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RESEARCH ARTICLE

Characterisation of magnetic minerals from southern Victoria Land, Antarctica

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Magnetic properties of sedimentary strata recovered in Antarctic drill-cores from southern McMurdo Sound have been used to deduce climatic processes, but interpretation is limited by lack of information regarding the magnetic mineralogy of potential source rocks. Here we assess the magnetic mineralogy, concentration and grain size of magnetic remanence carriers in exposed rocks of southern Victoria Land and evaluate their potential contribution to Holocene–modern sediments. Modern sediments contain high concentrations of Ti-magnetite likely derived from the McMurdo Volcanic Group and minor concentrations of high-coercivity minerals, possibly derived from the Skelton Group and Beacon Supergroup. Significant quantities of superparamagnetic grains are present in all cover sediments, which were probably generated through glacial (grinding) processes or during sediment transport. We suggest that modern, hyper-arid conditions in southern Victoria Land prevent alteration of superparamagnetic grains and that they may be a useful proxy for the modern climate state.

Keywords: Antarctica; environmental magnetism; geology; magnetic mineralogy; sedimentology; southern Victoria Land

Introduction

Southern Victoria Land has been the focus of several onshore and offshore drilling campaigns such as the Dry Valleys Drilling Project (DVDP, McGinnis 1981), Cenozoic Investigation of the Ross Sea (CIROS, Barrett & Hambrey 1992), McMurdo Sound Sediment and Tectonic Studies (MSSTS, Barrett & McKelvey 1981b), Cape Roberts Project (CRP, Florindo et al. 2005), and ANtarctic geological DRILLing Program (ANDRILL, Acton et al. 2009; Naish et al. 2009) projects, which were conducted to unravel the tectonic, volcanic and climate history of this sector of Antarctica throughout the Cenozoic.

Environmental magnetic studies have been conducted on the CIROS-1, MSSTS-1, CRP, and ANDRILL cores and, in turn, the results have been used to determine the sediment source and Cenozoic climate evolution in southern Victoria Land (e.g. Sagnotti et al. 1998; Verosub et al. 2000; Roberts et al. 2013). Environmental magnetic studies use changes of magnetic mineralogy, grain size (i.e. magnetic domain state) and/or concentration in sedimentary successions to understand and reconstruct environmental processes. Processes can include, but are not limited to: the erosion from a source (magnetic minerals can be provenance indicators); transport and weathering processes (e.g. reduction of grain size and/or oxidation of magnetic grains); depositional processes (e.g. sorting and winnowing in aquatic or aeolian environments); and post-depositional processes such as diagenesis, which may result in precipitation of new magnetic particles (see Verosub & Roberts 1995; Maher & Thompson 1999; Evans & Heller 2003 for comprehensive reviews on environmental magnetism). Interpretations of palaeomagnetic and environmental magnetic signals in Antarctic sedimentary successions have been hampered by incomplete knowledge of the magnetic mineralogy of source rocks and the evolution of magnetic mineralogy signal after erosion.

Here we present a map of the distribution of magnetic minerals in lithified ‘basement’ rocks of southern Victoria Land, including: Neoproterozoic–Ordovician granitoids (Granite Harbour Intrusives) and their host metasediments (Skelton Group) that are overlain by Devonian–Triassic sedimentary rocks (Beacon Supergroup) and intruded by Jurassic sills (Ferrar Dolerite); and Miocene–Holocene volcanic rocks (McMurdo Volcanic Group). Our aim is to quantify a key variable (mineralogy) in environmental magnetic studies with the hope that future palaeomagnetic studies of drill-core successions will be able to interpret the environmental magnetic signals more reliably. We focused on three main sampling areas (Figs 1, 2A–C) and supplemented our suite of field samples from the New Zealand rock and mineral reference collection (PETLAB, http://pet.gns.cri.nz).

Methods

Fieldwork in Antarctica was undertaken during the austral summer of 2008/2009. Surficial sedimentary samples were collected from varying depositional environments and a variety

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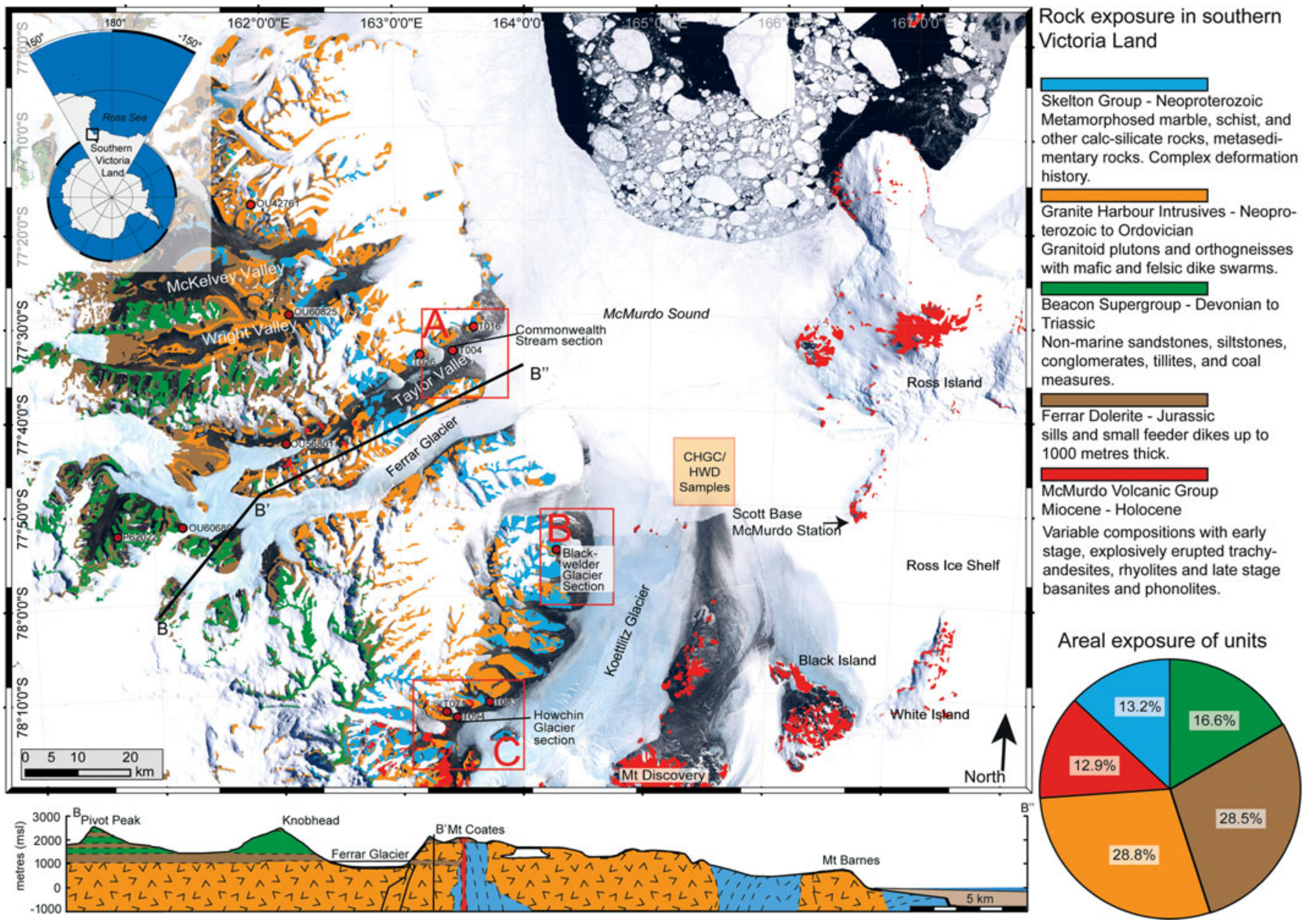

Figure 1 LandSat image mosaic of Antarctica (LIMA), southern Victoria Land, and McMurdo Sound region (inset), geological map and cross-section (note the vertical exaggeration) and pie chart of exposures of southern Victoria Land rocks and samples discussed in the text. For simplicity, the rocks are divided into five groups. Skelton Group: Precambrian (blue); Granite Harbour Intrusives: Neoproterozoic–Ordovician (orange); Beacon Supergroup: Devonian–Triassic sedimentary rocks (green); Ferrar Dolerite: Jurassic (brown); and the McMurdo Volcanic Group: Miocene–Holocene (red). Unshaded areas are covered by ice and/or modern/recent sediments. Red squares highlight the three areas that were the focus of sampling in this study. **A**, Taylor Valley; **B**, Cape Chocolate; **C**, Walcott Bay. Red points are the locations of key samples discussed in the text. Thermomagnetic analyses of southern Victoria Land rocks and surficial sediment where arrows indicate heating and cooling curves.

of lithologies were collected. Chip samples were collected from *in situ* rocks, consolidated sedimentary units and from erratics in till. Samples from the University of Otago (OU samples) and GNS Science (P samples) rock specimen collections were also analysed. Additional sea-ice surface sediment and ocean floor samples were obtained from Victoria University of Wellington.

The geological summary map (Fig. 2) was constructed from the 1:250,000 geological map of southern Victoria Land 'QMAP 22' database (Cox et al. 2012) using ArcGIS software. Proportions of different rock unit exposures were calculated by summing the areas of mapped outcrop polygons. Ice, snow and surficial sediment cover were excluded from the calculation, such that rock units concealed below cover were assumed to be present in the same proportions as where the rocks are exposed (notable exceptions, such as the McMurdo Volcanic Group, are discussed in the text).

Rock magnetic analyses were conducted at the Otago Paleomagnetic Research Facility (OPRF) in Dunedin, New Zealand, and at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy. Magnetic susceptibility (MS) was measured on the cut faces of 730 hand specimens using a handheld Bartington instrument MS2C magnetic susceptibility meter. Four measurements were made per specimen to check for homogeneity of MS. Data were calibrated using a multiplication factor determined from measurements using the more precise AGICO MFK-1CS Kappabridge MS meter.

Thermomagnetic curves were generated from crushed/powdered samples (0.25 cm^3) that were heated to temperatures of 700 °C in air while measuring MS using an AGICO MFK-1CS Kappabridge system. Samples were crushed using a mortar and pestle for soft sediments or a McCrone percussion mortar fitted with non-magnetic polycrystalline

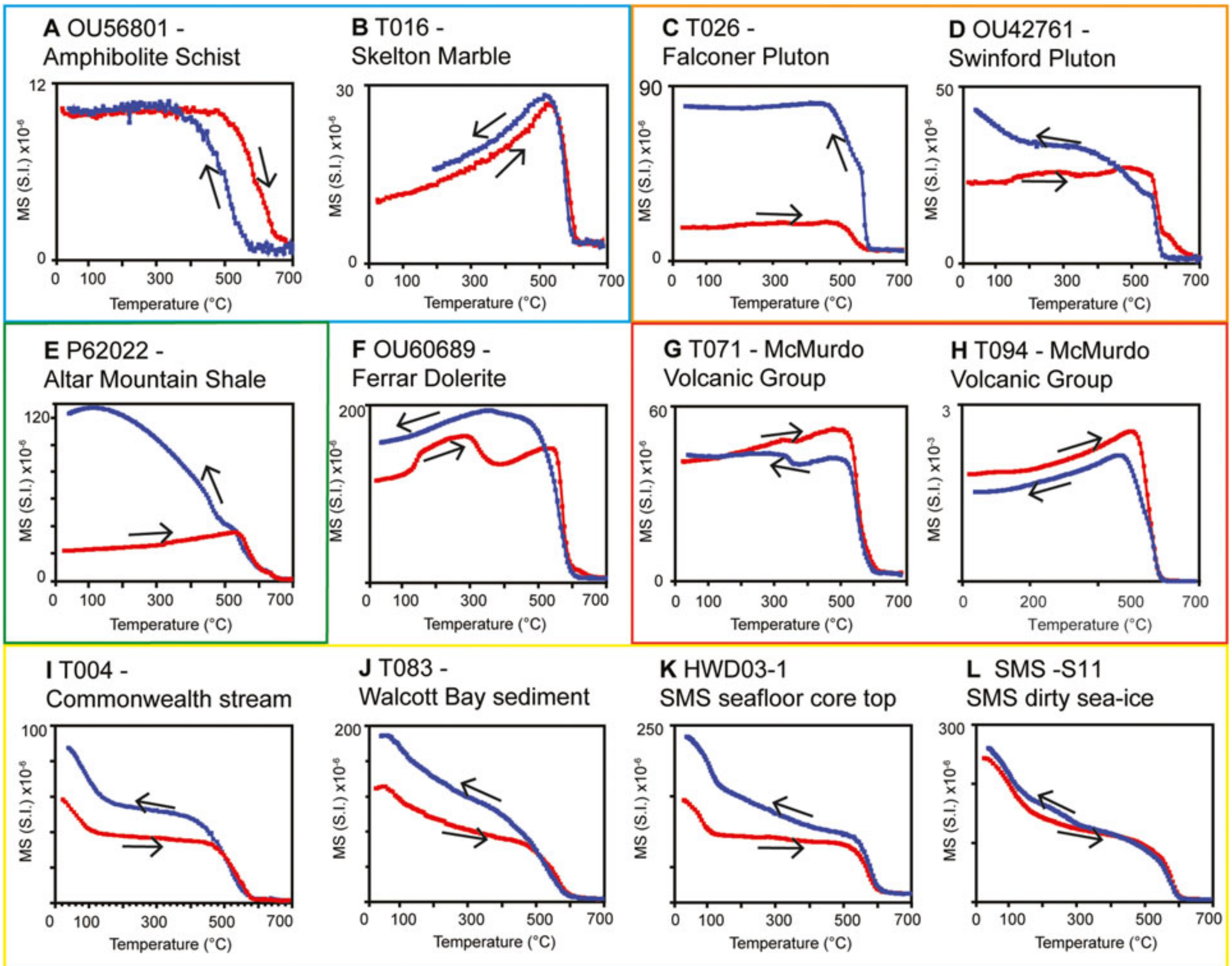

Figure 2 Thermomagnetic analyses of southern Victoria Land rocks and surficial sediment. **A,** OU56801, Koettlitz Amphibolite Schist; **B,** T016, Skelton Marble; **C,** T026, Falconer Pluton; **D,** OU42761, Swinford Pluton; **E,** P62022, Altar Mountain Shale; **F,** OU60689, Ferrar Dolerite; **G,** T071, McMurdo Volcanic Group Walcott Bay; **H,** T094, McMurdo Volcanic Group xenoliths; **I,** T004, Commonwealth Stream; **J,** T083, Walcott Bay cover sediment; **K,** HWD03-1, Southern McMurdo Sound seafloor core top; and **L,** SMS-S11, Southern McMurdo Sound dirty sea ice.

corundum grinding elements for harder samples. Curie/Néel temperatures were determined using the differential method of Tauxe (1998). Magnetic hysteresis, first-order reversal curve (FORC) and isothermal remanent magnetisation (IRM) acquisition analyses were performed primarily to determine coercivity (H_c) and coercivity of remanence spectra (H_{cr}). Measurements of rock fragments and crushed powder samples were made at the INGV, Rome, Italy, using a Princeton Measurements Corporation alternating gradient magnetometer/vibrating sample magnetometer (AGM/VSM, MicroMag 2900). FORC (Pike et al. 1999) measurements were made on 0.15–0.1 g samples and were conducted with a field spacing of 2 mT, H_u between –60 and +60 mT and H_c between 0 and 100 mT. FORC data were processed using the FORCinel software package (Harrison & Feinberg 2008). A smoothing factor (Roberts et al. 2000) of 1–3 was applied to data, the value depending on the magnetic mineral concentration and hence the noise level of the measurements. For a detailed explanation of FORC parameters, see Roberts et al. (2014) who provide an excellent review.

Southern Victoria Land rocks

The geographic distribution of major southern Victoria Land lithologies is illustrated in Fig. 2 after Cox et al. (2012). The oldest rocks are the Neoproterozoic Skelton Group (Fig. 2A, B), which comprises a complex suite of multiply deformed, greenschist to amphibolite facies metasediments. The Granite Harbour Intrusives (Fig. 2C, D) were emplaced episodically between Neoproterozoic and Ordovician times and contributed significantly to deformation of the Skelton Group. Granite Harbour Intrusives comprise granites, granodiorites, diorites and monzodiorites, with lesser mafic gabbro and diorite, gneisses and orthogneisses, and a suite of felsic and mafic dykes. These rocks were overlain unconformably by the Beacon Supergroup (Fig. 2E), which comprises a sequence of Early

Devonian–Triassic siliciclastic sediments (McKelvey et al. 1970) that were deposited on the regionally extensive Kukri Erosion Surface (Aitchison et al. 1988; Isbell 1999). Voluminous Ferrar Dolerite sills intruded during the Early Jurassic (Fig. 2F) and now extend some 3500 km along the Transantarctic Mountains. They locally attain thicknesses of 1000 m, although more commonly they have thicknesses of 400 m (e.g. Heimann et al. 1994; Fleming et al. 1997). As well as sills, the Ferrar Group in southern Victoria Land also includes volcaniclastic rocks (Carapace Sandstone and Mawson Formation) and flood basalts (Kirkpatrick Basalt) that overlie the Beacon Supergroup. The youngest intrusive rocks in southern Victoria Land are the Miocene–Holocene McMurdo Volcanic Group (Fig. 2G–H), which have varying compositions and are exposed as lava flows, cinder cones, dykes and plugs. For a more detailed discussion regarding outcrop locations, type sections and lithologies, the reader is referred to Cox et al. (2012).

Neoproterozoic Skelton Group

Neoproterozoic Skelton Group metasediments in southern Victoria Land mostly crop out in a NW–SE-trending belt, but there are numerous other localities that together occupy c. 13% of the map area (Fig. 2). Lithologies include variably metamorphosed, white-grey limestone (marble) with minor mudstone, siltstone and quartzite, marbles, sandstone conglomerates and volcaniclastic and pelitic schists, calc schists and gneisses (e.g. Blank et al. 1963; Findlay et al. 1984), with much interlayering at metre–decimetre scale. Radiometric dating of detrital zircon grains and conglomerate clasts indicates that Skelton Group rocks were deposited after 650 Ma (e.g. Wysoczanski & Allibone 2004; Cooper et al. 2011). The rocks are mainly well foliated, such that sedimentary structures and stratigraphy have largely been completely destroyed by deformation. Metamorphic grade is upper amphibolite facies (reaching incipient granulite facies) in the north of the map area, but middle amphibolite and greenschist facies in the south (Cook & Craw 2002; Cox et al. 2012).

Granite Harbour Intrusives

Numerous plutons of calc-alkalic, alkalic, and alkali-calcic plutonic rocks intrude Skelton Group metasedimentary rocks in southern Victoria Land and occupy c. 28% of the map area (Fig. 2). Early attempts to differentiate and subdivide these granitoids relied on grouping rocks with the same or similar appearance in hand specimen and thin-section (e.g. ‘pink biotite granite’, ‘grey granite’). Detailed mapping subsequently indicated that following this principle could (and did) result in discrete intrusions with different ages and field relationships being amalgamated into one unit. Instead, recent work has described and subdivided the Granite Harbour Intrusives in terms of plutons and suites (e.g. Smillie 1992; Allibone et al. 1993a,b; Read et al. 2002; Cox et al. 2012). Most intrusives in the map area have now been assigned by Cox et al. (2012) to one of four petrogenetic suites: (1) the predominantly mafic Koettlitz Glacier Alkaline Suite with A-type granite, in the south; (2) the DV1a Suite, dominated by hornblende-biotite granitoid rocks with calc-alkaline, Cordilleran I-type chemistry; (3) the DV1b Suite, dominated by evolved biotite granitoid rocks with adakitic chemistry; and (4) the younger DV2 Suite, dominated by discordant granitoid plutons.

Granite Harbour Intrusives have an estimated age range of 557–477 Ma, but their history of intrusion and deformation is not straightforward (summarised in Cox et al. 2012). Koettlitz Glacier Alkaline Suite rocks are the oldest, but are commonly undeformed (Cooper et al. 1997; Read et al. 2002). By way of comparison, the younger DV1a and DV1b suites include granitoids so deformed as to be termed orthogneisses, as well as unfoliated granitoids (Cox & Allibone 1991; Allibone et al. 1993b; Cox 1993). Late-stage DV2 Suite rocks are generally undeformed, discordant plutons or dykes (Smillie 1992).

The DV1a suite rocks are the most common in southern Victoria Land and are dominated by the regionally extensive Bonney Pluton (Cox 1993), which comprises granodiorite through quartz monzodiorite to monzodiorite, with tectonically foliated or flow-aligned alkali feldspar megacrysts, mafic enclaves and hornblende in a matrix of plagioclase, alkali feldspar, biotite and quartz with accessory clinopyroxene, allanite, zircon, apatite, monazite, titanite and opaque minerals. DV1b plutons have comparatively restricted compositions ranging from granite to granodiorite, in which biotite is the dominant mafic mineral with quartz, alkali feldspar and accessory zircon, allanite, apatite, titanite, garnet or magnetite. Outcrops of extensive DV1a and DV1b orthogneiss bodies occur in the map area, but these rocks are also interlayered within the mapped outcrops of Skelton Group metasediments (Cox & Allibone 1991). The DV2 granitoids are rarer with typical mineral assemblages of quartz, alkali feldspar (commonly pink), plagioclase and biotite with accessory hornblende, zircon, apatite, titanite and opaque minerals (Allibone et al. 1993a,b). Both mafic and felsic dyke swarms of the DV2 suite intrude large areas of the Dry Valleys.

Beacon Supergroup

Impressive outcrops of Beacon Supergroup sedimentary rocks dominate the Transantarctic Mountains and occupy c. 16% of the map area. This Early Devonian–Late Triassic sequence of non-marine quartzose sandstone, conglomerate and siltstone, minor titaniferous ironstone and coal is over 2000 m thick (McKelvey et al. 1970; Barrett et al. 1972). The Beacon rocks are little deformed and dip gently west, overlying Granite Harbour Intrusives and Skelton Group metasediments, separated by the regionally extensive Kukri Erosion surface (Isbell 1999). The lower part (Taylor Group) is also truncated by the regionally extensive, glacially eroded Maya Erosion Surface, which represents a period of non-deposition and/or erosion lasting for c. 100 Millions of years (Barrett & McKelvey 1981b). Along and near the crest of the Transantarctic Mountains, to the west of the map area, Beacon rocks are locally overlain by extrusive equivalents of the Ferrar sills, namely the Kirkpatrick Basalt and volcanogenic sediments of the Mawson Formation (Elliot & Hanson 2001; McClintock & White 2006; Ross et al. 2008).

Ferrar Dolerite

Spectacular Ferrar Dolerite sills are a prominent feature of the central Transantarctic Mountain landscape, occupying c. 28% of the map area. The sills generally consist of sub-ophitic to intergranular augite-pigeonite-plagioclase dolerite with accessory iron oxides, and minor quartz, orthoclase, apatite and rare biotite. They range from fine-grained, with chilled margins against adjacent rocks, to coarse-grained with doleritic to sub-ophitic texture. Minor granophyre and pegmatitic facies occur locally. Some sills contain cumulate textures with orthopyroxenite-rich layers and/or rhythmic layering, whereas others are relatively uniform quartz tholeiite (see Bédard et al. 2007). The sills have been estimated to comprise some 7000 km^3 of magmatic material and extend laterally for tens of kilometres and up to 1000 m in thickness (Fleming et al. 1997; Elliot et al. 1999). They intrude the Granite Harbour Intrusive and Skelton Group rocks, the Kukri Erosion Surface and the Beacon Supergroup. Several sills change laterally to upwards-ramping dykes and some have rafted large tracts of host rocks, moving them for considerable distances. Intrusion ages suggest relatively rapid emplacement at c. 184–179 Ma (Encarnacion et al. 1996; Fleming et al. 1997), and are believed to be associated with the early stages of Gondwana break-up (Heimann et al. 1994).

McMurdo Volcanic Group

McMurdo Volcanic Group rocks crop out as small cinder cones and flows throughout the Transantarctic Mountains in southern Victoria Land and as large volcanic centres in the western Ross Sea. McMurdo Volcanic Group rocks occupy c. 12% of the map area; however, this estimate may be significantly underestimated with respect to other rock units because the majority of Ross and White islands are covered with snow and ice, and Mount Discovery and Black Island are mantled by debris (Fig. 2). Widespread ash falls associated with volcanic activity throughout the late Neogene have aided in the dating of sedimentary successions and geomorphic features (e.g. Barrett et al. 1992; Marchant et al. 1996). The oldest rocks of the McMurdo Volcanic Group date to the Miocene in southern Victoria Land (e.g. Tonarini et al. 1997; Pompilio et al. 2001) with generally younger rocks to the east of the Transantarctic Mountains (Cooper et al. 2007; Martin et al. 2010). Most of the McMurdo Volcanic Group has strongly alkaline compositions, but a distinctive mildly alkaline early phase has been recognised (Martin et al. 2013). Trachytic peralkaline rocks appear to have dominated volcanism from c. 24 to c. 11 Ma. Greater volumes of rock have been preserved in the last 11 Millions of years and these are almost exclusively basanitic to phonolitic (Kyle 1990; Martin et al. 2013).

Southern Victoria Land sediments

Cover sediments crop out as scree, colluvium, recent glacial deposits at the edges of glaciers, mobile ice-cored till and as fluvial, lacustrine and aeolian sediments. Ross Sea Drift sediments (Stuiver et al. 1981) were also sampled but we do not treat these as unique deposits because they are so widespread. Armoured desert pavements are found on many southern Victoria Land valley floors and hill tops and can have polygonal patterned ground where polygons are covered with boulders, cobbles and pebbles and troughs are filled with sand. Aeolian deposits in the form of dune fields, surface ripples and sand sheets are found throughout the ice-free valleys and on sea ice and comprise loose, well sorted, fine- to medium-grained sand, silt and gravel. Summer melt results in surface and subterranean streams and deposition of sand and gravel.

Lacustrine and glacigenic sediments, such as those associated with glacial palaeolake Washburn in Taylor Valley (Hall & Denton 2000), were encountered in all three sampling localities (see Fig. 2 for locations) and comprise diamicts, bedded fine to coarse sands, and laminated and organic-rich muds. The three thickest and most significant successions were exposed in the walls of steep-sided stream gullies in Taylor Valley (Commonwealth Stream section), Cape Chocolate (Blackwelder Glacier section), and at Walcott Bay (Howchin Glacier section). These successions were sampled to determine magnetic mineralogy and magnetic mineral concentrations. Age constraints are available only for the Taylor Valley sections; we are therefore unable to correlate confidently between the successions.

Modern marine sediments

Modern marine sediments comprise sand, silt and clay (Atkins & Dunbar 2009) and were recovered on and beneath sea ice in McMurdo Sound and from beneath the Ross Ice Shelf (Fig. 2, CHGC/HWD samples).

Results: magnetic properties of southern Victoria Land rocks and sediments

The concentration, type and grain size of magnetic minerals of southern Victoria Land rocks and sediments are described in the following sections and summarised in Table 1. Thermomagnetic analyses of representative samples, which allow easy differentiation of magnetic mineral-diagnostic Curie/Néel temperatures, are presented in Fig. 3. Hysteresis and IRM analyses of representative samples are presented in Fig. 4 and FORC analyses are presented in Fig. 5. Magnetic mineral concentration estimates are based on MS and M_{rs}, saturation isothermal remanence. We make significant use of bi-plots (H_{cr} versus M_{rs}, Curie temperature versus M_{rs}, Day plots (Day et al. 1977), Fig. 6), which allow comparison of magnetic properties. Bi-plots are particularly useful in environmental magnetic studies because they allow comparison of datasets collected using different instruments (e.g. high-temperature Curie temperatures from the AGICO MFK-1CS Kappabridge system with M_{rs} data

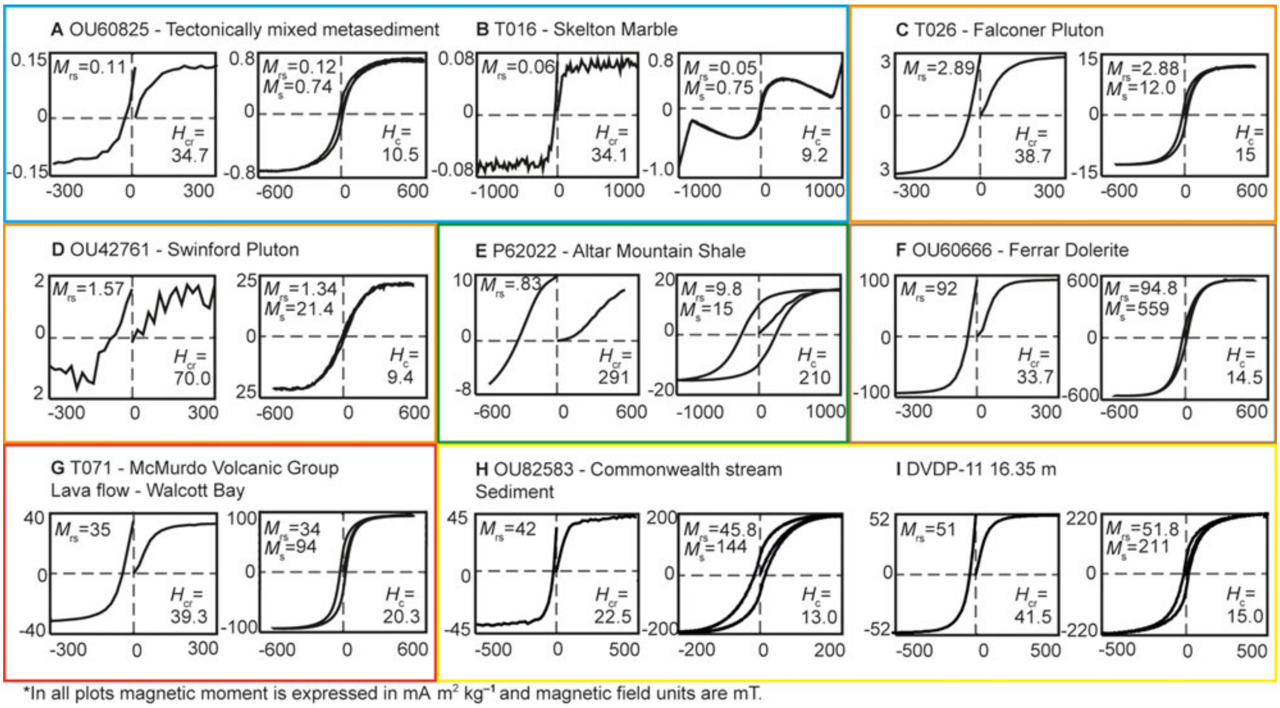

Figure 3 Hysteresis and IRM acquisition and backfield demagnetisation analyses of southern Victoria Land rocks and surficial sediment. **A,** OU60825—tectonically mixed metasediment; **B**, T016—Skelton Marble (raw data); **C**, T026—Falconer Pluton; **D**, OU42761—Swinford Pluton; **E**, P62022—Altar Mountain Shale; **F**, OU60666—Ferrar Dolerite; **G**, T071—McMurdo Volcanic Group, Walcott Bay; **H**, T071—Commonwealth Stream; and **I**, DVDP-11 16.25 m—Taylor Valley. All H_c and H_{cr} values are in mT and M_{rs} and M_s values are in mAm^2/kg^{-1}.

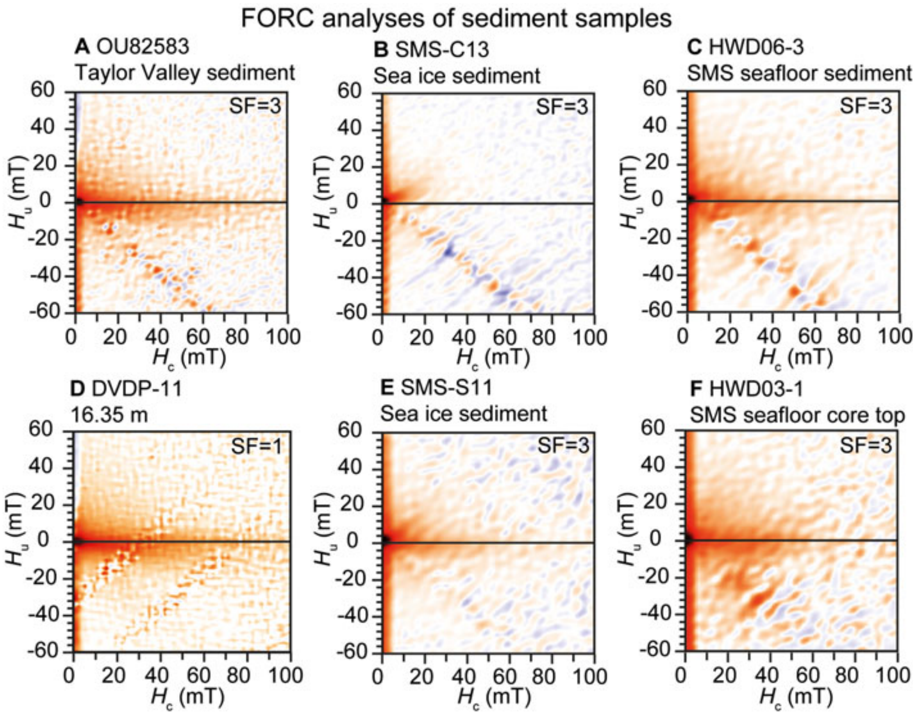

Figure 4 FORC analyses of surface sediment specimens with ubiquitous SP grains in all samples. **A,** OU82583 Taylor Valley Sediment; **B,** SMS-C13 sea-ice sediment; **C,** HWD06-3 SMS seafloor sediment; **D,** DVDP-11 sediment 16.35 m; **E,** SMS-S11 sea-ice sediment; and **F,** HWD03-1 SMS seafloor core top. Analyses were conducted with a field spacing of 2 mT, H_u between –60 and +60 mT and H_c between 0 and 100 mT. Data were processed using the FORCinel software package (Harrison & Feinberg 2008). The smoothing factor (Roberts et al. 2000) is indicated on each plot (SF).

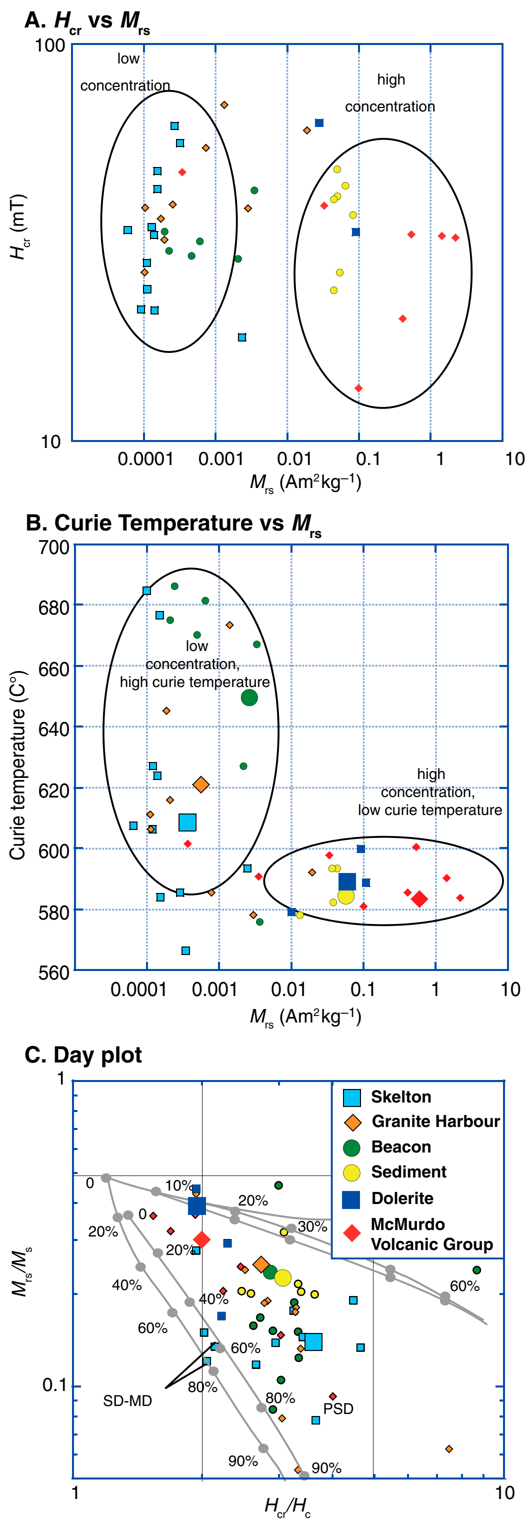

Figure 5 Bi-plots of data presented in Figs 3, 4. **A**, H_{cr} versus M_{rs} plot has two broad data distributions based on M_{rs} with high magnetic mineral concentrations found in sediments, Ferrar Dolerite and McMurdo Volcanic Group rocks and low magnetic mineral concentrations in Beacon Supergroup sediments, Skelton Group rocks and Granite Harbour Intrusives; **B,** Curie temperature versus M_{rs} distributions also separated into the same groups, where cover sediments, Ferrar Dolerite and McMurdo Volcanic Group rocks have magnetite-dominated Curie temperatures (c. 580 °C) and Beacon Supergroup, Skelton Group rocks and Granite Harbour Intrusives have low magnetic mineral concentrations and variable Curie/Néel temperatures typically ranging up to 680 °C (hematite); **C,** The Day plot (Day et al. 1977; Dunlop 2002a,b) indicates that Ferrar Dolerite and McMurdo Volcanic Group rocks on average have similar M_{rs}/M_s and H_{cr}/H_c ratios and Beacon Supergroup sediment, while Skelton Group and Granite Harbour Intrusive rocks have lower M_{rs}/M_s ratios and higher H_{cr}/H_c ratios. Cover sediments appear to plot with the range for Beacon Supergroup sediments and Granite Harbour Intrusive rocks, even though plots A and B indicate that they are more similar to Ferrar Dolerite and McMurdo Volcanic Group rocks. This is likely driven by the wasp-waisted nature of the hysteresis loops which can lead to depressed H_c values (see Jackson 1990; Roberts et al. 1995; Tauxe et al. 1996).

measured on the Princeton Measurements Corporation alternating gradient magnetometer/vibrating sample magnetometer). Magnetic mineralogy is determined from H_{cr} versus M_{rs} and Curie temperature versus M_{rs}, which are used to determine the magnetic remanence, coervicity and Curie/Néel temperatures of magnetic grains within samples. Magnetic grain size estimates were made using the Day plot and FORC analyses (Fig. 5).

Skelton Group

Skelton Group rocks have weak median susceptibility of 18 × 10^{-5} SI and M_{rs} 3.76 × 10^{-4} Am^2kg^{-1}. Thermomagnetic analyses (Fig. 3A, B) reveal susceptibility loss between 550 °C and 650 °C. Hysteresis and IRM analysis results are noisy and provide poorly constrained coercivity estimates. The marble (T016, Fig. 4B) did not saturate magnetically even at 1 T and a diamagnetic component (negative slope on raw data) is dominant. Overall, Skelton Group rocks have mean M_s [saturation magnetisation] of 1.45 × 10^{-2} Am^2kg^{-1}, M_{rs} of 3.76 × 10^{-4} Am^2kg^{-1} and H_c of 11.8 mT. IRM analyses resulted in a mean H_{cr} of 34.9 mT.

Magnetic mineralogy of Skelton Group

The low average magnetic susceptibility M_s and M_{rs} indicate low concentrations of magnetic minerals in the Skelton Group. Thermomagnetic analyses reveal variable Curie temperatures of 580 °C or greater indicating magnetite, maghemite or hematite mineralogy. Samples with the weakest susceptibilities (OU56801, Fig. 3A) have Néel temperatures of c. 680 °C, which indicates that hematite is the dominating mineral; thermochemical reduction of hematite to magnetite during heating is common. Overall, no single magnetic phase is characteristic of Skelton Group rocks.

Granite Harbour Intrusives

Granite Harbour Intrusive rocks have a median susceptibility of 16 × 10^{-5} SI (258 measurements from cut faces of bulk

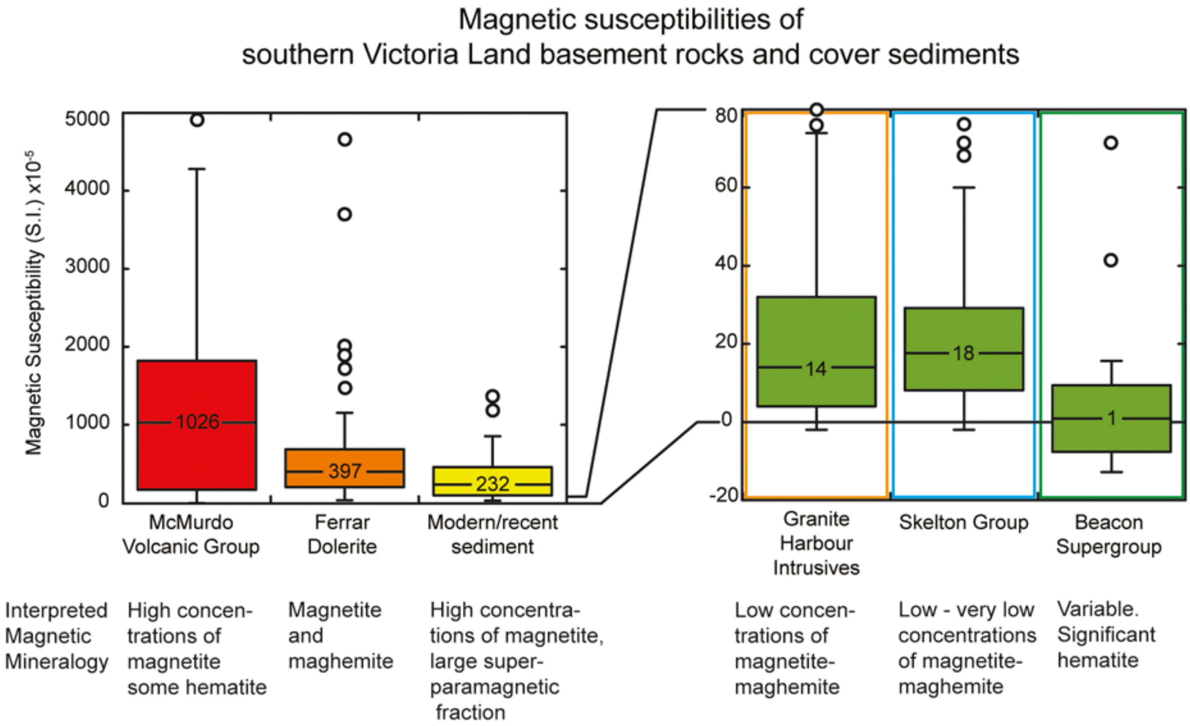

Figure 6 Box plot of southern Victoria Land MS data. Each box encloses 50% of the data with the median value indicated on the centre line. The top and bottom of the boxes mark the ±25% limits (upper and lower quartiles) of the susceptibility data in each group. Lines extending from the boxes mark the minimum and maximum susceptibilities. Outliers (circles) are defined as points that are ±1.5 × Interquartile Distance (IQD) from the upper (lower) quartile.

samples). Thermomagnetic analyses reveal a dominant susceptibility loss at c. 570 °C (Falconer Pluton, T026, Fig. 3C), however, some samples have higher Curie temperatures and non-reversible curves that are indicative of thermochemical alteration (e.g. Fig. 3D, Swinford Pluton for which a gradual decay to 0 SI is observed between 580 °C and c. 680 °C). Hysteresis and IRM analyses were often difficult to conduct because the coarse-grained nature of the rock resulted in noisy hysteresis loops with low coercivities. Hysteresis and backfield analyses resulted in a mean M_s of 3.16×10^{-3} Am^{2}kg^{-1}, M_{rs} of 5.54×10^{-4} Am^{2}kg^{-1} and H_c of c. 26.3 mT, and IRM analyses resulted in a mean H_{cr} of 41.2 mT.

Magnetic mineralogy of Granite Harbour Intrusives

Overall, plutonic rocks contain low concentrations of magnetite and maghemite as indicated by low magnetic susceptibilities, magnetisations, coercivities and Curie temperatures of 570 °C. In some samples, the rapid loss of susceptibility at 570 °C followed by a gradual decay at higher temperatures indicates higher Curie/Néel temperatures and therefore a mixed magnetite-maghemite-hematite mineralogy.

Beacon Supergroup

Beacon Supergroup sedimentary rocks have low median MS of 1×10^{-5} SI (11 measurements from cut faces of bulk samples). Several negative susceptibilities were measured in quartz-rich units where diamagnetic quartz dominates the susceptibility signal. Hystersis and IRM analyses of Beacon Supergroup rocks revealed variable behaviour but with dominant high coercivities. Hysteresis analyses of Altar Mountain Shale (Fig. 4E) reveal the presence of high coercivity minerals with a mean M_s of 6.69×10^{-3} Am^{2}kg^{-1}, M_{rs} of 1.47×10^{-3} Am^{2}kg^{-1} and H_c of c. 24.1 mT. IRM analyses indicate that saturation was not reached at 1 T with a mean M_{rs} of 2.10×10^{-3} Am^{2}kg^{-1} and H_{cr} of 99.9 mT. Thermomagnetic analyses indicate Curie/Néel temperatures of 580–680 °C with most samples undergoing thermochemical alteration, resulting in either higher or lower susceptibility after heating.

Magnetic mineralogy of Beacon Supergroup

Thermomagnetic analyses reveal Curie/Néel temperatures above the range expected for magnetite, indicating the presence of hematite and maghemite. Sandstone formations (such as the Lashly Sandstone) generally have Curie temperatures indicative of magnetite (580 °C). Conversely, the Altar Mountain shale is dominated by hematite or maghemite, as indicated by Curie/Néel temperatures above 580 °C and the high coercivities as indicated by hysteresis/IRM analyses. Despite a high degree of variability, the Beacon Supergroup has the highest concentrations of hematite and/or maghemite of southern Victoria Land rocks.

Table 1 Summary of magnetic properties of rock groups from southern Victoria Land, Antarctica.

Rock unit	MS SI ($\times10^{-5}$)	M_{rs} (Am^2kg^{-1})	H_{cr} (mT)	Dominant magnetic mineral
Skelton Group	18	3.76×10^{-5}	34.9	Magnetite/maghemite
Beacon Supergroup	1	1.47×10^{-3}	99.9	Hematite/variable
Granite Harbour Intrusives	16	5.54×10^{-4}	41.2	Magnetite/maghemite
Ferrar Dolerite	397	6.11×10^{-2}	72.8	Magnetite/maghemite
McMurdo Volcanic Group	1026	6.40×10^{-1}	31.4	Magnetite minor maghemite
Cover sediments	232	6.40×10^{-2}	35.0	Magnetite/superparamagnetism

Ferrar Dolerite

Ferrar Dolerite samples have high magnetic mineral concentrations with a mean M_{rs} of 6.11×10^{-2} Am^2kg^{-1} and with high median susceptibility of 397×10^{-5} SI (60 measurements from cut faces of bulk samples). Thermomagnetic analyses reveal a dominant Curie temperature of c. 580 °C (OU60689, Fig. 3F) with many specimens displaying a sharp susceptibility increase at c. 150 °C followed by a plateau and an equally sharp decrease between 300 °C and 350 °C. This behaviour was absent during reheating, which indicates that thermochemical alteration has occurred during heating. Hysteresis analyses indicate variable coercivities and saturation magnetisations. However, all loops close and are parallel-sided (OU60666, Fig. 4F). Analyses resulted in a mean M_s of 2.26×10^{-1} Am^2kg^{-1}, M_{rs} of 4.45×10^{-2} Am^2kg^{-1}, H_c of 34.9 mT and H_{cr} of 72.8 mT.

Magnetic mineralogy of Ferrar Dolerite

All analyses indicate that the Ferrar Dolerite has high concentrations of ferrimagnetic minerals with strong magnetisations and high susceptibilities. Thermomagnetic analyses reveal a dominant Curie temperature of 580 °C, consistent with magnetite as the dominant magnetic mineral, and a low-temperature component that occurs throughout the Ferrar Dolerite. The low-temperature component may indicate the presence of a thin layer of surficial maghemite which resulted from oxidation. The absence of the peak in cooling curves indicates that the mineral has undergone thermochemical alteration.

McMurdo Volcanic Group

McMurdo Volcanic Group rocks have strong magnetisations (mean M_{rs} of 5.17×10^{-1} Am^2kg^{-1}) and high median susceptibility of 1026×10^{-5} SI (133 samples). Thermomagnetic analyses of McMurdo Volcanic Group rocks reveal a dominant 580 °C Curie temperature (Fig. 3G, H); rare specimens have susceptibilities that persist above 580 °C. Hysteresis and IRM analyses reveal variable behaviour with most specimens (Fig. 4G) having relatively low coercivities (H_c c. 20 mT and H_{cr} c. 39 mT). Hysteresis loops are closed with parallel sides with a mean M_s of 2.22 Am^2kg^{-1}, M_{rs} of 6.40×10^{-1} Am^2kg^{-1}, H_c of 18.3 mT and H_{cr} of 31.4 mT.

Magnetic mineralogy of McMurdo Volcanic Group rocks

Susceptibility measurements and strong magnetisations indicate that the McMurdo Volcanic Group rocks have the highest concentrations of magnetic minerals in rocks from southern Victoria Land (median MS of 1026×10^{-5} SI). Thermomagnetic analyses reveal Curie temperatures of 580 °C, which is consistent with the dominant presence of magnetite. Many samples also contain a minor high-temperature susceptibility component, which likely indicates the presence of maghemite. However, most hysteresis analyses are consistent with the dominant presence of magnetite.

Magnetic properties of southern Victoria Land cover sediments

All cover sediments (unconsolidated aeolian, fluvial, deltaic, lacustrine and marine sediments) have high susceptibilities with median MS of 232×10^{-5} SI. Thermomagnetic analyses reveal a remarkably uniform behaviour for sediments from southern Victoria Land with 70% of samples undergoing a marked decrease in susceptibility between 20 °C and c. 150 °C followed by a rapid decrease between 500 °C and 580 °C (Fig. 3I–L). Thermomagnetic curves were not reversible in all cases, but the morphology of cooling curves mimicked the heating curves. Hysteresis analyses (Fig. 4H, I) indicate low coercivities (H_c) of 13–15 mT, M_s of 144–431 mAm^2kg^{-1} and saturation remanent magnetisations (M_{rs}) of 42–86 mAm^2kg^{-1}, with mild ‘wasp-waisted’ behaviour in sample OU82583. FORC analyses (Fig. 6) indicate a peak response centred at 0–5 mT with weak response up to c. 40 mT in all analyses.

Magnetic mineralogy of southern Victoria Land cover sediments

High MS and high M_{rs} values indicate high concentrations of magnetic minerals. Thermomagnetic analyses indicate Curie temperatures that are consistent with magnetite or titanomagnetite. Most thermomagnetic analyses also reveal a prominent low-temperature component. We did not identify similar behaviour in analyses of southern Victoria Land rocks, which provides evidence concerning its origin. Brachfeld et al. (2013) identified similar thermomagnetic behaviour in McMurdo Volcanic Group rocks from Ross Island and suggested that the low-temperature component results from the presence of titanium-rich titanomagnetite or ilmenite grains.

FORC analyses revealed a ubiquitous peak response centred at between 0 and c. 5 mT, which indicates the presence of significant quantities of superparamagnetic (SP) magnetite (Pike et al. 2001). However, a weak response up to 40 mT is probably indicative of SD grains (Roberts et al. 2000). Wasp-waisted hysteresis behaviour (Fig. 4H) is consistent with FORC analyses and also indicates the presence of mixed single-domain (SD) and SP magnetite grains (Jackson et al. 1990; Jackson 1990; Roberts et al. 1995; Tauxe et al. 1996). Overall, our analyses indicate that the magnetic characteristics of cover, lacustrine and offshore sediments are virtually indistinguishable.

Magnetic minerals of southern Victoria Land

Magnetic analyses of southern Victoria Land rocks and cover sediments allow us to identify their magnetic mineralogy and to develop a picture of how erosion of these rocks contributes magnetic minerals to the sedimentary system in southern Victoria Land.

Magnetic mineral-producing potential of Transantarctic Mountain rocks

Even though southern Victoria Land contains a wide range of lithologies, two broad groups are apparent based on magnetic mineralogy and magnetic mineral concentration variations. High coercivity phases are most common in Skelton Group and Beacon Supergroup rocks, which together comprise c. 30% of the outcrop exposure in southern Victoria Land. While concentrations of these minerals are low in most of these rocks, these units erode relatively easily so they may be a significant contributor of high-coercivity minerals to the sedimentary system. However, the relative proportion and contribution from source rocks of high-coercivity phases in sediments may be underestimated because the spontaneous magnetisation of magnetite is c. 200 times greater than hematite. Ferrar Dolerite has high concentrations of magnetite and minor concentrations of maghemite, and comprises almost a third of outcrop exposure in southern Victoria Land. However, because Ferrar Dolerite is also extremely competent and forms high cliffs, it may not be a major contributor of magnetite/maghemite to the sedimentary system. Granite Harbour Intrusives occupy large areas of the hinterland (c. 29%) and, in most cases, are dominated by magnetite and minor concentrations of maghemite. McMurdo Volcanic Group rocks contain high concentrations of magnetite with minor quantities of oxidised magnetite or maghemite. Overall, the McMurdo Volcanic Group is probably a significant contributor of magnetite to the cover sediments.

Figure 6A (H_{cr} versus M_{rs}) indicates that there are two groups of samples based largely on magnetic mineral concentration. Cover sediments, Ferrar Dolerite and McMurdo Volcanic Group rocks have high magnetic mineral concentrations, while Beacon Supergroup, Skelton Group and Granite Harbour Intrusive rocks have low magnetic mineral concentrations. Figure 6B (Curie temperature versus M_{rs}) indicates that these same magnetic mineral groups can be separated by Curie/Néel temperatures where cover sediments, Ferrar Dolerite, and McMurdo Volcanic Group rocks have magnetite-dominated Curie temperatures (c. 580 °C), whereas Beacon Supergroup, Skelton Group and Granite Harbour Intrusive rocks have variable Curie/Néel temperatures that range between 580 °C (magnetite) and 680 °C (hematite). The Day plot (Fig. 6), which is typically used to determine grain-size distributions in titanomagnetite-magnetite-dominated systems (Day et al. 1977), indicates that Ferrar Dolerite and McMurdo Volcanic Group rocks, on average, have similar behaviour with M_{rs}/M_s and H_{cr}/H_c ratios approaching 0.5 whereas Beacon Supergroup, Skelton Group and Granite Harbour Intrusive rocks have lower M_{rs}/M_s ratios and higher H_{cr}/H_c ratios.

MS measurements allow additional grouping on a finer scale (Fig. 7). Group one (Fig. 7, green) contains lithologies with low magnetic mineral concentrations (median susceptibility of 1–18 × 10^{-5} SI) that include Beacon Supergroup, Skelton Group and Granite Harbour Intrusive rocks. Group two (Fig. 7, yellow) contains sediments which have moderate to high susceptibilities (median of 232 × 10^{-5} SI, ranging up to 1500 × 10^{-5} SI). Group three (Fig. 7, orange) contains Ferrar Dolerite rocks with high susceptibilities (median of 397 × 10^{-5} SI) and group four (Fig. 7, red) contains McMurdo Volcanic Group rocks with very high susceptibilities (median of 1026 × 10^{-5} SI).

Magnetic characteristics of southern Victoria Land cover sediments

Samples of cover sediments from throughout southern Victoria Land have similar magnetic mineral concentrations and mineralogy, regardless of depositional environment. Thermomagnetic analyses reveal the presence of magnetite and, in rare cases, maghemite or hematite. In the rare samples where maghemite or hematite is present, the concentrations were so low that it was difficult to accurately determine the Curie/Néel temperatures. Numerous samples (73%) have a low-temperature component between 20 °C and c. 150 °C, which we attribute to the presence of volcanically derived titanium-rich titanomagnetite or ilmenite as suggested by Brachfeld et al. (2013). Hysteresis, FORC and IRM analyses confirm the presence of magnetite and indicate a mixture of SD and SP grain sizes. FORC analyses indicate significant contributions of SP grains in cover sediments regardless of depositional setting. Our analyses did not reveal regionally systematic magnetic concentration or mineral variations. The magnetic mineralogy, and furthermore their concentrations in surface sediments, is independent of source lithologies as shown by the geographic distribution of MS in Fig. 7. The magnetite-rich McMurdo Volcanic group rocks are confined mostly to the east of the Transantarctic Mountains and large areas of southern Victoria Land are dominated by Beacon Supergroup rocks, which have low magnetic mineral concentrations (Fig. 7, green). Rocks

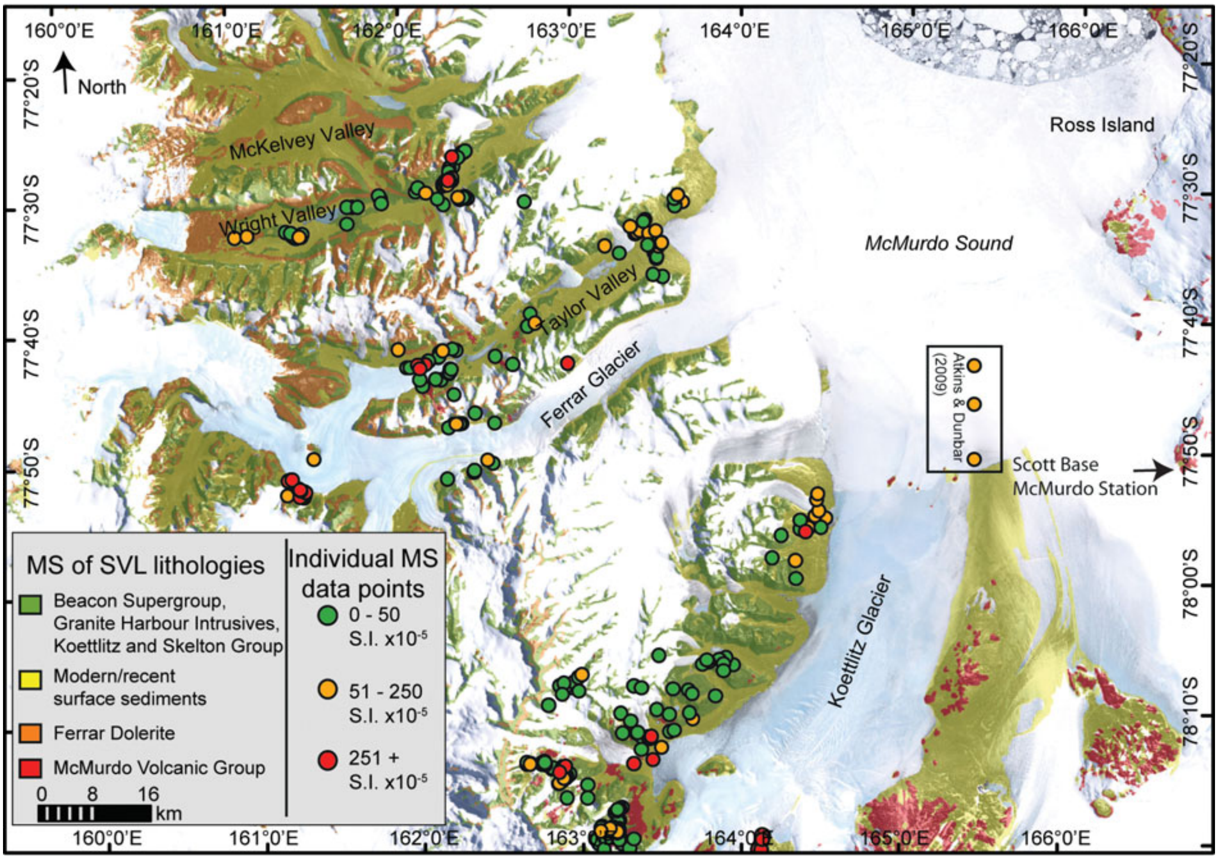

Figure 7 Geographic distribution of MS values for sampled cover sediments and basement rock groups in southern Victoria Land. Individual data are divided into three groups based on MS. Green points have low MS (0–20 SI × 10^{-5}), Orange points have moderate MS (21–250 SI × 10^{-5}), and red points have high MS (≥251 SI × 10^{-5}). Rock units are grouped according to MS and also to indicate areas with different concentrations of magnetic minerals. Green outcrops comprise Skelton Group metamorphic rocks, Granite Harbour Intrusives and Beacon Supergroup sediments, which have the lowest magnetic mineral concentrations and the largest geographic distribution. Yellow areas (uncoloured in Fig. 1) represent southern Victoria Land cover sediments, which are derived from all rocks and have moderate magnetic mineral concentrations. Orange areas comprise outcrops of Ferrar Dolerite which have high MS, and red outcrops are McMurdo Volcanic Group rocks which have very high MS.

with low concentrations of ferrimagnetic minerals (Fig. 7, green) are surrounded by modern and recent surface cover sediments, which have moderate ferrimagnetic mineral concentrations (Fig. 7, yellow).

Sources of magnetite in southern Victoria Land cover sediments

We suggest that the high concentrations and dominant proportion of ferrimagnetic minerals in modern and holocene sediments can be attributed to high concentrations of detritus derived from McMurdo Volcanic Group rocks, as indicated by the large proportion of sediment samples with volcanically derived oxidised magnetite or maghemite. We do not think the Ferrar Dolerite contributes significant quantities of magnetic minerals to the modern sediments because it is resistant to erosion. A dominance of magnetite rather than higher coercivity minerals (maghemite/hematite) also indicates that the Beacon Supergroup or Skelton Group, which contain higher coercivity phases, are not major contributors of magnetic minerals to cover sediments in Southern Victoria Land.

The glacially deposited, volcanic-rich Ross Sea Drift sediments are known to blanket the hills in the map area and form a characteristically dark sediment cover on the mountain slopes at the edge of McMurdo Sound (Stuiver et al. 1981; Denton & Marchant 2000). Southern Victoria Land sediments analysed during this study included the Ross Sea Drift sediments and other sediments (e.g. samples collected at high elevations or from the sea floor). We see no distinction between the Ross Sea Drift sediments and other deposits, which indicates further dispersal and mixing of sediments since deposition of the Ross Sea Drift or that the sediments have a common source.

Sources of superparamagnetism in southern Victoria Land sediments

FORC and hysteresis analyses of southern Victoria Land sediments reveal the presence of significant proportions of SP magnetite regardless of geographic origin or depositional environment (Fig. 5). Superparamagnetism in rocks is caused by the presence of ultrafine ferrimagnetic particles (typically <30 nm for most grain shapes; Dunlop 1973; Muxworthy & Williams 2009). Previous studies of glacigenic sediments (e.g. Rosenbaum & Reynolds 2004) have identified that fine magnetic grains may be generated through glacial processes (e.g. grinding of rocks by clasts entrained in basal glacier ice). Aeolian transport of magnetic grains may be an alternative mechanism for rounding, sorting and reducing the grain size of particles and may also be responsible for generating ultrafine magnetic particles through grain-on-grain impacts during saltation (e.g. Krinslye & Donahue 1968). It is unlikely that SP grains are sourced from palaeosols (e.g. Fang et al. 1999) because modern or recent hyper-polar conditions prevent their formation. We suggest that glaciers and/or wind transport have generated the SP grains found in southern Victoria Land sediments. SP behaviour in sediments in moist or oxidising environments is relatively rare because magnetite is highly reactive; the large surface area to volume ratios of ultra-fine grains leads to rapid oxidation under warm and wet conditions (e.g. Canfield et al. 1992). We suggest that SP magnetite in Antarctic sediments likely survives complete oxidation because of the hyper-arid climate conditions in Antarctica and is therefore recognisably ubiquitous in modern sediments regardless of depositional environment.

Conclusions

We have presented a study of the magnetic mineralogy of rocks and cover sediments from southern Victoria Land, Antarctica, which indicates that the majority of exposed rocks in southern Victoria Land (Skelton Group, Granite Harbour Intrusives and Beacon Supergroup) contain low concentrations of ferrimagnetic minerals. Granite Harbour Intrusive and Skelton Group rocks are dominated by varying mixtures of magnetite and maghemite, whereas Beacon Supergroup rocks contain dominant high-coercivity phases such as hematite and maghemite. Ferrar Dolerite rocks have high concentrations of magnetite with minor maghemite. McMurdo Volcanic Group rocks have the highest concentrations of ferrimagnetic minerals in rocks of southern Victoria Land and their magnetic mineralogy is dominated by magnetite with minor quantities of high coercivity phases, which are typically associated with discrete oxidised outcrops.

Analyses of southern Victoria Land cover sediments (scree, colluvium, recent glacial deposits at the edges of glaciers, mobile ice-cored till, fluvial, lacustrine, aeolian and sea floor) have moderate concentrations of magnetite which, we suggest, is largely derived from McMurdo Volcanic Group rocks. However, studies of Ross Sea drill-core successions that span the Eocene before the appearance of the McMurdo Volcanic Group have also identified significant quantities of magnetite, indicating that the Ferrar Dolerite may once have been a significant contributor of magnetic minerals under a different climatic setting (e.g. Sagnotti et al. 1998; Roberts et al. 2013). FORC analyses of surface sediments reveal superparamagnetic behaviour. We attribute this behaviour to the presence of ultrafine, sub-micron (<30 nm) magnetite, which was likely generated by glacial transport (and possibly aeolian) processes and preserved under the modern, hyper-arid conditions. Superparamagnetic behaviour in cover sediments may therefore be a useful indicator of the modern terrestrial climate state.

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