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Provenance of Ross Sea Drift in McMurdo Sound (Antarctica) and implications for middle-Quaternary to LGM glacial transport: new evidence from petrographic data

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Abstract

The provenance of Ross Sea Drift deposits from the McMurdo Sound region (Antarctica), ranging from middle Quaternary to a Last Glacial Maximum (LGM) age, has been investigated by means of petrographic techniques. A total of 19 bulk till samples from four areas was analyzed for three different granulometric fractions: pebble to cobble, granule, and coarse to very coarse sand grain size. Deposits were classified following the lithological composition of clasts and occurrence of different petrographic groups was evaluated for each sample. Clasts composition predominantly reflects source rocks cropping out in the region between Mackay and Koettlitz glaciers, with McMurdo Volcanic Group rocks being the most represented lithologies in the Royal Society Range foothills, while Granite Harbour Intrusive Complex rocks are more widespread in Taylor and Wright valleys. The lithological distribution of collected samples supports a distal provenance related to a grounded Ross Ice Sheet in Taylor Valley, while the specific distribution of volcanic lithologies in Royal Society Range foothills is evidence for a northward ice flow from Koettlitz Glacier catchment, thus supporting previous glaciological models of an expanded lobe during the LGM. In addition, middle-Quaternary Trilogy Drift composition from Wright Valley accounts for a local provenance, thus allowing the hypothesis of a thickened Wilson Piedmont Glacier rather than a grounded Ross Ice Sheet during past ice advances.

Keywords: Sediment provenance; Last Glacial Maximum; Paleo ice-flow reconstruction; McMurdo Sound; Antarctica.

1.Introduction

The Antarctic Ice Sheet (AIS) is of fundamental use to study ice dynamics and climate influence, as it is the largest fresh water reservoir on the Earth. A key region to study AIS dynamics in the past is the Ross Sea Embayment, as it drains about one third of ice masses both from West and East Antarctica.

During the Last Glacial Maximum (LGM), the Ross Sea was occupied by an advancing grounded ice sheet. Its extension and timing of expansion and retreat has been studied and constrained with several marine and terrestrial geological and geophysical investigations (Hall et al., 2013; Anderson et al., 2014, and references therein). After the ice retreated, it left glacial deposits in the form of sheet drifts and moraines along the glaciated coasts of the Ross Embayment. These deposits have been used to study maximum ice extension and thickness during the LGM, and they also have been used to produce numerical models for the reconstruction of the LGM AIS and its drainage pattern (Pollard and DeConto, 2009; Golledge et al., 2012, 2013).

In the McMurdo Sound, ice supplied by Skelton and Mulock Glaciers during the LGM flowed over the volcanic islands and peninsulas of the region and into the Dry Valleys (Stuiver 1981; Denton and Hughes 2000; Denton and Marchant, 2000; Hall and Denton, 2000). The glacial deposits left by this ice sheet are known in the region as Ross Sea Drift (Stuiver et al. 1981; Cox et al., 2012) and they are the result of multiple advances and retreats of the ice sheet occurred during the Quaternary. Onshore reconstructions of the LGM grounded ice sheet in McMurdo Sound are based essentially on the extension of the most recent of these deposits, the Ross Sea 1 Drift (Cox et al., 2012). The geomorphology, chronology and erratic distributions of these glacial sediments have been extensively investigated (Denton and Hughes, 2000; Denton and Marchant, 2000; Hall and Denton, 2005; Hall et al., 2013; Anderson et al., 2014). However, ice flow directions in McMurdo Sound during the LGM are still under debate, since different models have been proposed so far, based on several marine and terrestrial geological evidence (Stuiver et al., 1981; Denton and Hughes, 2000; Wilson, 2000; Greenwood et al., 2012; Anderson et al., 2017). In particular, conflicting interpretations are due to the non perfect matching between geomorphological evidence and distribution of erratic clasts within these deposits. Moreover, available data lack a detailed petrographic characterization of erratics composing these deposits. Some recent reconstructions have been proposed in addition to the initial model of Stuiver et al. (1981) and Denton and Hughes (2000) of a prevalently westward and southwestward ice flow towards southern McMurdo Sound and the Transantarctic Mountains front (e.g., Greenwood et al., 2012; Anderson et al., 2017). The most recent hypothesis suggests at least a two stages setting for McMurdo Sound ice flow reconstruction during the LGM, with a shift in the direction of ice occurred between ~18.7 kyr and ~10-11 kyr (Anderson et al., 2017).

In this paper, we applied sediment provenance analysis using a petrographic approach to the study of late Quaternary and LGM glacial sediments from the area of McMurdo Sound. Petrographic analysis has been widely applied in Antarctica as a provenance tool, both from medium sand sized detrital sediments and from gravel-sized clasts analysis (e.g., Licht et al., 2005; Licht and Palmer, 2013; Talarico et al., 2012). Point counting methods have been used to discriminate the provenance of LGM sediments in the Ross Embayment (Licht et al., 2005; Licht and Palmer, 2013), while gravel clast analysis has been successfully used to identify glacially eroded source areas and to reconstruct ice drainage pattern during the LGM and past glacial cycles (e.g.. Sandroni and Talarico, 2006; Talarico and Sandroni, 2009; Talarico et al., 2012; Cornamusini and Talarico, 2016; Perotti et al., 2017). In this work, different granulometric fractions composing the Ross Sea Drift collected in different regions from the McMurdo Sound coast have been studied in order to establish their lithological and mineralogical composition. Petrographic analysis of the sampled clasts allowed us to discriminate different lithologic distributions among the analyzed samples, and to identify eroded source areas in the region, thus providing new data on the existing reconstructions of late Quaternary (including LGM) ice flow drainage patterns in McMurdo Sound.

2. Geological setting

2.1 Geology of the study area

The investigated area extends between Wright Valley to the north of McMurdo Sound and Royal Society Range (RSR) foothills to the south (Fig. 1).

The western side of McMurdo Sound is topographically dominated by the South Victoria Land (SVL) sector of the Transantarctic Mountains. A late Proterozoic-Cambrian metamorphic basement is composed of upper-amphibolite to upper greenschist facies rocks of the Skelton Group, in the past referred as the Koettlitz Group (Findlay et al., 1984; Cook and Craw, 2001; Cox et al., 2012). In general, regional metamorphism of the Skelton Group is of low Pressure/high Temperature conditions (Allibone, 1992). The main lithologies belonging to the Skelton Group exposed in the region north of the Koettlitz Glacier are pure and impure marbles, calc-silicates rocks, paragneisses, amphibolites and amphibolitic schists (Findlay et al., 1984), To the southwest of Mount Discovery, Skelton Group rocks in the Skelton and Mulock glaciers area include mainly lower greenschist to lower amphibolite facies metasediments, consisting of metalimestones, marbles, quartzites, metaconglomerates and metasandstones (Skinner, 1982; Cook and Craw, 2002; Cook, 2007). Skelton group rocks have been extensively intruded by the Cambro-Ordovician granitoids of the Granite Harbour Intrusive Complex (Gunn and Warren, 1962; Smillie, 1992; Cox et al., 2012). The latter is composed of heterogeneous undeformed and foliated plutons cropping out extensively in the Dry Valleys area (Allibone et al., 1993a; Cox et al., 2012), including biotite (±) hornblende granites, granodiorites, tonalites, quartz monzo-diorites and diorites. The most extended pluton of the Dry Valleys area is the Bonney Pluton, a northwest trending foliated pluton which extends for a length of 53 km from the Ferrar Glacier to the Olympus Range (Allibone et al., 1993a; Cox et al. 2012). Minor lamprophyric, felsic and mafic plugs and dykes also constitute multiple intrusions in the Granite Harbour Intrusive Complex (Allibone et al., 1993a,b; Cox et al., 2012). Biotite (±) hornblende orthogneisses are intercalated with metasediments of the Skelton Group and are interpreted as the deformed precursor of the younger plutons (Cox and Allibone, 1991). Moreover, some minor alkaline quartz-syenites and granites crop out in the same region, in particular in Teall Island and in the Mulock Glacier area (Cottle and Cooper, 2006; Carosi et al., 2007).

Emplacement of plutons of the Granite Harbour Intrusive Complex was followed by an uplift and erosion stage, with the development of a regional erosion surface (Kukri Peneplain) and deposition during the Devonian to Triassic of sub-horizontal strata of sandstones, conglomerates, siltstones and minor coal measures of the Beacon Supergroup (Harrington, 1965; Barrett, 1981). Beacon Supergroup rocks are restricted to inland exposures at about 25-40 km from the coastline of McMurdo Sound (Cox et al., 2012). During the Jurassic, both basement rocks and Beacon Supergroup units were involved in the emplacement of dolerite sills and dykes of the Ferrar Supergroup and its extrusive component, the Kirkpatrick Basalt, in response of the initiation of the West Antarctic Rift (Kyle et al., 1981).

The region of McMurdo Sound is extensively characterized by Cenozoic volcanic centres (Mount Morning-Mount Discovery complex to the south, Brown Peninsula, Minna Bluff, Black Island and White Island to the east, Ross Island to the north, Fig. 1). Volcanic centres belong to the alkalic Erebus Volcanic Province of the more extended McMurdo Volcanic Group (Kyle, 1990), and their activity is divided into an earlier phase (18.7 to 11.4 Ma; Martin et al., 2010) of mainly trachytic rocks, and a more voluminous second phase (last 10 Ma), mainly characterized by basanitic to phonolitic rocks.

During the Plio-Pleistocene, the same region was involved in multiple advances and retreats of a grounded Ross Ice Sheet that shaped the coast and left glacial deposits of the Ross Sea Drift (Stuiver et al., 1981; Hall et al., 2000, Cox et al., 2012). These deposits are widespread from Wright and Taylor valleys to the foothills of the RSR. In the case of the Dry Valleys region, westward re-entrant glaciers fed by a grounded Ross Ice Sheet penetrated into the mouths of the valleys leaving geomorphologic traces in the form of lateral and arcuate moraines and mantle drift sheets (Stuiver et al., 1981; Denton and Hughes, 2000; Denton and Marchant, 2000; Hall and Denton, 2000). These deposits have been divided based on their chronology in four distinct units by Cox et al. (2012). The youngest of these deposits is the Ross Sea 1 drift, composed of unweathered to slightly weathered loose till, waterlain diamicton, glaciolacustrine silt, stratified sand, with interbedded silt, sand and gravel (Stuiver et al., 1981, Hall et al., 2000, Cox et al., 2012). Locally, Ross Sea 1 Drift is defined by lacustrine facies (Cox et al., 2012). The chronology of this deposit testifies to a grounded ice sheet in McMurdo Sound as described by Denton and Marchant (2000): the last grounding event occurred in the region at ~ 27 kyr BP, with the ice sheet becoming more extensive during the LGM and retreating during mid to late Holocene.

2.2 Late Quaternary geomorphological setting and ice-flows reconstruction

The Southern McMurdo Sound region during the late Quaternary experienced more than one episode of flowing grounded ice, mainly supplied by outlet glaciers of the Transantarctic Mountains. Volcanic edifices influenced the development of the McMurdo Ice Shelf that is an extension of the Ross Ice Shelf, and constrained the behavior of a grounded Ross Ice Sheet in the region (e.g. Denton and Hughes, 2000; Naish et al., 2009; McKay et al., 2012). The distribution of erratics belonging to Ross Sea 1 Drift and the morphology of moraines were adopted by Stuiver et al. (1981), Denton and Marchant (2000) and Denton and Hughes (2000) to reconstruct LGM surface elevation of the Ross Sea Ice Sheet and paleo-ice flows in the region. Stuiver et al. (1981) and Denton and Hughes (2000) argued that part of the LGM grounded ice of the Ross Sea Ice Sheet flowed westward and southwestward in the direction of Victoria Land coast, bypassing Ross Island. This grounded ice dammed the mouth of the Dry Valleys and flowed from the northern tip of Ross Island southward to Miers Valley in the Royal Society Range foothills. The geologic basis for this model are mainly the slope of moraines across the Sound and the presence of anorthoclase-phyric phonolite erratics on the flanks of the RSR and in the Dry Valleys (Denton and Marchant, 2000), since the only known outcrop of anorthoclase-phyric phonolite (in the past referred as kenyte; Cox et al., 2012) is in the western coast of Ross Island.

However, an alternative reconstruction proposed by Wilson (2000) comprises three grounded glacial lobes in southern McMurdo Sound on the basis of geomorphological evidence and erratics distribution. In this reconstruction, a Koettlitz Glacier lobe flowed northward and coalesced with a Minna Bluff northwest lobe and northward Ross Ice Shelf lobe that covered White Island and flowed north of Black Island. Recently, an interpretation of this reconstruction, based on new chronology and sediment provenance data, led to a two-stage scenario for LGM and post-LGM events (Anderson et al., 2017): the first stage occurred prior the Last Glacial Termination, (interpreted by Hall et al. (2015) between 18.7 and 12.2 kyr BP). This stage reflects the reconstruction of Wilson (2000), with mainly a northward and northwest ice flow fed by Ross Sea grounded ice and an expanded Koettlitz Glacier ice. The second stage occurred between ~18.7 kyr BP and the major retreat of grounded ice in the Sound (~10-11 kyr BP) and is characterized by reduction of the Koettlitz Glacier lobe that led to intrusion of westward and northward ice fed by the Ross Sea Ice Sheet into McMurdo Sound (Anderson et al., 2017).

Westward glacial flow from Ross Island towards Victoria Land Coast has been also demonstrated by offshore marine studies. A four-stages model applying multibeam bathymetric analysis of the seafloor of McMurdo Sound has been presented by Greenwood et al. (2012). The latter shows evidence mainly from a sector locate north of Black Island and Brown Peninsula. Moreover, immediately north of Ross Island, also deglaciation shows a prevalently westward direction of movement, as shown by back-stepping wedges and marginal moraines on the sea floor (Halberstadt et al. 2016).

Despite the number of studies mentioned above, lithological evaluation of clasts composing these glacial deposits has not been developed in depth, and systematic petrographic analyses of onshore sediments have not been sufficiently detailed. In this paper, we applied such methodology in order to obtain new data to be discussed within the interpretations described above.

3. Materials and Methods

Nineteen bulk till samples were collected in the Dry Valleys region in a coastal area between the Wright Valley and the foothills located in front of the RSR (Fig. 2, Table 1). Four main sampling areas are: Wright Valley, Taylor Valley, RSR foothills (Marshall and Miers Valleys), Howchin Glacier/Walcott Bay (Fig. 2). At each sampling site at least one surficial and one 15-20 cm depth bulk till sample were taken. Target samples are bulk loose till sediments of the Ross Sea Drift. Specifically, samples from Taylor, Miers, Marshall valleys and Walcott Bay deposits were taken from the continuous drift sheet that covers the eastern slopes and coastal valleys south from Marble Point, occurring also as extensive deposits on Brown Peninsula, Black Island, Minna Bluff and on Ross and White islands (Stuiver et al., 1981). This is called Ross Sea 1 Drift (ur1) in the geological map of Cox et al. (2012). Samples from Wright Valley were taken from an older deposit, specifically the Trilogy Drift, that is a sandy diamicton with stained and ventifacted clasts, defined by 1-3 m high moraines mainly located in the north side wall of the Wright Valley (Hall and Denton, 2005)(Fig. 3A). An age of early-middle Quaternary has been proposed for this deposit, on the basis of stratigraphic position in respect of the overlying Brownworth Drift, which has been dated with ^{14}C at > 49 kyr BP (data from an overlying lacustrine algal deposit, uncorrected dates from Hall and Denton, 2005). This drift belongs to the Ross Sea 3 Drift deposit in the geological map of Cox et al. (2012).

Bulk till samples were dried and sieved in order to obtain different granulometric fraction for each sample. For specific petrographic analysis the fraction >4 mm was analyzed macroscopically and some thin sections were made. For the macroscopic analysis, each clast was classified into broad lithological groups and counted for each sample. Granulometric fractions between 4 to 2 mm (granules) and 2 mm-425 µm (very coarse to coarse sand) were impregnated with epoxy and made into thin sections for petrographic analysis, following same procedures applied by Licht et al. (2005).

For the granulometric fraction 4-2 mm, microscopic petrographic analysis was aimed to identify the grain lithologies present. Volcanic lithic fragments were classified on the basis of the mineral assemblages recognised in thin section, following the classifications adopted by Pompilio et al. (2007) and Panter et al. (2008) for clasts recovered in ANDRILL cores (AND-1B and AND-2A, respectively). Thus volcanic lithologies were grouped in three different compositions: (i) basaltic (occurrence of phenocrysts of clinopyroxenes (Mg-rich), olivine and plagioclase); (ii) intermediate (phenocrysts of plagioclase ± kaersutitic amphiboles ± clinopyroxene); and (iii) felsic (phenocrysts of K-feldspar ± kaersutite ± sodic clinopyroxene (aegirine-augite).

For the 2 mm-425 µm thin sections, the Indiana Point Counting method (Suttner, 1974; Suttner et al., 1981) was carried out. With this method, at least 300 counts for each sample were made, identifying both single mineral and lithic fragment petrography. The lithic fragment classification used for point counts was the same as described by Licht et al. (2005) for bulk till sediments analysis. Note that not every sample reached 300 counts because of the limited number of grains present in some thin sections.

Chemical analysis of some mineral phases identified by petrographic microscope were carried out with an X-ray energy dispersive system EDAX DX4 attached to a scansion electron microscope Philips XL30 at the Department of Physical Sciences, Earth and Environment in Siena (Italy). Analytical conditions were 20 kV of accelerating voltage, 25 µA of emission current, and a beam spot size of 0.2 µm. Natural minerals were used as standards. Fe^{3+} concentration in clinoamphiboles and clinopyroxenes was estimated by the equation of Droop (1987), assuming charge balance. For each thin section, several analytical spots were carried out on specific mineral phases belonging both to volcanic and basement (i.e. granitoids and metamorphic lithics) clasts. In the case of pyroxenes, also single mineral grains were analyzed throughout thin sections. Analyzed minerals include pyroxenes, feldspars and clinoamphiboles. All samples are stored in the rock repository of Museo Nazionale dell'Antartide (Siena University, Italy, online database http://www.mna.it/collezioni/catalogo-rocce-sede-di-siena).

4. Results

4.1.1 Wright Valley

In Wright Valley samples were collected from a drift sequence within 1-2 m high lateral moraines along the northern flank of the central valley (Figs. 2A and 3A). The sediment is an unconsolidated sandy diamicton with heterometric, moderately ventifacted clasts composed of variably foliated granitoids, mafic intrusive rocks, rare pinkish porphyries and rare basalts. Compositionally, the 4 samples from Wright Valley yielded a quite homogeneous lithological distribution (Fig. 4 and Table 2). Macroscopic analysis carried out for the gravel size fraction is shown in Table 2. The samples exhibit a composition dominated by granitoids (average value of 62% of the total number of counted clasts), variably distributed from medium to fine grained, isotropic to foliated biotite-leucogranite to monzogranite, to intermediate compositions (granodiorite to quartz-diorite). Some granitoid rock fragments exhibit a porphyritic texture with coarse grained k-feldspar phenocrysts. A significant amount of fine grained isotropic mafic intrusive rocks is also present (microdiorite, dolerite, gabbro, average value of 18 % of the total number of counted clasts). A minor component of schistose rock fragments and basaltic volcanic rocks is also present (average of 7% and 3%, respectively). Microscopically, the petrographic composition of 4-2 mm fraction is shown in Figure 4. Samples from Wright Valley are dominated by felsic and intermediate granitoids (average of 74% of counted clasts), isotropic or foliated, characterized by biotite or biotite-hornblende monzogranite to quartz-diorite (modal mineralogy was only semiquantitatively determined because of the small size of lithic clasts). The lithic association also has a minor occurrence of dolerite, mafic intrusives rocks, such as diorite and gabbro (average of 12%), and a series of metamorphic rock clasts (mainly Ca-silicates, amphibolites and orthogneisses, average of 12%). Dolerites exhibit fine grained isotropic intergranular to sub-ophitic texture, while diorites show an hypidiomorphic biotite-clinoamphibole-plagioclase texture. Metamorphic rocks are generally foliated heterogranular fine to medium grained biotite ± clinoamphibole schists, and gneisses with granolepidoblastic texture, while granofels lithic fragments commonly exhibit fine grained plagioclase-quartz-clinopyroxene±clinoamphibole granoblastic texture. Very rare volcanic lithic fragments are present (below 1% of the total counted clasts).

Point counting analysis of the 2 mm-425 µm samples yielded results summarized in Figure 5. In the latter it is evident from the Quartz-Feldspar-Lithics (QFL) diagram that lithic fragments are the main constituents, with minor quartz and feldspars;

Taking in consideration only single minerals grain counts (see tables in supplementary materials), Wright Valley samples are mainly characterized by a combination of quartz, pyroxenes and feldspars, with minor amounts of opaques and amphiboles (up to 2% of the total counts).

4.1.2 Taylor Valley

Some samples from Taylor Valley werefrom tills at the bottom of the valley, southeast of the Commonwealth Glacier, from the glaciolacustrine facies of the Ross Sea 1 Drift (Fig. 2A), while others were sampled from the section incised by the Commonwealth Stream east of the same glacier (Table 1 and Fig. 2A for sample locations). The first group of samples are from an unconsolidated sandy diamicton composed of heterometric, moderately unweathered clasts of variably foliated granitoids, mafic intrusive rocks, and basalts. The second group come from an unconsolidated diamicton overlain by laminated silty sands. Macroscopically, these samples have a homogeneous clast composition; the only exception is sample 20-01-15 P10A, which yielded an anomalously high proportion of volcano-clastic sand-sized lithic fragments (about 70% of the total). The other samples show a lithological composition defined mainly by felsic granitoids (medium to fine grained, isotropic to slightly foliated pink to brownish leuco-granites to monzogranites, average of 35% of the total), intermediate granitoids (fine to medium grained variably foliated granodiorite to quartz-diorite, average of 12% of the total), foliated biotite-orthogneisses (average of 3%) and a variable amount of aphanitic, sometimes vesicular, basaltic clasts (from 4% to ~25% of the total). Moreover, a variable amount of dolerite was found, ranging from ~1% to 16% of the total, with the only exception of the volcanoclastic lithic-dominated sample. A minor amount of olocrystalline, very fine grained microdiorite was also present, up to ~10% of the total in one sample, and below 10% in the other samples. Other lithologies are represented in negligible amount from these samples.

Figure 4 shows the lithic fragments distribution for the 4-2 mm granulometric fraction from Taylor Valley samples. Most samples show a major granitoid (both felsic and biotite-hornblende intermediate composition, average of 40% of the total) occurrence, together with a variably rich percentage of mafic rocks (dolerite, fine grained gabbro, biotite-hornblende diorite, average of 14% of the total) and metamorphic lithologies (prevalently biotite-orthogneisses with minor amount of Ca-silicates, amphibolites and marbles, average of 12% of the total). Moreover each sample has a consistent component of volcanic lithic fragments (average of 27% of the total, excluding the volcano-clastic rich sample), composed mainly by porphyritic microcrystalline to vitrophyric basalt with ubiquitous clinopyroxene micro-phenocrysts and widespread olivine micro-phenocrysts; isotropic ipocrystalline textures are common but also pylotaxitic and trachytic textures are frequent. Groundmasses are characterized by the presence of plagioclase, clinopyroxenes and opaques. In some cases (e.g., some clasts from samples 23-P5 and 23-P6) kaersutitic brown amphibole was recognized as micro-phenocrysts, set in a groundmass of plagioclase, opaque minerals and sometimes blackish to brownish glass.

4.1.3 Marshall and Miers valleys

Samples from Marshall Valley were taken from the main section incised by the stream along the central axis of the valley (Fig. 2B). They consist of bulk samples from a loose till composed of sandy diamicton with heterometric clasts from granules to boulder size, alternated with some dark silty laminations. Among cobbles and boulders, foliated granitoids, aphiric basalts and plagioclase-phyric intermediate volcanites were recognized in the field (Fig. 3D). The Miers Valley sample was taken from a basalt-rich outcrop of evaporitic glaciolacustrine facies along the section of the main stream of the valley, composed of alternated silty and sandy laminae and heterogeneous loose till.

Macroscopically, granule and cobble compositions of these samples identify the dominance of volcanic lithic fragments, in one case constituting up to~90% (sample 21-P16, Table 2); granitoids are the second most representative lithologies with predominant isotropic to variably foliated felsic varieties (e.g samples 21-P19 and 21-P21, average value of 26% of the total). Metamorphic rocks are rare, with few Bt-schists and orthogneisses (average value of 2% of the total), while sedimentary rocks are completely absent (Table 2).

Lithic fragment petrographic analysis of the 4-2 mm fraction is shown in Figure 4. Volcanic lithic fragments are the most common, with a prevalence of fine grained microporphyritic ipocrystalline to olocrystalline basaltic rocks (average value of 63% of the total). Colourless to light brown clinopyroxene is the most widespread phenocryst species, often associated with microporphyritic olivine. Groundmasses are prevalently ipocrystalline with plagioclase, opaque minerals and clinopyroxenes associated to a brownish to yellowish glassy amorphous matrix. In these samples, also a variable percentage of felsic volcanic rocks is present, in particular in samples from Marshall Valley (average value of 9% of the total): these clasts show an olocrystalline trachytic texture with aligned laths of plagioclase and alkaline-feldspar associated with intergranular green clinopyroxenes, opaque minerals and in some cases brown kaersutitic amphiboles. Hypidiomorphic isotropic to slightly foliated granitoid rock fragments are also present (15% of the total). Metamorphic lithic fragments are prevalently fine grained clinopyroxene-quartz-plagioclase ± amphiboles granofels with granoblastic texture, granolepidoblastic biotite schists and gneisses and rare marbles (average of 12% of the total). In one case (21-P19 from Marshall Valley) two clasts of medium grained sandstone were recognized. The results of point counting analysis of finer granulometric fraction (2 mm-425 µm) show a prevalent volcanic lithic fragment composition, with the Miers Valley sample composed almost exclusively by volcanic clasts (Fig. 5).

4.1.4 Walcott Bay

Two clast-rich loose diamicton samples were taken from Walcott Bay area, along the Howchin Glacier stream. Samples belong to the Ross Sea 1 Drift of Cox et al. (2012) and are composed of an unconsolidated till defined by a yellowish sandy matrix and heterometric clasts ranging from granules to boulders. Sometimes this diamicton is alternated with dark sandy laminated layers and overlies a more consolidated till. Macroscopically, granules and cobbles are composed dominantly of basaltic rocks, up to 50% of the total, followed by felsic leucocratic granitic rocks and intermediate granodioritic to Qtz-dioritic variably foliated rocks (average of 33% of the total; Table 2).

Microscopic analysis on the 4-2 mm fraction yielded a lithologic distribution defined mainly by basaltic lithic fragments (average of 63% of the total; Fig. 4); these are characterized by a micro-porphyritic ipocrystalline to vitrophyric texture, with micro-phenocrysts of clinopyroxene and olivine set in a groundmass composed of plagioclases, clinopyroxenes, opaque minerals and, when present, a black/brownish to yellowish glass. Volcanic lithic fragments were classified exclusively as basic volcanics. Sample 21-P15A also shows a relative amount of volcanoclastic lithic fragments (34% of the total; Fig. 4). Isotropic felsic granitoids are minor (average of 27%), together with metamorphic lithic fragments composed mainly by Bt±Cam schists, gneisses, and minor Cpx- granofels and marbles (average of 9% of the total). The Walcott Bay 2 mm-425 µm petrographic analysis is shown in Figure 4. The two samples are composed mainly of volcanic lithic grains, and their position in the L_m-L_{g+m}-L_v diagram is very close to the L_v vertex, as is the one from Miers Valley.

4.2 Mineral geochemistry

Geochemical analyses were carried out on seven thin sections. All mineral compositions are listed in tables available as Supplementary Materials (SA, SB, SC, SD, respectively, for amphiboles, plagioclases, pyroxenes and olivines).

Pyroxenes have been found as micro-porphyritic brownish to purplish crystals as far as groundmass phases in most volcanic clasts, of basic and intermediate composition; moreover, mafic lithic fragments (e.g. dolerites and gabbros) contain clinopyroxenes and orthopyroxenes. Some metamorphic lithic clasts such as granofels contain colourless clinopyroxenes. Figure 8a shows the composition of analyzed pyroxenes in the quadrilateral diagram of Morimoto et al. (1988).

Clinopyroxenes from volcanic clasts range from diopside to titaniferous augite composition. In some cases they are zoned, with enrichment of Mg and depletion of Fe from cores to rims. In some others they are homogeneous in composition. There are no significant differences in composition of volcanic clinopyroxenes between samples taken from different areas. Clinopyroxenes from basement metamorphic clasts are mainly diopsidic. Orthopyroxenes of enstatitic composition have been found from intrusive lithics fragments (gabbro and dolerite) in samples from Taylor, Wright and Marshall valleys (Fig. 7a). Clinopyroxenes from Taylor Valley show a general Fe enrichment in comparison with other areas.

Feldspars representative composition are shown in Figure 7b in a ternary diagram. Plagioclases from volcanic lithic fragments are mainly bytownitic to labradoritic, ranging from An84 to An45. Instead, some volcanic lithic fragments of felsic mineralogy yielded mainly alkaline-feldspar of anorthoclase composition (Fig. 7b). The latter have been identified only in Marshall Valley samples. Feldspars from other metamorphic and intrusive lithologies yielded a main andesine-oligoclase composition, with few samples being bytownitic in composition.

Amphiboles were analyzed in samples taken from Marshall, Taylor and Wright valleys. All analyzed amphiboles are members of the calcic amphibole group (Leake et al., 1997)(Fig. 8). Amphiboles from Wright Valley are mainly ferro-hornblende and magnesio-hornblende, in some cases they exhibit strong zonation (X_{Mg} varying from 0.47 to 0.55 from core to rim), while in others weak zonation (X_{Mg} from 0.38 to 0.30 from core to rim). Amphiboles from Taylor Valley vary from ferro-edenitic hornblende to ferro-pargasite (with weak zonation, X_{Mg} from 0.44 to 0.46 from core to rim). Amphiboles from Marshall Valley yielded both a ferro-edenitic hornblende composition and a magnesio-hornblende composition, with two crystals from volcanic lithic fragments that are kaersutite ($Ca_B \geq 1.50$; $(Na+K)_A \geq 0.50$ and $Ti > 0.50$ a.p.f.u., Fig. 8).

Olivines from analyzed clasts are mainly forsteritic, with a composition ranging from Fo_{88} to Fo_{70}; only in a few cases (clasts from Taylor Valley samples), olivine has a composition of Fo_{60} to Fo_{57}.

5. Discussion

5.1 Clast provenance

Recovered clasts that compose the Ross Sea 1 Drift and the Trilogy Drift along the southern coast of McMurdo Sound and in Wright and Taylor valleys contain mainly rocks sourced from the intrusive basement complex and volcanic rocks supplied by the several volcanic centers of the region. However, a more detailed discussion about the specific provenance of lithologies composing the drifts is needed.

The source of isotropic and foliated intermediate granitoids can be confidently assigned to the several plutons of the Granite Harbour Intrusive Complex that crop out in the region from the Wright Valley to the Koettlitz Glacier. Modal mineralogy was impossible to achieve for the small dimensions of lithic grains, so it is also possible that lithics classified as felsic granitoids (quartz-feldspathic composition with minor mafic minerals, following the classification adopted here) could belong to a generic granitic/granodioritic composition. In particular, one possible source for felsic granitoids recovered in Wright Valley could be the Brownworth Pluton, a coarse grained alkali-feldspar megacryst granite cropping out in the eastern valley (Allibone et al., 1993a). Similarly, the isotropic biotite-leucogranite Catspaw Pluton crops out in eastern Taylor Valley (Allibone et al., 1993a; Cox et al., 2012), and could be considered as one possible source rock for felsic granitoid lithic fragments recovered in eastern Taylor Valley. Alternatively, biotite leucomonzogranite forms porphyritic varieties of cross-cutting dykes of the Bonney and Hedley plutons in the region of the Ferrar Glacier (Smillie, 1992). Biotite-hornblende isotropic and foliated intermediate granitoids could be associated with the Bonney Pluton, which is the most extensive pluton of the region, cropping out from Wright Valley to Koettlitz Glacier area (Cox et al., 2012). However, since this pluton crops out west of the sampling sites in Wright and Taylor Valleys and in RSR foothills, a Ross Sea provenance of the drift would exclude it as the main source of biotite-hornblende granitoids, unless its occurrence is considered the result of a recycling process of already eroded material. However, any textural evidence of recycled material has been found from the analyzed samples. Thus, the likely sources of the biotite-hornblende granitoid rock fragments could again be identified in the smaller Brownworth and Catspaw Plutons, that contain both biotite and hornblende (Allibone et al., 1993a; Forsyth et al., 2002). Also, the chemical composition of amphiboles from Wright and Taylor Valley samples matches very well the Southern Victoria Land intrusives field, with also some amphiboles from Taylor Valley which exhibit a Fe-tschermakitic composition, resembling those obtained by Talarico et al. (2011) for bedrock samples in the Britannia Range area (Fig. 8).

Metamorphic clasts recovered from the sampling sites could be related to the generic Skelton Group rocks (previously referred as the Koettlitz Group; Cox et al., 2012). Indeed, amphibolites, biotite-actinolite schists, clinopyroxenes-actinolite granofels are common lithologies among the Marshall Formation (Miers-Garwood valleys) and the Hobbs Formation (Victoria Valley-Koettlitz Glacier area) of Findlay et al. (1984), as far as marbles from the Salmon Marble Formation. All these formations could be generally grouped in the Skelton Group (Cox et al., 2012). Biotite orthogneisses are intercalated with the Skelton Group rocks in many outcrops, including in the Garwood Valley and Wilson Piedmont Glacier areas (Cox et al., 2012). In a few cases, amphiboles from samples located in Marshall Valley match the composition of amphiboles of the Skelton-Mulock glacier area (Talarico et al., 2011) (Fig. 8).

Mafic intrusive lithic fragments could be related to gabbros and dolerites of the Ferrar Supergroup, cropping out as dykes in the basement complex and sills within Beacon Supergroup sequences and along the Kukri Peneplain surface (Gunn and Warren, 1962; Cox et al., 2012). Gabbros are typical of the centre of the sills, whereas dolerites are widespread in the sill margins (Gunn and Warren, 1962). Mineral chemistry analysis supports a provenance from Ferrar Supergroup rocks, with some samples yielding orthopyroxenes comparable with composition reported by Haban and Elliot (1985) for the Ferrar Dolerite (Fig. 7a). Gabbros are also present in the upper Koettlitz Glacier within the Dromedary Mafic Complex (Simpson and Aslund, 1996; Cox et al., 2012) and intruding Skelton Group rocks close to Panorama Glacier (Panorama Pluton; Mellish et al., 2002). In particular, the Dromedary Mafic Complex is characterized by orthopyroxene-bearing lithologies such as norites and pyroxenites ($X_{en\ 0.75-0.78}$; Simpson and Aslund, 1996) so occurrence of detrital orthopyroxenes grains could not be considered exclusive of a Ferrar Group source.

Volcanic clasts are related to the McMurdo Volcanic Group, Erebus Volcanic Province, cropping out extensively on Ross, White and Black Islands and in the Mount Morning-Mount Discovery area (Kyle, 1990). Minor and scattered Pliocene-Pleistocene basanite scoria cones are present also in the eastern Wright Valley, between the Bartley and Goodspeed Glacier and in Taylor Valley, around Taylor Glacier snout and Lake Bonney and in the Kukri Hills (Wright and Kyle, 1990a; Cox et al., 2012). Also in the foothills of the RSR, over 50 basanite vents and scoria cones are present, mainly of Pleistocene ages (Wright and Kyle, 1990b; Cox et al., 2012). Petrography and mineralogy of analyzed clasts reflect a composition related to basic lithologies, such as basanites/tephrites; in some cases they exhibit a mineralogy suggesting an intermediate composition (mainly feldspar phenocrystals and kaersutitic amphiboles), up to a felsic mineralogy with flow-aligned K-feldspar and green clinopyroxenes, that reflect a felsic source rock such as trachytes (Fig. 6). Chemical composition of clinopyroxenes of volcanic clasts (diopside to titaniferous augites) corresponds to those obtained by Gamble et al. (1986) for Erebus Volcanic Province rocks. Olivine chemical compositions (Mg-rich olivine) found in clasts from the analyzed samples correspond in most cases to a basic-ultrabasic type source rock, according to data from Kyle et al. (1992) for the Mount Erebus lavas and from Wright-Grassham (1987) for the Mount Morning area. According to the same authors, Fe-richer olivine (Fo_{60}), found only in some Taylor Valley lithic grains, corresponds to a more differentiate source rock of intermediate composition (tephriphonolite to phonolite type).

5.2 Implications for ice-flow patterns

Clast distributions of Ross Sea 1 Drift and Trilogy Drift revealed by this study show a clear difference between the composition found in Taylor and Wright Valleys samples and those found in samples from RSR foothills (Marshall and Miers Valley and Walcott Bay). In particular the main difference regards the eastern Wright Valley (Figs.4, 5, Tables 2, 3), where the analyzed samples substantially lack volcanic lithologies of the McMurdo Volcanic Group, being characterized only by basement rocks such as granitoids, mafic intrusives and metamorphic rocks. Comparing Wright Valley samples with those from other sampled areas in the QFL diagram (Fig. 5a), the former have a slight increase in quartz and feldspars than the latter. The greatest difference is shown in Lm-Lg+m-Lv diagram (Fig. 5b), with Wright Valley samples yielding a larger proportion of granitoid and metamorphic lithic fragments and a minor proportion of volcanic lithic fragments, in comparison with other samples. This difference is also clear in the 4-2 mm fraction analysis (Fig. 4). Samples from the Taylor Valley area and foothills of the RSR all contain volcanic lithic fragments, transported by grounded ice that eroded McMurdo Volcanic Group outcrops, thus suggesting a seaward Ross Ice Sheet provenance. This possibility is plausible if the small vents and scoria cones scattered in the flanks and bottom of western Taylor Valley are excluded as source rocks.

A deeper discussion of petrographic data obtained in this study is necessary to explain the differences between Ross Sea 1 Drift and Trilogy Drift compositions. The latter, located in the eastern Wright Valley, is a deposit older than the LGM (early to mid-Quaternary age based on its weathering; Hall and Denton, 2005). Clast composition of Trilogy Drift from Hall and Denton (2005), as well as in this study, reveals a minor percentage of McMurdo Volcanic Group basalts (Figs. 4, 5; Tables 2, 3). This opens two possible interpretations for the origin of this drift, already considered by Hall and Denton (2005): (a) advance of grounded ice directly from Ross Sea, carrying volcanic lithics derived from known volcanic outcrops in the region; or (b) local advance of the Wilson Piedmont Glacier inland towards the site of deposition of the drift, carrying local lithologies and few volcanic clasts that lie beneath the glacier in small cones and vents. This second interpretation is more consistent with our results. Indeed, our petrographic data reveal a distribution of clasts for Wright Valley samples that is compatible with local lithologies cropping out in eastern Wright Valley (granitoids and metamorphic rocks of the Skelton

Group); also dolerites of the Ferrar Group, that are present in samples from this study (and also in Hall and Denton, 2005), could not be considered as far-travelled erratics, since some sills of dolerite crop out in eastern Wright Valley, north of Brownworth Lake (Cox et al., 2012), thus allowing the possibility of a local Ferrar dolerite source. Moreover, looking at samples from Taylor Valley, in which a grounded ice incursion during the LGM is well documented (Denton and Marchant, 2000; Hall et al., 2000), McMurdo volcanic group lithics make up a consistent percentage of total clast assemblage (5-25% for >4 mm fraction, ~20-25% for 2-4 mm fraction, ~30-50% for 2 mm-425 µm fraction). Volcanic clast composition in Taylor Valley samples is quite variable, with a majority of basic lithologies, followed by intermediate compositions and rare felsic rocks, suggesting a source area defined by different volcanic lithologies. Assuming a Ross Sea grounded ice incursion during the mid-Quaternary in Wright Valley, one would expect a similar percentage of McMurdo volcanic lithics for the assemblage found in Trilogy Drift, given the proximity between Taylor and Wright valleys. Instead, occurrence of basaltic clasts found in the four Wright Valley samples is documented by significantly lower amounts than those of all other samples of our dataset (5-10% for >4mm fraction, less than 5% for 2-4 mm fraction, 1-4% for the 2 mm-425 µm fraction, Figs. 4, 5). These low percentages are consistent with a scenario of few volcanic cones widespread between Lake Brownworth and the Bay of Sails rather than an extended volcanic centre such as the islands of McMurdo Sound, which could provide much more volcanic detritus. If this hypothesis is valid, then the main transport for Trilogy Drift would be consistent with a phase of thickening and advance of the Wilson Piedmont Glacier, as happened in the LGM, during which grounded Ross Sea ice did not extend to the eastern Wright Valley (Hall and Denton, 2005). However, this hypothesis is in contrast with the magnitude of thickening required for the Wilson Piedmont Glacier alone to extend so far into the interior of Wright Valley (Hall and Denton, 2005), so the question remains contentious.

The second point to underline is the difference in composition between Taylor Valley samples and samples from RSR foothills; the latter have a larger percentage of McMurdo Volcanic Group rocks (up to 90% in 2-4 mm fraction of one sample from Miers Valley). This could be caused by the geographic position of the RSR foothills, closer to the main volcanic centres of Minna Bluff, Brown Peninsula, Mount Morning and Mount Discovery, than Taylor Valley. However, some specific differences between samples from these two areas exist. In particular, the volcanic clast distribution is noteworthy. In a strict petrographic sense, without a precise available bulk chemical composition of volcanic clasts, and considering the context of the Erebus Volcanic Province rocks (Kyle, 1990), basic lithologies can be identified as including “basanite-tephrite” type rocks; intermediate lithologies can be identified as including as “phono-tephrite to phonolite” type rocks; and felsic lithologies as “phonolitic-trachytic” type rocks. In particular, volcanic clasts of samples from Marshall and Miers valley in some cases reveal a mineralogy typical of trachytoids rocks (anorthoclase to sanidine k-feldspar ± green clinopyroxene ± opaque minerals; Fig. 6), while volcanic clasts from Taylor Valley and Walcott Bay are almost exclusively of basaltic or intermediate composition. The most widespread volcanic rock types in the McMurdo Sound are basanitic to phonotephritic lavas (Kyle, 1990; Cox et al., 2012), while felsic rocks of trachytic mineralogy are less widespread and mainly concentrated in the southern portion of

McMurdo Sound: the west side of Brown Peninsula (Kyle et al., 1979), some lavas from Black Island (Cole and Ewart, 1968) and the Phase I lavas from the Mount Morning volcanic complex (Wright-Grassham, 1987; Martin et al., 2010). Given this distribution across McMurdo Sound, it is possible that felsic trachytoid clasts found in samples from Marshall and Miers valleys could derive from erosion of some southern volcanic centers. For instance, Mount Morning volcano had an important mildly alkaline magmatism phase between 18.7 and 11.4 Ma and rocks of felsic composition (mainly trachytes and rhyolites) are believed to be much more voluminous beneath present day ice that covers the area (Martin et al., 2010). To deposit trachytoid rocks from a southern volcanic centre to the latitude of Marshall and Miers valleys, a northward ice flow is necessary. If so, this hypothesis would imply an extended Koettlitz Glacier lobe at the time of deposition of the Ross Sea 1 Drift, at least to Marshall Valley, confirming the initial statement of Wilson (2000) of a three-ice lobe setting in McMurdo Sound at the LGM.

Additionally, rarity of dolerites and gabbros from the southern samples in our dataset (Marshall Valley, Miers Valley, Walcott Bay areas) suggest an eroded area with minor outcrops of Ferrar Group rocks, such as the catchment area of the Koettlitz Glacier, in which only the Dromedary Mafic Complex and the Panorama Pluton could provide mafic intrusive rocks. Moreover, these rocks are petrographically distinct from those of the Ferrar Group (Simpson and Aslund, 1996; Mellish et al., 2002). By contrast, Taylor Valley samples, as well as drifts on Black and White islands, Minna Bluff and the eastern sides of Brown Peninsula, contain dolerite erratics (Denton and Marchant, 2000), suggesting a different ice flow that carried Ferrar Group clasts (as well as sandstones of Beacon Supergroup and Eocene erratics; Talarico et al., 2013) from regions located farther south along the Transantarctic Mountains. In addition, ferro-tschermakitic amphiboles of some analyzed clasts from Taylor Valley are similar in composition to those found by Talarico et al. (2011) for basement lithologies located in the Britannia Range area, in the region between Mulock and Byrd glaciers. This would imply for Taylor Valley a LGM grounded ice sheet able to provide detritus initially eroded from southern regions, as already demonstrated for past glacial cycles in ANDRILL cores (Talarico and Sandroni, 2009, 2011; Sandroni and Talarico, 2011; Talarico et al., 2012).

Thus, ice-flow reconstruction based on petrographic data supports a scenario characterized by a local provenance (i.e., Koettlitz Glacier) for samples of the RSR foothills, and a distal provenance from a westward ice flow in Taylor Valley. This scenario is shown in Figure 9. The hypothesis of a westward ice-flow intrusion in Miers Valley area, occurred after Koettlitz Glacier retreat (Greenwood et al., 2012; Anderson et al., 2017), which would also explain the presence of anorthoclase-phyric phonolite erratics in these drifts, is not in contrast with our data. Indeed, it is possible that the drifts we sampled from RSR foothills refer to the early phase of expansion of the Koettlitz Glacier lobe, that afterwards retreated and led to the westward advance of a Ross Ice Sheet lobe, as demonstrated by Anderson et al. (2017). Composition of samples from Miers and Marshall valleys could also be coherent with west-south-west ice flow lines not involving Koettlitz Glacier expansion but considering detritus carried from the south over Minna Bluff and Brown Peninsula. Indeed, volcanic felsic lithologies are present also in the eastward side of Mount Morning complex, at Mason Spur (Martin et al., 2010), and so occurrence of these rocks in Miers and Marshall valleys could alternatively be ascribed to a northward Koettlitz Glacier ice flow, or a south-westward Ross Ice Sheet expansion. The only doubt on this second hypothesis would be scarcity of dolerite clasts in these samples compared with those from the Taylor Valley; according to Marshall and Miers Valleys' petrographic data, the catchment of Koettlitz Glacier appears to be more likely, with absence of far-travelled erratics such dolerites or sandstones, that are widespread on the east side of Brown Peninsula, suggesting that ice during the LGM did not flow over Brown Saddle into Walcott Bay (Anderson et al., 2017). Recent LGM ice-flow reconstruction (Anderson et al., 2017), and also the results of this work are partially in contrast with the early McMurdo Sound models of Stuiver (1981) and Denton and Hughes (2000). The main debatable question is the occurrence of anorthoclase-phyric phonolite in the coastal drift of RSR foothills. The only known outcrop of this rock is in the western coast of Ross Island. However, the presence of anorthoclase-phyric phonolite erratics at Black Island (Anderson et al., 2017) and clasts from Quaternary sequences of AND-1B drillcore, associated with detrital clasts belonging to rocks located in the Skelton and Mulock Glaciers area (McKay et al., 2012; Talarico et al., 2012), suggests a grounded ice sheet flowed from the south into McMurdo Sound during past glacial periods. This aspect suggests a possible source other than western Ross Island for this kind of rock, thus far undetected in the region. Alternatively, multicycle erosion may have occurred, with initial erosion of phonolites, transport south of Ross Island, and successive glacial transport into the western portion of McMurdo Sound (i.e., RSR foothills). This second hypothesis has no evidence in data presented here, since any reworking features have been found in the entire dataset. Moreover, the lithological composition of the three analyzed granulometric fractions is very homogeneous and there are not significant differences between grain sizes for each sample. Thus, glacial transport of the analysed deposits may have occurred as a single ice advance, with no grain size variability except for the selective erosion of the source rocks.

6. Conclusions

New petrographic data presented here provide evidences that lithological composition of Ross Sea 1 Drift supports a glacial transport from a grounded ice sheet from Ross Sea in Taylor Valley and RSR foothills during the LGM.

Taylor Valley samples composition reflect a distal west-northwestward ice flow from an expanded Ross Ice Sheet, able to transport detritus from southern regions. Instead, clast composition recovered from RSR tills predominantly shows source rocks which crop out in the region between Mackay and Koettlitz glaciers. This implies a different transport pathway, related to an expanded Koettlitz Glacier lobe over sites of deposition, unable to carry far-travelled erratics from regions located further south such as Skelton and Murlock glaciers catchments. The reconstruction that provide for an expanded lobe of Koettlitz Glacier advancing northward, at least to Marshall Valley, during the LGM is consistent with trachytoid volcanic lithic fragments recovered from Ross Sea 1 Drift tills in the coast facing RSR. This scenario is in accordance with latest geomorphological and chronological studies and accounts for a local input of flowing ice at least in an early stage during LGM. On the contrary, the hypothesis of a southwestward flowing ice from Ross Island, as interpreted by early studies on LGM ice setting in the region, does not match with data presented here.

The lithological composition of Trilogy Drift (middle Quaternary) from Wright Valley reflect local sources, possibly due to a thickening of the Wilson Piedmont Glacier, as happened during the LGM, that reduced glacial transport of high quantities of volcanic lithics from volcanic centers across McMurdo Sound.

The lack of significant differences in the lithological composition suggests that there was no differentiation due to the particle size and no different transport mechanism involved the three analyzed granulometric fractions. This aspect, together with the absence of reworking features, suggest an homogeneous transport mechanism related to a single ice advance.

New petrographic data presented here are in good agreement to the latest ice flow reconstructions in McMurdo Sound during the LGM. These results suggest the alternating role of local glaciers and grounded EAIS advances, thus allowing the possibility of a multi stages scenario occurred during the LGM and the following deglaciation.

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FIGURE CAPTIONS

Figure 1. Simplified geologic map of the southern Victoria Land in Antarctica. The red boxes refer to the sampling areas (the same are enlarged in Figure 3). (A): Wright and Taylor valleys; (B): foothills of the Royal Society Range (RSR). Geologic map is taken from Sandroni and Talarico (2011) and Cox et al. (2012).

Figure 2. Geological map of the areas from the two boxes (A and B) shown in Figure 1, with sampling sites location and simplified legend. Maps from Cox et al. (2012). Deposits from which samples were taken are also shown, following the nomenclature given by Cox et al. (2012).

Figure 3. (A) Lateral moraines of the Trilogy Drift on the north wall of the lower Wright Valley (arrows). (B) Detail of the sampled surface with scattered clasts of different lithologies. (C) Diamicton facies of Ross Sea 1 Drift from Marshall Valley incised stream, underlain by bedrock. (D) Cobbles of granitoids and plagioclase-phyric intermediate volcanites from the same site. Hammer is about 30 cm long, while shovel is 1 m long.

Figure 4. Relative distribution of lithologies in 4-2-mm fraction petrographic analysis. n: total number of analyzed clasts.

Figure 5. (A) QFL diagram and (B) L_m-L_{g+m}-L_v diagram for 2 mm-425 µm point counting petrographic analysis. L_m= mafic intrusive lithic fragments; L_{g+m}= granitoids and metamorphic lithic fragments; L_v= volcanic lithic fragments. Data are normalized to 100.

Figure 6. Representative photomicrographs of volcanic clasts recovered in Ross Sea Drift samples. (A) microporphyritic clinopyroxene-olivine ipocrystalline basaltic clasts (plane polarized light, PPL, Walcott Bay sample); (B) microporphyritic sanidine-plagioclase-brown amphibole intermediate clast (crossed polarized light, XPL, Marshall Valley sample) (C) olocrystalline trachytic feldspars-green clinopyroxenes felsic clast (PPL, Marshall Valley sample); (D) same lithology as C (XPL, Marshall Valley sample).

Figure 7. (A) Pyroxenes diagram of analyzed clasts from Ross Sea Drift. Coloured fields show pyroxenes chemical composition of the Erebus Volcanic Province (after Gamble et al. 1986, light blue) and from the Ferrar Province (after Haban and Elliot 1985, grey). (B) Feldspar ternary diagram of analyzed clasts. Abbreviations: V= volcanic lithic fragments; B= metamorphic and intrusive lithic fragments.

Figure 8. Calcic-amphiboles classification (Leake et al., 1997) for Ross Sea Drift clasts. Coloured fields are amphibole compositions from known bedrock sources (Talarico et al., 2011, 2013): yellow=Skelton-Mulock glacier area; purple=Southern Victoria Land granitoids; green: Britannia Range area. Circled spots are kaersutite amphiboles ($(Na+K)_A \geq 0.50$ and $Ti > 0.50$ a.p.f.u.).

Figure 9. Ice-flow reconstruction in McMurdo Sound during the LGM, based on the results of Wilson (2000), Anderson et al. (2017) and petrographic data from this study. Yellow points are location of sampling sites. Orange lines show the limit of Ross Sea 1 Drift (Denton and Marchant, 2000; Cox et al., 2012), while purple line marks the limit of Trilogy Drift in Wright Valley (Hall and Denton, 2005). Location of AND-1B is shown.

Table captions

Table 1. List of analyzed samples. Abbreviations follow the legend of geologic map from Cox et al. (2012): ur3- Ross Sea 3 Drift; ur1-Ross Sea 1 Drift; uk1-Ross Sea 1 Drift lacustrine facies. Ages are from Denton and Marchant, (2000) and Hall and Denton, (2005). Samples are shown labelled elsewhere in the text. Samples marked with an asterisk have been analyzed with SEM-EDS.

Area	Sample	Label	Latitude	Longitude	Deposit	Age
Lower Wright Valley	20-01-P1*	20-P1	-77.441	162.534	ur3 (Trilogy)	early-middle Quaternary
Lower Wright Valley	20-01- P2	20-P2	-77.441	162.534	ur3 (Trilogy)	early-middle Quaternary
Lower Wright Valley	20-01- P3	20-P3	-77.441	162.536	ur3 (Trilogy)	early-middle Quaternary
Lower Wright Valley	20-01- P4	20-P4	-77.441	162.536	ur3 (Trilogy)	early-middle Quaternary
Lower Taylor Valley	20-01-P10A	20-P10A	-77.562	163.400	ur1	LGM
Lower Taylor Valley	22-01- P14	22-P14	-77.564	163.425	ur1	LGM
Lower Taylor Valley	22-01-P15*	22-P15	-77.564	163.425	ur1	LGM
Lower Taylor Valley	22-01- P16	22-P16	-77.564	163.425	ur1	LGM
Lower Taylor Valley	23-01- P1	23-P1	-77.589	163.371	uk1	LGM
Lower Taylor Valley	23-01- P2	23-P2	-77.589	163.371	uk1	LGM
Lower Taylor Valley	23-01- P3	23-P3	-77.589	163.361	uk1	LGM
Lower Taylor Valley	23-01- P4	23-P4	-77.589	163.361	uk1	LGM
Lower Taylor Valley	23-01- P5	23-P5	-77.589	163.361	uk1	LGM
Lower Taylor Valley	23-01- P6	23-P6	-77.589	163.361	uk1	LGM
Marshall Valley	21-01-P19*	21-P19	-78.067	164.315	ur1	LGM
Marshall Valley	21-01-P21*	21-P21	-78.067	164.315	ur1	LGM
Miers Valley	21-01-P16*	21-P16	-78.111	164.124	ur1	LGM
Walcott Bay (Howchin Glacier)	21-01-P14*	21-P14	-78.216	163.492	ur1	LGM
Walcott Bay (Howchin Glacier)	21-01-P15A	21-P15A	-78.216	163.492	ur1	LGM

Table 2. Lithological composition of clasts from >4 mm granulometric fraction. Values are expressed as percentage related to the total number n of recovered clasts. Classification based on macroscopic appearance. Abbreviations are Lc: medium to fine grained isotropic to slightly foliated leucogranite; Mg: medium to fine grained, isotropic to slighlty foliated monzogranite to monzonite; Mic: microgranitoid; Ig: intermediate granitoid (medium to fine grained granodiorite to qtz-diorite); Dol: dolerite/microgabbro; Md: microdiorite; Or: foliated granitoid/ orthogneiss; Ss: schist; Bas: basalt; Por: Basic or intermediate porphyry and lamprophyre; Q: quartzite; San: sandstone; Ls: loose sediments; Vc: volcanoclastic.

AREA	Sample ID	Lc	Mg	Mic	lg	Dol	Md	Or	Ss	Bas	Por	Q	San	Silt	Ls	Vc	ND	n
Wright Valley	20-P1	7.9	24.9	6.6	28.7	4.4	17.7	0.0	7.3	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	317
	20-P2	31.6	19.6	0.0	5.6	3.2	4.8	17.2	14.4	0.0	1.2	0.0	0.0	0.0	0.0	0.0	2.4	250
	20_P3	23.3	21.4	0.0	19.8	7.3	19.8	2.7	0.0	5.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	262
	20-P4	17.2	17.2	0.0	27.6	0.0	17.2	0.0	6.9	10.3	3.4	0.0	0.0	0.0	0.0	0.0	0.0	29
Taylor Valley	20-P10A	7.3	3.0	0.0	4.3	0.0	4.6	0.3	0.0	4.6	0.0	0.0	0.3	3.6	0.3	69.9	1.7	302
	22-P14	13.3	29.1	3.9	15.1	9.5	4.9	1.4	0.0	20.7	0.4	0.0	0.0	0.0	0.0	1.8	0.0	285
	22-P15	30.4	12.0	0.0	10.5	13.6	11.0	0.5	0.0	20.4	0.0	0.0	0.0	1.0	0.0	0.0	0.5	191
	22-P16	24.7	23.5	0.0	12.7	13.9	5.4	0.6	0.0	18.1	0.0	1.2	0.0	0.0	0.0	0.0	0.0	166
	23-P1	16.7	11.3	3.0	16.1	12.1	2.0	7.7	0.0	24.8	3.0	0.0	0.0	0.0	0.0	1.4	2.0	504
	23-P2	36.5	4.7	1.2	14.1	11.8	10.6	1.2	0.0	12.9	7.1	0.0	0.0	0.0	0.0	0.0	0.0	85
	23-P3	13.9	5.2	1.7	11.3	13.9	0.0	0.9	0.0	16.5	1.7	0.0	0.0	0.0	0.0	0.0	34.8	115
	23-P4	32.	6.7	8.	8.0	13.	8.0	0.0	0.0	20.	4.	0.	0.	0.	0.	0.0	0.0	75

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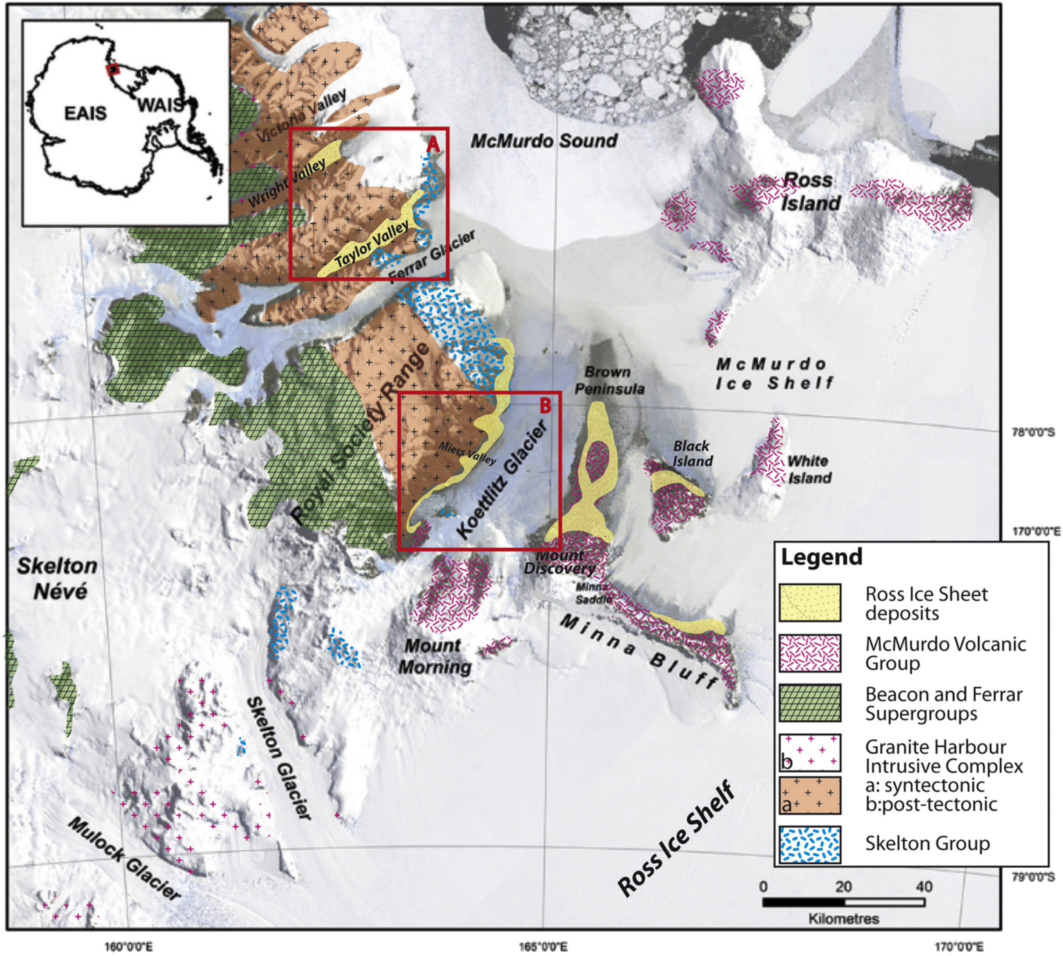
	23-P5	19.2	26.0	1.4	13.7	1.4	0.0	0.0	0.0	17.8	2.7	0.0	0.0	0.0	0.0	6.8	11.0	73
	23-P6	7.9	13.5	0.0	20.2	16.9	3.4	18.0	1.1	15.7	2.2	0.0	0.0	0.0	0.0	0.0	1.1	89
Marshall Valley	21-P19	18.5	23.1	0.0	6.8	4.0	4.0	2.2	0.0	32.0	0.6	0.0	0.0	0.0	0.0	0.3	5.8	325
	21-P21	15.8	11.1	7.1	5.1	2.0	0.0	2.8	0.0	53.8	0.4	0.0	0.0	0.0	0.0	0.0	1.6	253
Miers Valley	21-P16	3.8	0.0	0.0	0.0	0.0	0.0	0.0	1.9	90.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53
Walcott Bay	21-P14	12.5	18.7	4.5	5.3	0.0	4.6	1.0	1.5	46.2	0.2	0.0	0.0	0.0	0.0	0.0	4.8	582
	21-P15A	0.0	23.3	1.9	0.0	0.0	0.0	0.0	0.6	58.5	0.0	0.0	0.0	0.0	0.0	2.5	13.2	159
																		4115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Brown Peninsula
McMurdo Ice Shelf
Black Island
White Island
Skelton Névé
Mount Discovery
Minna Saddle
Mount Morning
Minna Bluff
Skelton Glacier
Mulock Glacier
Ross Ice Shelf
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79°0'0"S
160°0'0"E
165°0'0"E
170°0'0"E
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40
Kilometres
Legend
Ross Ice Sheet deposits
McMurdo Volcanic Group
Beacon and Ferrar Supergroups
Granite Harbour Intrusive Complex
a: syntectonic
b:post-tectonic
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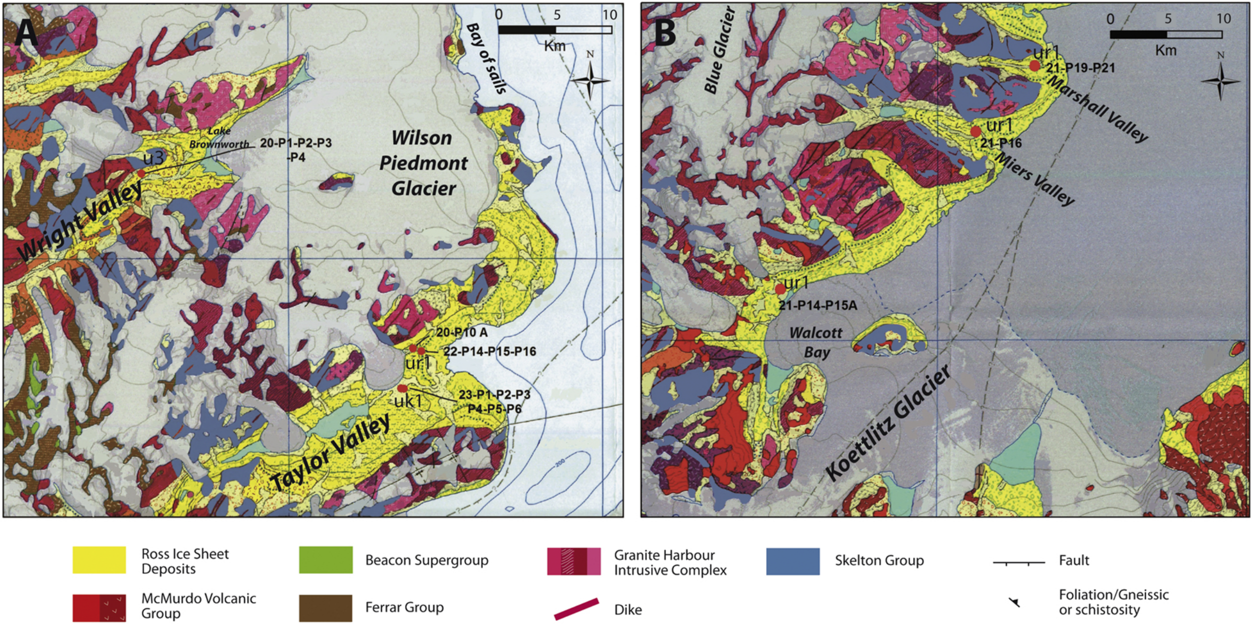
Skelton Group

Figure 1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Taylor Valley
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B
Blue Glacier
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Marshall Valley
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Miers Valley
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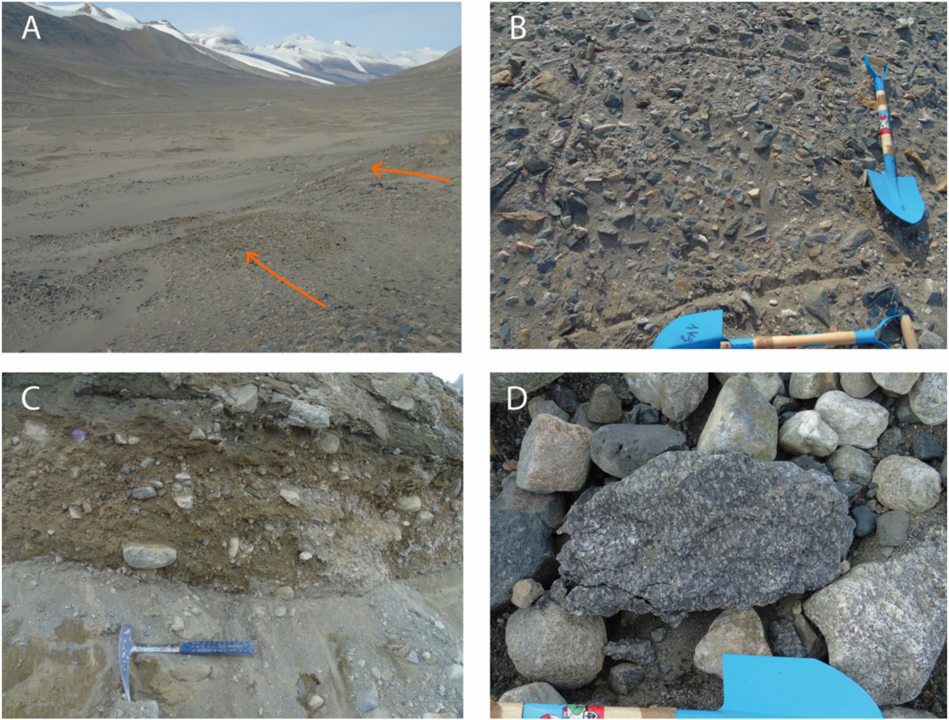
Walcott Bay
Koettlitz Glacier
Ross Ice Sheet Deposits
McMurdo Volcanic Group
Beacon Supergroup
Ferrar Group
Granite Harbour Intrusive Complex
Dike
Skelton Group
Fault
Foliation/Gneissic or schistosity

Figure 2



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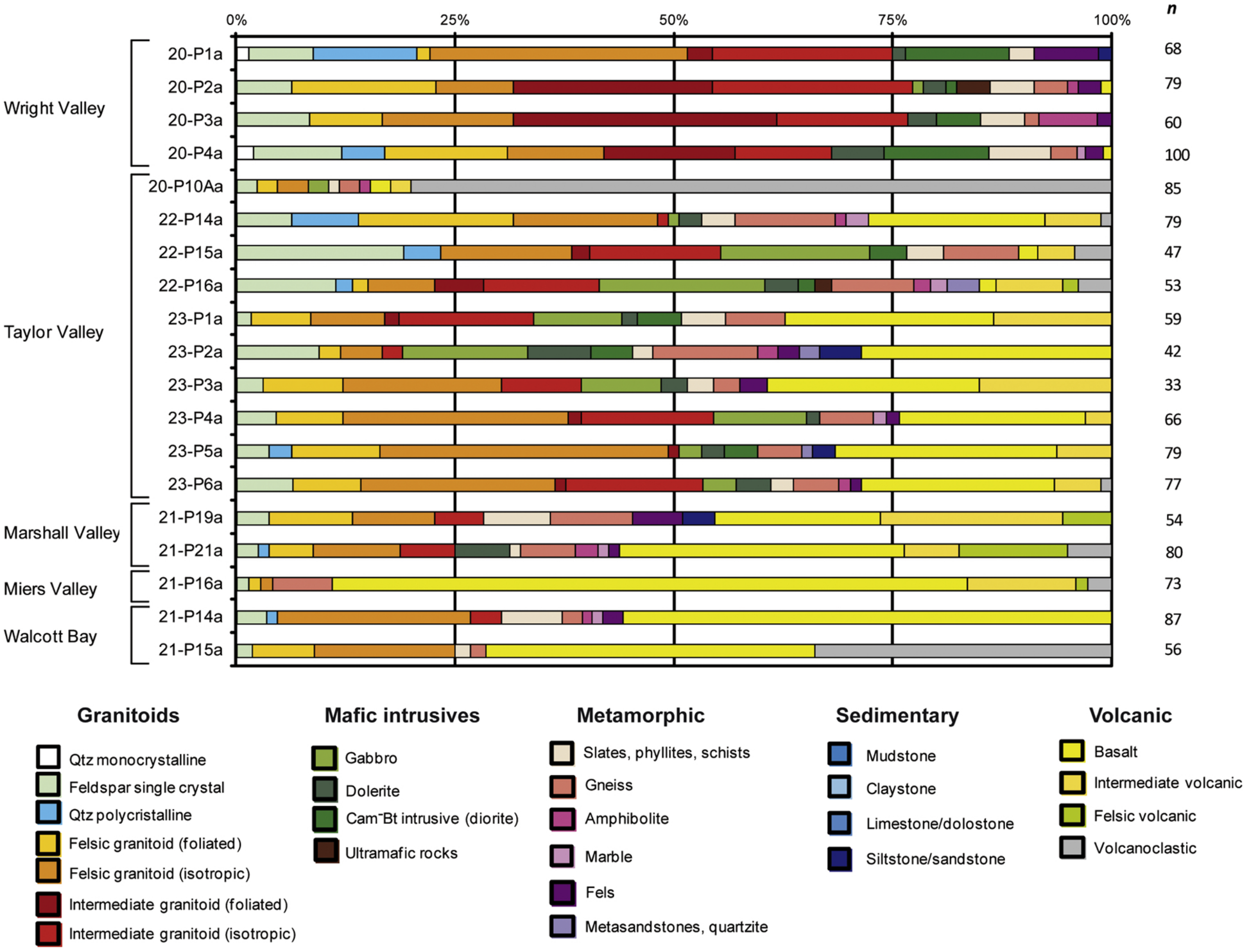
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Marshall Valley
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Granitoids
Qtz monocrystalline
Feldspar single crystal
Qtz polycristalline
Felsic granitoid (foliated)
Felsic granitoid (isotropic)
Intermediate granitoid (foliated)
Intermediate granitoid (isotropic)
Mafic intrusives
Gabbro
Dolerite
Cam-Bt intrusive (diorite)
Ultramafic rocks
Metamorphic
Slates, phyllites, schists
Gneiss
Amphibolite
Marble
Fels
Metasandstones, quartzite
Sedimentary
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Claystone
Limestone/dolostone
Siltstone/sandstone
Volcanic
Basalt
Intermediate volcanic
Felsic volcanic
Volcanoclastic

Figure 4

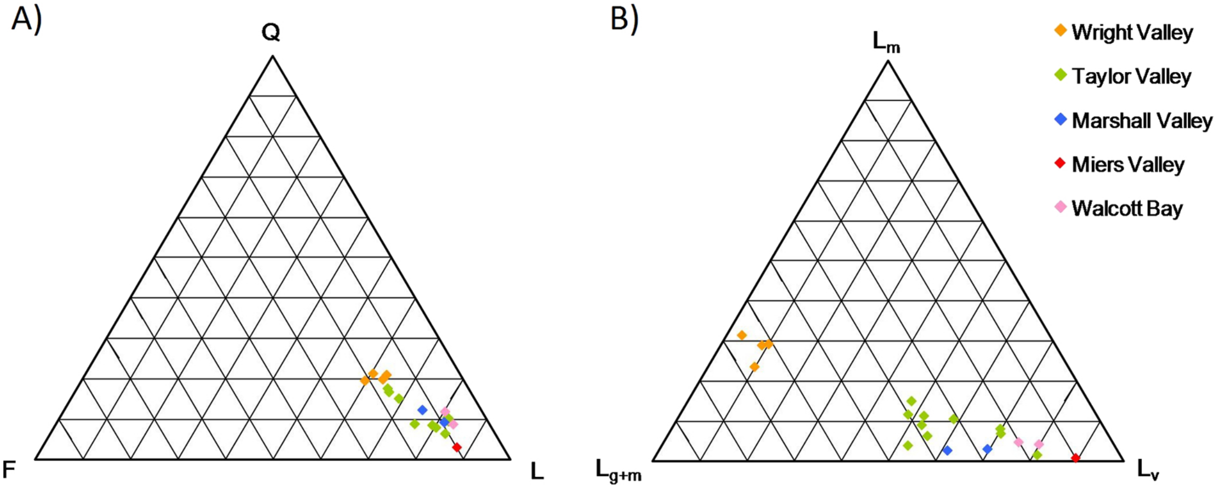
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Figure 5

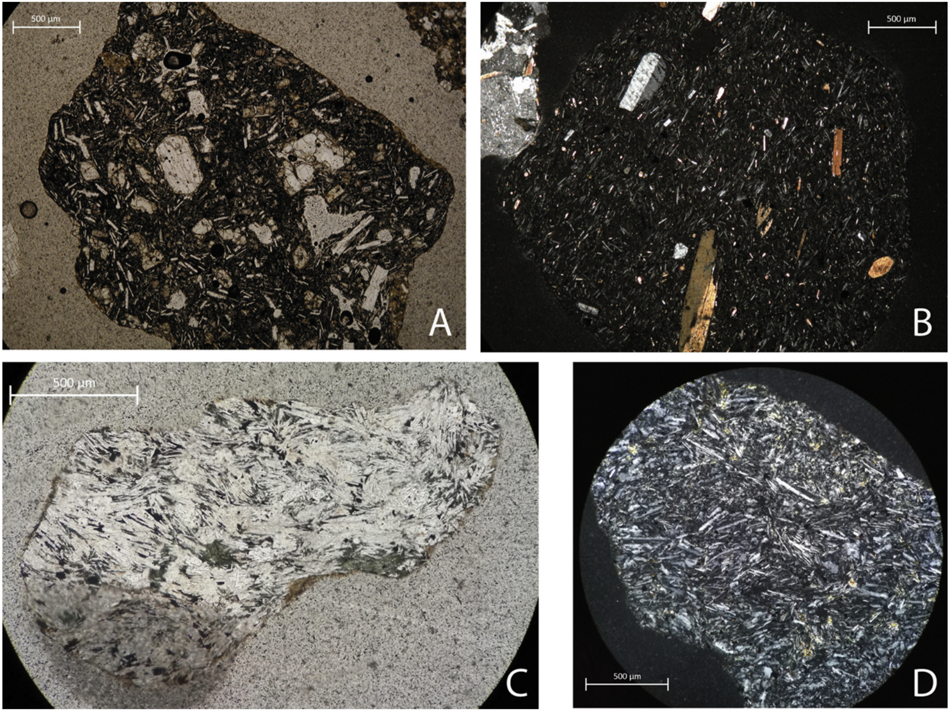

Figure 6

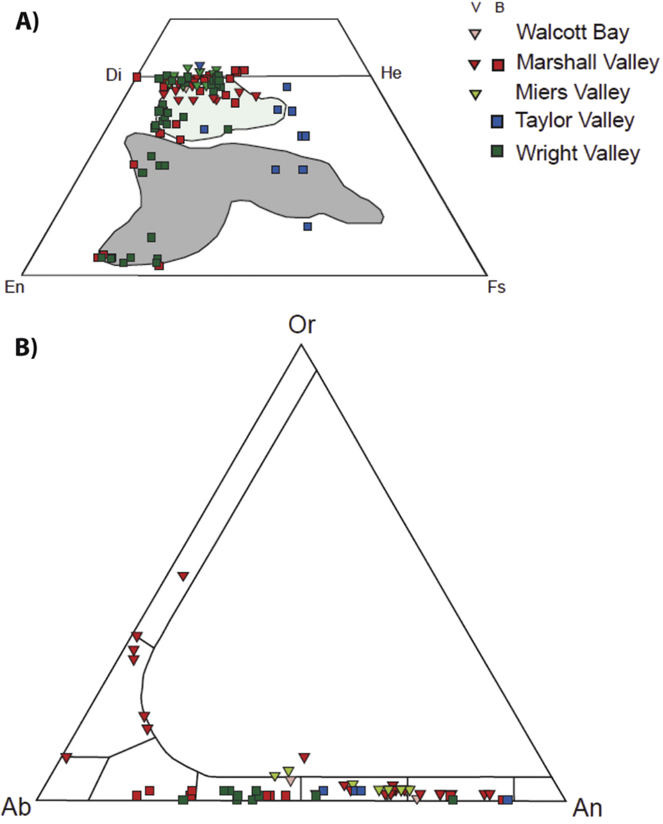
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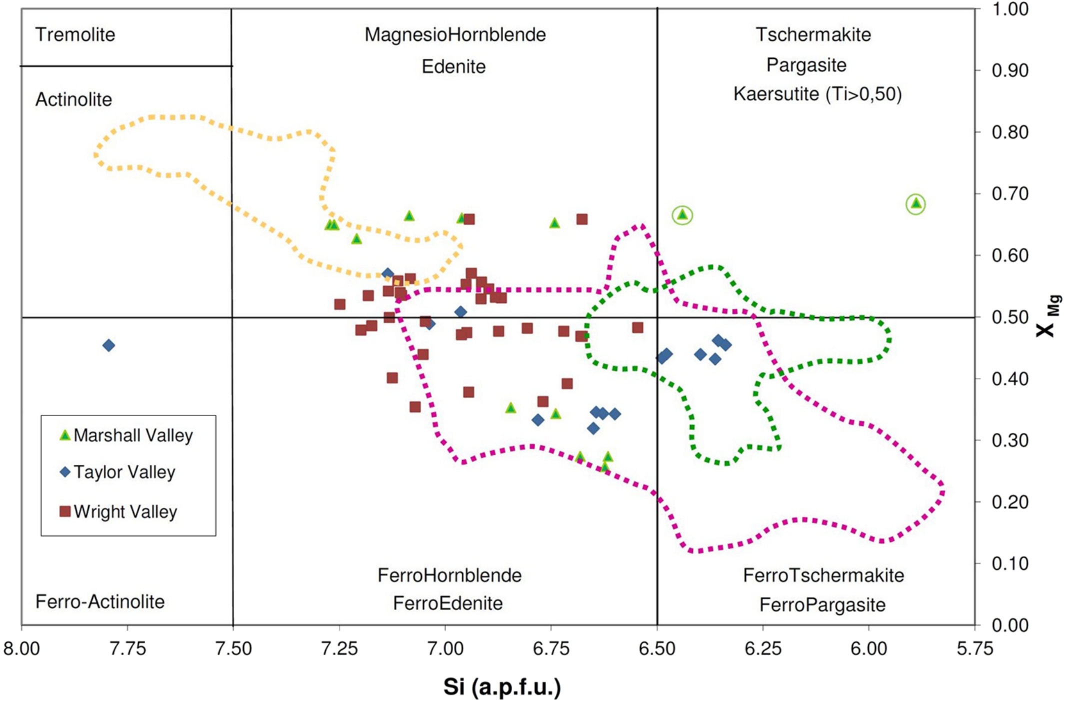
Figure 7


Tremolite
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MagnesioHornblende
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Pargasite
Kaersutite (Ti>0,50)
Ferro-Actinolite
FerroHornblende
FerroEdenite
FerroTschermakite
FerroPargasite
▲ Marshall Valley
◆ Taylor Valley
■ Wright Valley
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
X Mg
8.00
7.75
7.50
7.25
7.00
6.75
6.50
6.25
6.00
5.75
Si (a.p.f.u.)

Figure 8

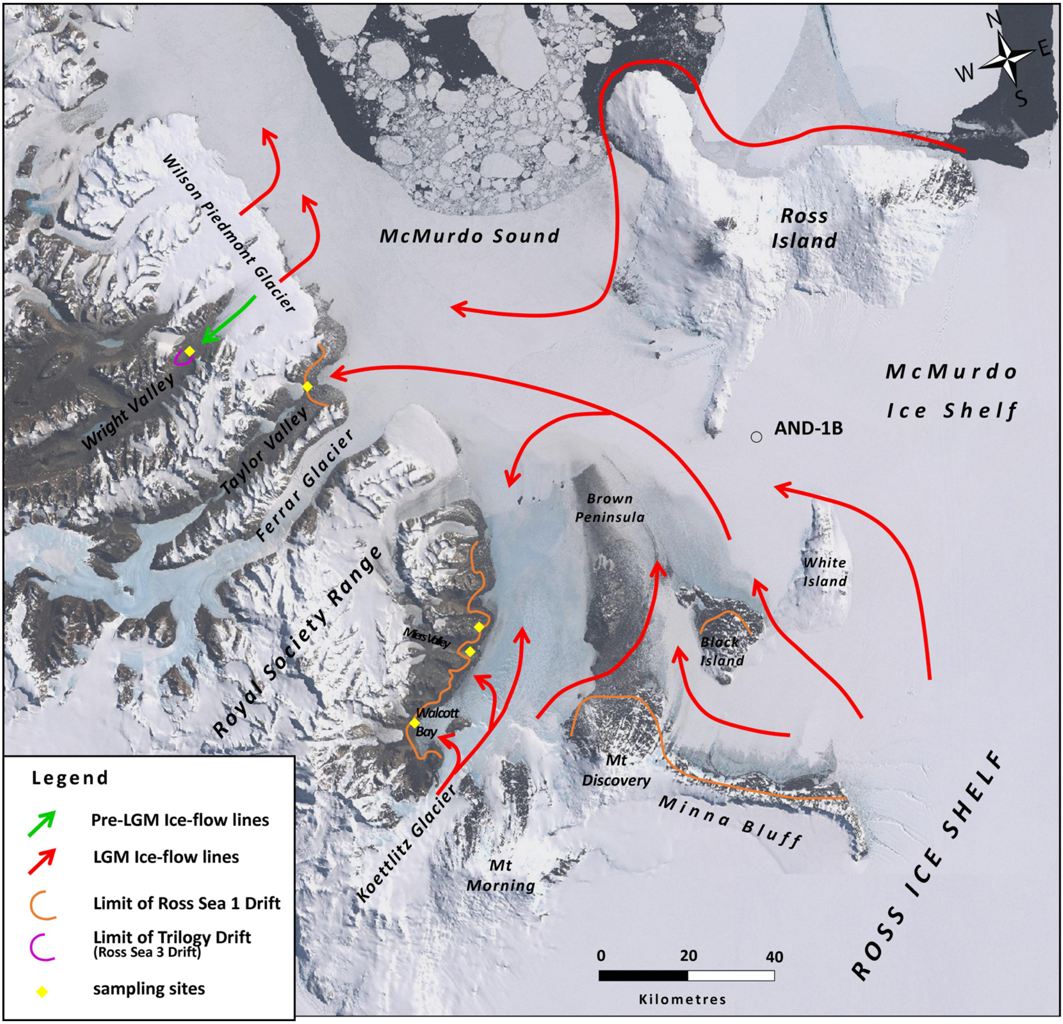
N
W
E
S
Wilson Piedmont Glacier
McMurdo Sound
Ross Island
McMurdo Ice Shelf
AND-1B
Wright Valley
Taylor Valley
Ferrar Glacier
Brown Peninsula
White Island
Black Island
Royal Society Range
Miers Valley
Walcott Bay
Mt Discovery
Minna Bluff
Koettlitz Glacier
Mt Morning
ROSS ICE SHELF
0
20
40
Kilometres
Legend
Pre-LGM Ice-flow lines
LGM Ice-flow lines
Limit of Ross Sea 1 Drift
Limit of Trilogy Drift (Ross Sea 3 Drift)
sampling sites

Figure 9