change. Modern Antarctic glaciers are cold based and therefore not erosive and fluvial erosion is confined to small melt water streams which are active only during the warm summer months.

The strong katabatic winds operating today in the Antarctica are responsible for transporting the majority of the eroded fine grained material to the sedimentary sink. During aeolian transport the magnetic grain size may be reduced through grain on grain impacts and through abrasion of rock faces. It is possible that the paramagnetic component seen in modern cover sediments is driven by the presence of ultra fine grained magnetic or super paramagnetic particles which were produced during aeolian transport. Fluvial transport occurs during the summer months in relatively small melt
water streams in valley floors. The modern glaciers in southern Victoria Land are cold based and do not move significant quantities of sediment. Alteration of magnetic grains is not expected to occur during aeolian transport under modern climate conditions because chemical and biological weathering rates are so slow.

Here it is suggested that the modern cold, dry interglacial climate can be recognised in the sedimentary sink through high concentrations of unaltered magnetic grains of mixed sizes and mineralogies. These grains are derived from throughout the Transantarctic Mountains. Concentrations are high because of winnowing during aeolian transport. Because chemical and biological weathering rates are low even the finest magnetic grains are preserved which may be the driver of the strong paramagnetism behaviour observed in thermomagnetic analyses.

15.5 Late Neogene climate evolution from the New Harbour drill cores

The new magnetostratigraphic age models and environmental magnetic records reveal a progression of climate controlled depositional events in New Harbour which are correlated with the terrestrial and oceanographic records.

15.5.1 Late Miocene - early Pliocene dynamic expanded glaciers

The new magnetostratigraphic age models revealed that the DVDP-11 succession contains the only record of the behaviour of EAIS outlet glaciers during latest Miocene and early Pliocene period (5.35 - 4.9 Ma).

Terrestrial deposits in the McMurdo Dry Valleys indicate that glaciers were warm and wet-based. In DVDP-11 the presence of thin marine muds separated by thicker diamicrites indicates multiple oscillations of a dynamic Taylor Glacier. Unconformities have short durations suggesting the expanded Taylor Glacier was only modestly erosive.

15.5.2 Early-mid Pliocene deglaciation and warmth

Thick marine muds and ice distal facies in the DVDP and CIROS-2 successions indicate that the Taylor and Ferrar glaciers had retreated significantly during the Pliocene warm period. It is likely that the EAIS was much smaller at this time. Off shore stratigraphic records and ice-sheet models indicate extended periods of reduced ice
volume and warmth in Antarctica between 4.1 Ma and 4.6 Ma. Evidence from the AND-1B succession indicates that Ross Sea was warm with minimal sea ice.

### 15.5.3 Late Pliocene - early Pleistocene cooling

The New Harbour successions reveal a two step cooling and ice-sheet growth process during the late Pliocene and early Pleistocene.

Significant grounding of thick EAIS glaciers is recognised in the New Harbour successions by a fragmented record with long duration unconformities after ~3.5 Ma. ~900 kyr later the expansion of the WAIS across the Ross Embayment is recognised in the New Harbour successions at ~2.6 Ma by an ice grounding event and a switch to current winnowed sediments which are rich in McMurdo volcanics debris.

### 15.5.4 Pleistocene to modern transition to hyper-polar conditions

The continuing uplift of the Transantarctic Mountains means that accommodation space in the Taylor Valley is all but exhausted after 1.7 Ma. Matters are worsened by the large glacio-eustatic sea-level fluctuations in response to Northern Hemisphere ice-sheet growth. However, the retreat of the Taylor Glacier after ~2.6 Ma allows for a new glacio-marine and lacustrine sequences to be preserved.

The DVDP successions reveal that the Ross Ice Sheet extended to the DVDP-11 for the last time at ~1.2 Ma and in DVDP-10 some ~400 kyr later at 0.8 Ma. In the adjacent Ferrar Fiord the CIROS-2 drill core also records a reduced deposition from beneath the Ross Ice Sheet after 1.2 Ma. After ~1 Ma sediments are dominantly lacustrine in both the Taylor Valley and Ferrar Fiord indicting that the Ross Ice Sheet was grounded further from the coast resulting in the formation of large, fresh water lakes during glacial maxima.

### 15.6 Sensitivity of environmental magnetic records to climate

Environmental magnetic records developed during this study revealed that magnetic minerals are sensitive climate proxies in Antarctic sediments even under modern, polar conditions.
15.6.1 Soil formation and a dynamic Taylor Glacier during the Late Miocene - early Pliocene

During the Pliocene period, soils probably formed on land and at the edges of the deep Taylor and Ferrar Fiords during warm conditions with significant melt water or precipitation. Oxidation of magnetic minerals in wet soils resulted in the production of significant quantities of maghemite and variably oxidised magnetite. Likewise extensive ground water systems were probably active during interglacial periods which also resulted in oxidation of magnetic minerals.

Gradual expansion of the Taylor Glacier resulted in the progressive removal of soils and alluvium and the deposition of variably oxidised magnetite and maghemite rich diamictite. The gradual thickening of the Taylor Glacier eventually cleaned the Taylor Valley of soils and alluvium thus allowing fresh basement rocks to be eroded and deposited as magnetite rich diamictites.

Three cycles are recognised, of soil formation under warm conditions followed by gradual cooling and glacial expansions, culminating in glacial maxima where fresh, unaltered basement sourced sediments are delivered into the fiord.

15.6.2 Pliocene warmth

The DVDP-11 record contains a 40 m interval which is dominated by mud rich, ice-distal facies and foraminiferal assemblages which indicate water depths of between 600 and 900 m. Sediments from this interval have the weakest magnetisation recognised in this study indicating low input of terrigenous sediment and geographic reconstructions indicate that the ocean probably extended some 30 km inland of the drill sites.

Increasing, cyclic magnetic coercivity and concentration variations leading up to a major unconformity in DVDP-11 may be driven by pulses of melt water under extreme warmth or by the advancing grounding line of the Taylor Glacier.

15.6.3 Late Pliocene - early Pleistocene

The expansion of EAIS glaciers is recognised by a permanent increase in magnetic concentration and switch to magnetite dominated mineralogy in the Taylor Valley successions after 3.5 Ma. Maghemite and oxidised magnetite minerals are less common after this time suggesting that the climate cooled and biological and chemical weathering of remanence carriers was less prevalent.
15.6.4 Paramagnetism and the late Pleistocene transition into the deep freeze

After ~2.6 Ma magnetic concentrations in sediments increase even further in response to the influx of volcanogenic rich sediments sourced from the Ross Sea. The magnetic mineralogy of sediments is dominated by magnetite and after 2.2 Ma a strong paramagnetic component is recognised in the successions.

Paramagnetism in sediments may be driven by ultra fine grained magnetite which is generated during aeolian transport and therefore may indicate the initiation of the strong katabatic winds. The alternative hypothesis is that the paramagnetic minerals were produced throughout the Neogene period but that climatic conditions cooled and dried below a threshold where the paramagnetic minerals survive alteration.

15.6.5 Is there a conflict between the onshore and offshore records?

The New Harbour successions contain sedimentary evidence of multiple grounding events during the mid Pliocene indicating that the Taylor and Ferrar glaciers had expanded down valley. New chronologies developed in this study indicate that the timing of the expansion agrees with geomorphic records from the Wright, Taylor and Ferrar valleys which all indicate expanded EAIS. Thus the chronologies of geomorphic records have at least been partially reconciled with the downstream New Harbour successions.

The problem, therefore, may lie in the interpretation of the geomorphic or drill core records. Sedimentologic and environmental magnetic evidence presented here indicates that during the Pliocene warm period the Taylor and Ferrar fiords received little glacigenic sediment under very different climatic conditions from today; this agrees well with palaeoecological evidence of much warmer than present conditions. Evidence of warmer than present conditions in Taylor and Ferrar fiords contrasts with the formation of cryoturbated desert pavements only few kilometres inland which have been presented as evidence of cold, hyper polar conditions (Hall et al., 1993; Wilch et al., 1993a; Marchant et al., 1996; Hall et al., 1997; Swanger et al., 2010). The geomorphic records have provided valuable chronologies for the behaviour of the southern Victoria Land glaciers. However, it is possible that they are not sensitive indicators of the long term climate state. Therefore the importance of the buried evidence for cold polar climates may be overstated.
References


381


383


386


395


Appendix A

Notes on units and acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full name</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>Antarctic Circumpolar Current</td>
</tr>
<tr>
<td>AF</td>
<td>Alternating Field</td>
</tr>
<tr>
<td>AGM</td>
<td>Alternating Gradient Magnetometer</td>
</tr>
<tr>
<td>AMGRF</td>
<td>Antarctic Marine Geology Research Facility</td>
</tr>
<tr>
<td>AMS</td>
<td>Anisotropy of Magnetic Susceptibility</td>
</tr>
<tr>
<td>ARM</td>
<td>Anhysteretic Remanent Magnetisation</td>
</tr>
<tr>
<td>ANDRILL</td>
<td>ANtarctic DRILLing Project</td>
</tr>
<tr>
<td>CIROS</td>
<td>Cenozoic Investigation in the western Ross Sea</td>
</tr>
<tr>
<td>CRP</td>
<td>Cape Roberts Project</td>
</tr>
<tr>
<td>DRM</td>
<td>Detrital Remanent Magnetisation</td>
</tr>
<tr>
<td>DSDP</td>
<td>Deep Sea Drilling Program</td>
</tr>
<tr>
<td>DVDP</td>
<td>Dry Valleys Drilling Project</td>
</tr>
<tr>
<td>DWBC</td>
<td>Deep Western Boundary Current</td>
</tr>
<tr>
<td>EAIS</td>
<td>East Antarctic Ice Sheet</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy dispersive X-ray spectrometry</td>
</tr>
<tr>
<td>EPMA</td>
<td>Electron Probe Micro Analysis</td>
</tr>
<tr>
<td>GIS</td>
<td>Greenland Ice Sheet</td>
</tr>
<tr>
<td>GPTS</td>
<td>Geomagnetic Polarity Timescale</td>
</tr>
<tr>
<td>MIS</td>
<td>McMurdo Ice Shelf or Marine Isotope Stage</td>
</tr>
<tr>
<td>MS</td>
<td>Magnetic Susceptibility</td>
</tr>
</tbody>
</table>

Continued on next page...
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ms</td>
<td>Saturation Magnetisation</td>
</tr>
<tr>
<td>Mr</td>
<td>Saturation Remanent Magnetisation</td>
</tr>
<tr>
<td>Hc</td>
<td>Coercivity</td>
</tr>
<tr>
<td>Hcr</td>
<td>Coercivity of Remanence</td>
</tr>
<tr>
<td>IBRD</td>
<td>Iceberg Rafted Debris</td>
</tr>
<tr>
<td>INGV</td>
<td>Istituto Nazionale di Geofisica e Vulcanologia</td>
</tr>
<tr>
<td>IRM</td>
<td>Isothermal Remanent Magnetisation</td>
</tr>
<tr>
<td>JOIDES</td>
<td>Joint Oceanographic Institutions for Deep Earth Sampling</td>
</tr>
<tr>
<td>LSU</td>
<td>Lithostratigraphic Unit</td>
</tr>
<tr>
<td>LIMA</td>
<td>Landsat Image Mosaic of Antarctica</td>
</tr>
<tr>
<td>MAD</td>
<td>Maximum Angular Deviation</td>
</tr>
<tr>
<td>MD</td>
<td>Multi Domain</td>
</tr>
<tr>
<td>ODP</td>
<td>Ocean Drilling Program</td>
</tr>
<tr>
<td>OPRF</td>
<td>Otago Paleomagnetic Research Facility</td>
</tr>
<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
</tr>
<tr>
<td>PSD</td>
<td>Pseudo Single Domain</td>
</tr>
<tr>
<td>RIS</td>
<td>Ross Ice Shelf</td>
</tr>
<tr>
<td>SD</td>
<td>Single Domain</td>
</tr>
<tr>
<td>SMS</td>
<td>Southern McMurdo Sound</td>
</tr>
<tr>
<td>SST</td>
<td>Sea Surface Temperature</td>
</tr>
<tr>
<td>SVL</td>
<td>southern Victoria Land</td>
</tr>
<tr>
<td>TAM</td>
<td>Transantarctic Mountains</td>
</tr>
<tr>
<td>VLB</td>
<td>Victoria Land Basin</td>
</tr>
<tr>
<td>VSM</td>
<td>Vibrating Sample Magnetometer</td>
</tr>
<tr>
<td>WDS</td>
<td>Wavelength Dispersive Spectrometry</td>
</tr>
<tr>
<td>WAIS</td>
<td>West Antarctic Ice Sheet</td>
</tr>
<tr>
<td>WARS</td>
<td>West Antarctic Rift System</td>
</tr>
</tbody>
</table>
Appendix B

Data DVD

The included DVD contains all raw NRM, ARM, thermomagnetic, hysteresis,IRM and magnetic susceptibility data from all rocks analysed during this study. Also included are data tables in .xls and .txt format of cleaned and processed data, polarity determinations and age constraints. A PDF version of the thesis can be downloaded from the Otago University Website.