Applied Geochemistry 107 (2019) 91–104

Contents lists available at ScienceDirect

Applied Geochemistry

journal homepage: www.elsevier.com/locate/apgeochem

The geochemistry of glacial deposits in Taylor Valley, Antarctica: Comparison to upper continental crustal abundances

Carolyn B. Dowling[a], Susan A. Welch[b,c,*], W. Berry Lyons[b,c]

[a] Department of Geological Sciences, Ball State University, 2000 West University Ave, Muncie, IN, 47306, USA
[b] School of Earth Sciences, Ohio State University, 125 South Oval Mall, Columbus, OH, 43210, USA
[c] Byrd Polar and Climate Research Center, Ohio State University, 108 Scott Hall, Columbus, OH, 43210, USA

ARTICLE INFO

Editorial handling by Prof. M. Kersten

Keywords:
polar dry-based glaciers
Geochemistry
Glacial deposits
Taylor valley
Antarctica

ABSTRACT

Wet-based glacial deposits have been used traditionally as an analog for upper continental crust (UCC) abundances. To provide more information on the validity of using glacial deposits from wet-based glaciers, samples deposited by the dry-based polar glaciers located in Taylor Valley, Antarctica, were collected. Stream channel sediments, comprised of igneous, metamorphic, and sedimentary rocks initially deposited as glacial tills by polar glaciers, were analyzed by XRF, ICP-MS, and SEM. Based on the Chemical Index of Alteration values and A–CN–K ternary diagram, there are low levels of chemical weathering in these tills. Additionally, major and trace element geochemical data are compared to the average UCC values. The observed discrepancies between the mean UCC and Antarctic samples develop from the existence of mafic components, most likely the McMurdo Volcanic Group and Ferrar Dolerite, being present in the Taylor Valley tills. Even though the mafic material typically comprises 3–7% of the till, the volcanic rocks have a significant influence on the tills' bulk geochemistry. The existence of this mafic fraction in the dry-based glacial tills results from the reduced rate of weathering, as compared to wet-based glaciers. Geochemical analyses of the dry-based glacial tills in polar deserts, such as those found in Taylor Valley, may provide a better representative composition of the original material than wet-based glaciers and need to be incorporated into upper continental crust calculations.

1. Introduction

Determining the chemical composition of various components of the Earth has been a fundamental quest of modern geochemistry. Some of the earliest attempts to define the chemical composition of the crust were by Daly (1914) and Clarke and Washington (1924). Some of the latest compilations were presented by Taylor and McLennan (1985), Wedepohl (1995), Rudnick and Gao (2005), and Hu and Gao (2008). Goldschmidt (1933) analyzed the fine-grained fraction of Pleistocene glacial till from Norway to determine an estimate of crustal composition. Faure (1998) noted that these fine-grained tills described by Goldschmidt (1933) have less Ca and Na than other crustal composition estimates and speculated that this was due to chemical weathering. Additionally, Goldschmidt's tills are also poorer in Ti, which may reflect regional differences in bedrock lithogies (Faure, 1998) or chemical weathering (Young and Nesbitt, 1998). More recent studies from the Canadian Cordillera have shown that till-based crustal abundances can yield both marked elemental enrichments and depletions compared to other compilations (Canil and Lacourse, 2011). Tills containing small amounts of basaltic rocks may lead to these discrepancies as suggested by Nesbitt and Young (1996) and Canil and Lacourse (2011).

Even though later work confirmed that glacial deposits are a good representation of the chemistry of the upper crustal bedrock materials, especially if differential transport and sorting are taken into account (Nesbitt and Young, 1996), the geochemical compilations typically use geochemical data from wet-based glaciers (Daly, 1914; Clarke and Washington, 1924; Goldschmidt, 1933; Wedepohl, 1995; Rudnick and Gao, 2005; Hu and Gao, 2008). It has been observed that chemical weathering in a polar dry-based (i.e., frozen to the base) glacial system (Scott Turnerbreen Glacier, Svalbard, Norway) is significantly lower than weathering rates observed in wet-based and polythermal glacial regions (e.g., Eyles et al., 1982; Hodgkins et al., 1997), implying that tills from dry-based glaciers would provide a more accurate representation of the upper continental crust composition. Lower chemical weathering rates lead to the persistence of minerals that are more susceptible to chemical weathering (e.g., olivine) and must be accounted for within the upper continental crust geochemical compilations. Unfortunately, there is a paucity of data on the chemical

* Corresponding author. School of Earth Sciences, Ohio State University, 125 South Oval Mall, Columbus, OH, 43210, USA.
E-mail addresses: cbdowling@bsu.edu (C.B. Dowling), welch.318@osu.edu (S.A. Welch), lyons.142@osu.edu (W.B. Lyons).

https://doi.org/10.1016/j.apgeochem.2019.05.006
Received 13 December 2018; Received in revised form 14 May 2019; Accepted 15 May 2019
Available online 17 May 2019
0883-2927/

composition of polar glacial deposits.

In this paper, we have analyzed a series of stream channel sediments, which were originally deposited as tills by dry-based polar glaciers, from Taylor Valley, Antarctica (77–78°S) to evaluate how their geochemical composition compares to the average upper crustal abundances. Stream channel sediments were sampled instead of soils because Antarctic soils can accumulate large concentrations of salts, depending on their landscape position (Ugolini and Jackson, 1982; Gibson et al., 1983; Bockheim, 1997; Bisson et al., 2015). For the most part, the ephemeral stream channel materials retain no salts, as the meltwater streams flow in the austral summer. Thus, the bulk geochemistry of the surface channel sediments represent a better measure of the chemistry of the tills, as they are unaffected by salt accumulation and intense chemical weathering. This investigation was performed to both further our understanding of the geochemistry of tills as well as to provide more information on the validity of using glacial deposits from both dry-based and wet-based glaciers as upper continental crustal geochemistry analogs.

2. Study area

2.1. Taylor Valley geology

The bedrock in Taylor Valley consists of igneous, metamorphic, and sedimentary units that include Precambrian to early Paleozoic metasediments, granites and granodiorites, and Paleozoic-early Mesozoic sedimentary rocks (Haskell et al., 1965). Jurassic-age dolerite sills intrude both the metasedimentary-igneous basement complex and the younger sedimentary rocks, and lamprophyre and porphyry dikes intrude the basement complex. In addition, McMurdo Volcanic rocks of Neogene age occur at higher elevations in central Taylor Valley (Wright and Kyle, 1990). There are considerable geochemical data published on the McMurdo Volcanic Group (Gunn, 1966; Kyle, 1981; Allibone et al., 1993; Cooper et al., 2007).

The Pleistocene geologic history of Taylor Valley is well documented (Hall et al., 2000; Higgins et al., 2000). During interglacial periods, the East Antarctic Ice Sheet (EAIS) moves west to east, down valley (towards McMurdo Sound and Ross Sea); while during glacial times, the West Antarctic Ice Sheet (WAIS) moves northward along the Victoria Land coast. At times around the glacial maximum, the WAIS intrudes up valley into the eastern portion of the Taylor Valley (Hall et al., 2000). Kenyte, a rare phonolite that does not outcrop in Taylor Valley but occurs on Ross Island to the southeast, is found in eastern Taylor Valley, confirming the movement of WAIS ice into the mouth of the valley and far into the Fryxell basin (Fig. 1) (Stuiver et al., 1981). Thus, the valley floor in the Fryxell basin has deposits (Ross Sea Drift) that are relatively young, deposited during the Last Glacial Maximum, while the tills to the west in the Hoare and Bonney basins (Bonney Drift) have been thought to be much older, deposited during the previous interglacial period (Hall et al., 2000; Higgins et al., 2000). Recent work does suggest that at least portions of the Hoare basin may also have been influenced by the WAIS (Toner et al., 2013). Both the Ross Sea Drift (younger, eastern deposits) and the Bonney Drift (older, central and western deposits) contain ≤5% fine-grained material (Hall et al., 2000). The petrology of the Ross Sea Drift is dominated by diorite and granite, but kenyte (0–3.8%), marble (0.6–4.9%), Ferrar Dolerite (12.6–15.2%), and McMurdo Volcanic Group rocks (3.3–21.5%) are also measurable (Hall et al., 2000). The Bonney Drift is dominated by granodiorite/granite-gneiss/diorite with smaller amounts of Ferrar Dolerite (12.4%). The percentage of the marble (1.8%) is approximately half that of Ross Drift (0.6–4.9%) (Hall et al., 2000). The McMurdo Volcano Rocks (6.9%) in the Bonney Drift are derived from the

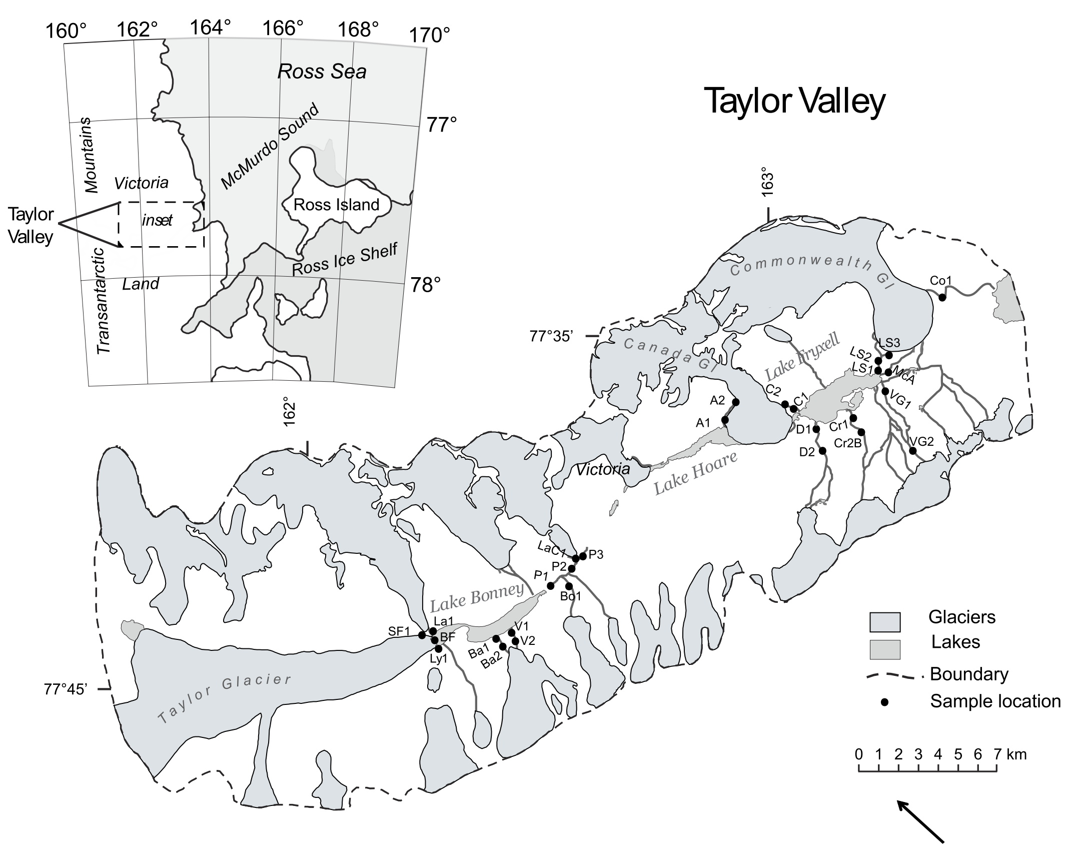

Fig. 1. The location of the sediment samples in Taylor Valley, McMurdo Dry Valleys, Antarctica. The label abbreviations are located in Table 1. The North direction is arbitrary and used for simplicity. Taylor Valley is divided into individual basins: McMurdo Sound, Lake Fryxell, and Lake Hoare in Eastern Taylor Valley and West and East Lake Bonney basins in Western Taylor Valley.

weathering of the volcanic outcrops of cinder cones and scoriaceous mounds within the Bonney basin when the West Antarctic Ice Sheet flowed into the valley (Wilch et al., 1993; Hall et al., 2000). There is no kenyte in the Bonney Drift (Hall et al., 2000).

2.2. Taylor Valley glaciology

In Taylor Valley, the polar glaciers are dry-based, in which the interior and basal ice are frozen to the ground underneath (Fountain et al., 1998; Atkins and Dickinson, 2007). Unlike the basal sliding of wet-based glaciers, polar glaciers move more slowly because their movement is entirely dependent on gravity and internal deformation. The dry-based glaciers generate little or no rock flour (Nezat et al., 2001). With interior and basal temperatures well below freezing (~ −20 °C), a drainage system cannot develop within the glacier and basal flow cannot occur, as liquid water will freeze in the fractures or underlying sediment (Fountain et al., 1998). Therefore, the subglacial streams that are often observed in wet-based glaciers (either directly or indirectly through depositional features, such as eskers) are not present. During the austral summer, the polar glaciers' runoff is limited to surface or near-surface flow (Fountain et al., 1998; Fortner et al., 2005). The Taylor Valley meltwater streams flow for 4–10 weeks per year, and the stream discharge is highly variable (both daily and annually) (Conovitz et al., 1998; Fountain et al., 1999). Gooseff et al. (2002) demonstrated that the chemical weathering of the surface channel sediments is limited.

3. Methods

The surface stream channel sediments were collected from ephemeral streams throughout Taylor Valley during the 2002/2003 austral summer (Fig. 1). Unlike Antarctica soils, the stream channel sediments do not accumulate salts, as flowing glacial meltwater dissolves the salts.

The streams can be further divided into individual basins. McMurdo Sound, Lake Fryxell, and Lake Hoare are located in Eastern Taylor Valley, and West and East Lake Bonney basins are in Western Taylor Valley. The sediment samples were labeled with the stream name and approximate location relative to the lake. The lowest number (such as Anderson-1) denotes that the sample was collected near or at the mouth of the stream. The sediments were sampled using a polyethylene scoop and stored frozen in plastic storage bags. They were dried and powdered at Byrd Polar Research Center, Ohio State University, using an alumina ceramic Shatterbox. The samples were then sent to XRAL Laboratories (now a division of SGS Canada, a commercial laboratory) to be analyzed for major and trace elements using X-ray Fluorescence spectroscopy (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) according to their standard procedures (pressed pellet and sodium peroxide fusion respectively). To determine the precision of the analytical methods, selected samples were run as duplicates. The standard deviation averages were 0.41% (range: 0.00–1.97%) and 2.38% (range: 0.00–6.76%) for XRF and ICP-MS, respectively. Tin (11.8%), hafnium (14.1%), and tungsten (23.4%) had standard deviations larger than 10% when measured by ICP-MS.

The grain size of each sediment sample was measured at Byrd Polar Research Center, Ohio State University by sieving into fines (< 150 μm), sands (150–2000 μm), and gravels (> 2000 μm) on another aliquot.

For the SEM analyses, aliquots of the sand size fractions from selected samples were mounted on carbon tape on an aluminum stub and coated with gold-palladium using a Denton precious metal coater. Samples were subsequently analyzed using a FEI Quanta 250 FEG scanning electron microscope (SEM) equipped with a Bruker energy dispersive X-ray spectrometer (EDS). Mineralogy of select grains was discerned by comparing relative intensity of the characteristic element X-ray signals from the EDS detector to standard minerals, gray scale level from the back scattered electron detector (BSE), and mineral morphology.

4. Results and discussion

4.1. Grain size distribution

Where previously measured, channel bed sediments in the McMurdo Dry Valleys have median diameters of 4.6 mm (Mosley, 1988). No particles greater than 64 mm were observed, and less than 5% were finer than 0.25 mm (Mosley, 1988). The distribution of particles size varied greatly among the samples though most were dominated by the sand sized fraction (Table 1). In the stream sediments we sampled, the fine fraction (clay and silt; < 150 μm) was equal to or greater than 15% in only four samples: Commonwealth (McMurdo Sound basin) and McKnight (Fryxell basin) streams in the eastern valley and in Priscu-3 (upstream) and Santa Fe in the Bonney basin. Based on grain-size analyses of our stream channel sediments, most of the sediments are sand-sized (72 ± 21%; 150–2000 μm), and the remainder is composed of gravels (19 ± 22%; > 2 mm) and clay- and silt-sized (9 ± 7%; < 150 μm) (Table 1).

4.2. Elemental values normalized to upper continental crust

The 55 analyzed elements are normalized to upper continental crust composition using the recently compiled data of Rudnick and Gao (2005) and Hu and Gao (2008) (henceforth called the Rudnick/Gao composite), the most current dataset available. Refer to the extensive work done Rudnick and Gao (2005) for in-depth discussions between different UCC datasets. Figs. 2, 3a and 3b illustrate the pattern of the normalized elemental values based on compatibility for the whole valley, Eastern Taylor, and Western Taylor, respectively (Gaillardet et al., 1999). For all 26 sediment samples, the concentrations and normalized values with the standard deviations (calculated by the measured variations in the sediment analyses) are given in Appendices (A-1, A-2, A-3, and A-4). Fig. 3a and b demonstrate the differences between the eastern and western parts of Taylor Valley. Twenty-four elements have values within ± 25% of the mean crustal abundance and hence are in reasonable agreement. Six more incompatible elements (Cs, U, Th, Hf, Zr and Li) have values lower than 25% of the Rudnick/Gao composite. On the other hand, fifteen elements have average normalized concentrations more than 25% of the UCC. Of these, five are between 25 and 50% higher (Pb, Sr, P, Sc, and Nb) and another five are 50–100% higher (Eu, Ca, Co, Mg, and Bi). Finally, an additional five elements are substantially higher than the mean upper crust (Ta, Cr, Ni, Cd, and W). Because of the high standard deviations in the ICP-MS analyses of the Sn, Hf, and W values, we have chosen not to discuss these results in detail. The elements showing higher than mean crustal values can be divided into two groups: i) Ca and elements that can be partitioned into Ca-rich minerals as well as Sr and Eu, and ii) compatible elements such as Ti, Fe, Co, Mg, Cr, Ni, and Sc. Overall, Eastern Taylor Valley has higher values of certain elements, such as Ba, La, Zr, Sr, and Ti, as compared to west (Fig. 3).

As noted above, Hall et al. (2000) evaluated the composition of both the Ross Sea and the Bonney Drifts. Granitic/dioritic/granodioritic debris provides up to ~69% and ~59% of the Ross Sea and Bonney Drifts, respectively. The remainder is composed of the McMurdo Volcanic Group (mostly basanites), Ferrar Dolerite and various metamorphic rocks (including marble). Based on these analyses, it might be expected that the sediments/tills should resemble the average upper continental crust based on the Rudnick/Gao composite. The accumulation of chemical weathering products such as smectite, vermiculite, and montmorillonite may lead to an enrichment of some elements (Mg,

Table 1
Particle size distribution and Chemical Index of Alteration of Taylor Valley sediments.

Sample	Map Label	Watershed	Grain size (%)			CIA
			Gravel-sized and larger (> 2 mm)	Sand-sized (150–2000 mm)	Clay- and silt-sized (< 150 mm)	
Eastern Taylor Valley						
Commonwealth-1	Co1	McMurdo Sound	0.1	68.7	31.2	43.1
Canada-1	C1	Fryxell	77.2	19.1	3.8	45.8
Canada-2	C2	Fryxell	0.6s	87.8	11.6	46.6
Lost Seal-1	LS1	Fryxell	32.6	56.4	11.0	48.1
Lost Seal-2	LS2	Fryxell	8.2	79.8	12.0	45.2
Lost Seal-3	LS3	Fryxell	48.4	38.1	13.5	45.9
McKnight-A	McA	Fryxell	0.6	78.6	20.8	43.4
Crescent-1	Cr1	Fryxell	5.6	88.3	6.0	44.5
Crescent-2B	Cr2B	Fryxell	31.5	63.3	5.2	46.4
Delta-1	D1	Fryxell	7.0	88.1	4.9	45.7
Delta-2	D2	Fryxell	7.9	83.3	8.8	44.0
Von Guerard-1	VG1	Fryxell	NA	NA	NA	46.9
Von Guerard-2	VG2	Fryxell	1.6	90.8	7.5	45.9
Anderson-1	A1	Hoare	66.7	30.2	3.1	46.7
Anderson-2	A2	Hoare	19.0	74.2	6.8	43.7
Western Taylor Valley						
LaCroix-1	LaC1	East Bonney	0.9	93.4	5.8	46.8
Barlette-1	Ba1	East Bonney	16.2	80.4	3.3	45.6
Barlette-2	Ba2	East Bonney	2.3	94.6	3.1	42.8
Bohner-1	Bo1	East Bonney	0.9	95.6	3.5	39.0
Priscu-1	P1	East Bonney	NA	NA	NA	45.2
Priscu-2	P2	East Bonney	14.1	76.8	9.1	46.1
Priscu-3	P3	East Bonney	0.0	75.2	24.8	43.2
Vincent-1	V1	East Bonney	0.4	92.3	7.2	42.4
Vincent-2	V2	East Bonney	25.2	68.5	6.3	45.8
Blood Falls	BF	West Bonney	50.0	43.4	6.6	47.3
Lawson-1	La1	West Bonney	8.6	89.0	2.3	41.4
Lyons-1	Ly1	West Bonney	41.1	56.2	2.6	45.0
Santa Fe-1	SF1	West Bonney	32.0	53.4	14.6	48.3

Fe, and Ti) but would not explain the other discrepancies. However, most of the inconsistencies may result from mafic rocks present in the till. Both Nesbitt and Young (1996) and Canil and Lacourse (2011) have observed that small amounts of mafic materials can lead to elemental enrichments. Fig. 4 displays evidence of mafic minerals such as olivine, Ca–Mg–Fe pyroxene and volcanic ash in the sediments, representing the McMurdo Volcanic Group (MVG) and Ferrar Dolerite (FD) in Taylor Valley (Welch et al., 2013).

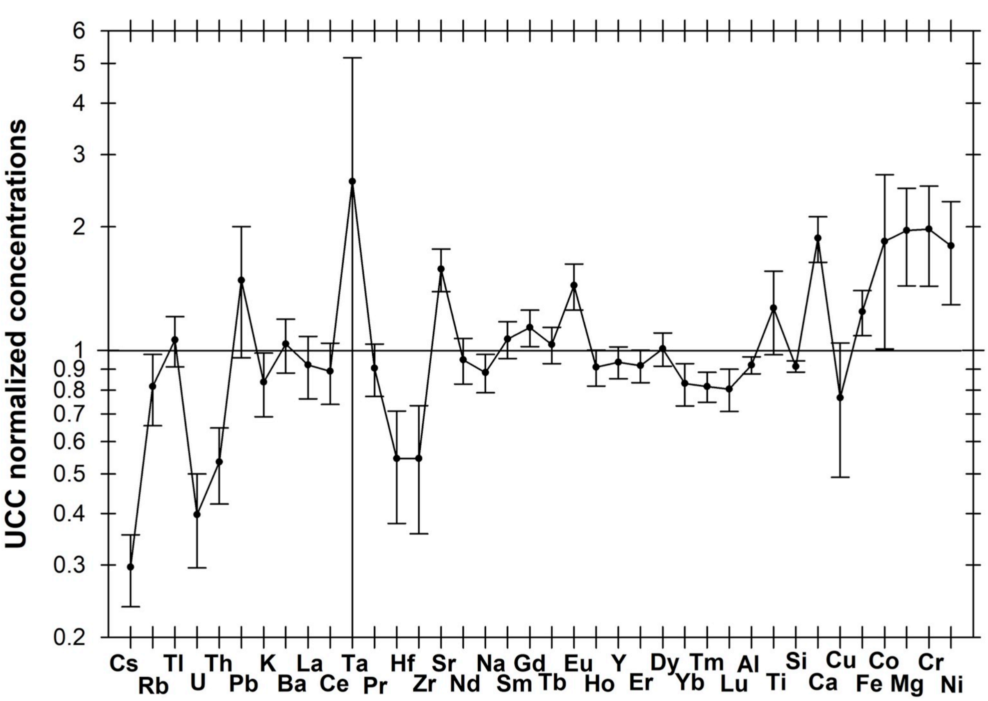

Fig. 2. Upper continental crust (UCC) normalization for stream channel sediments in Taylor Valley, Antarctica. The XRF (Na and Si) and ICP-MS data were normalized to the Rudnick/Gao composite (Rudnick and Gao, 2005; Hu and Gao, 2008). Elements are ranked on the X-axis according to their compatibility (Gaillardet et al., 1999).

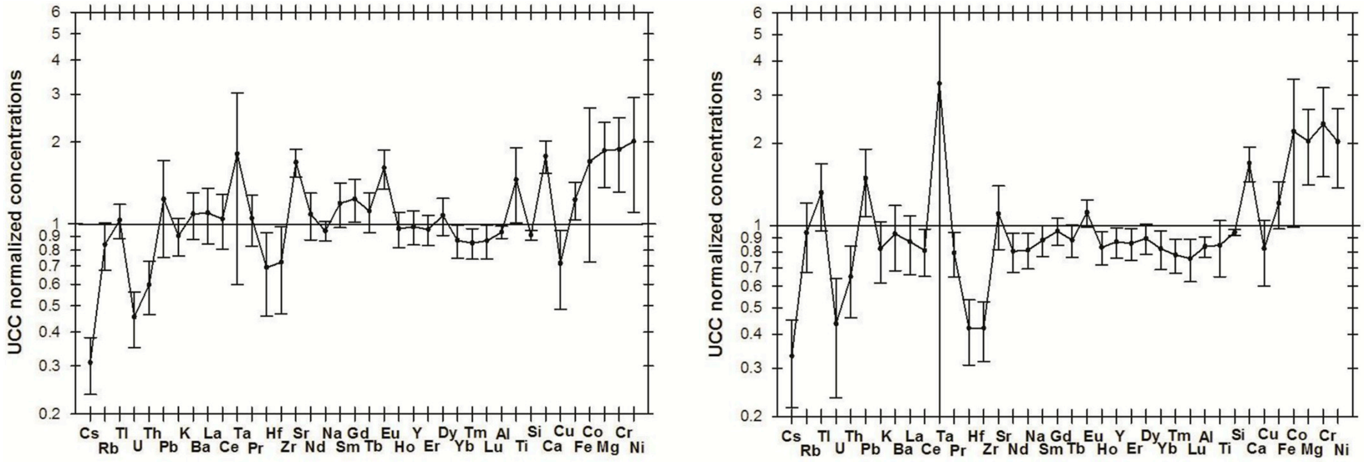

Fig. 3. Upper continental crust (UCC) normalization for stream channel sediments in A) Eastern (left) and B) Western Taylor Valley (right), Antarctica. The XRF (Na and Si) and ICP-MS data were normalized to the Rudnick/Gao composite (Rudnick and Gao, 2005; Hu and Gao, 2008). Elements are ranked on the X-axis according to their compatibility (Gaillardet et al., 1999).

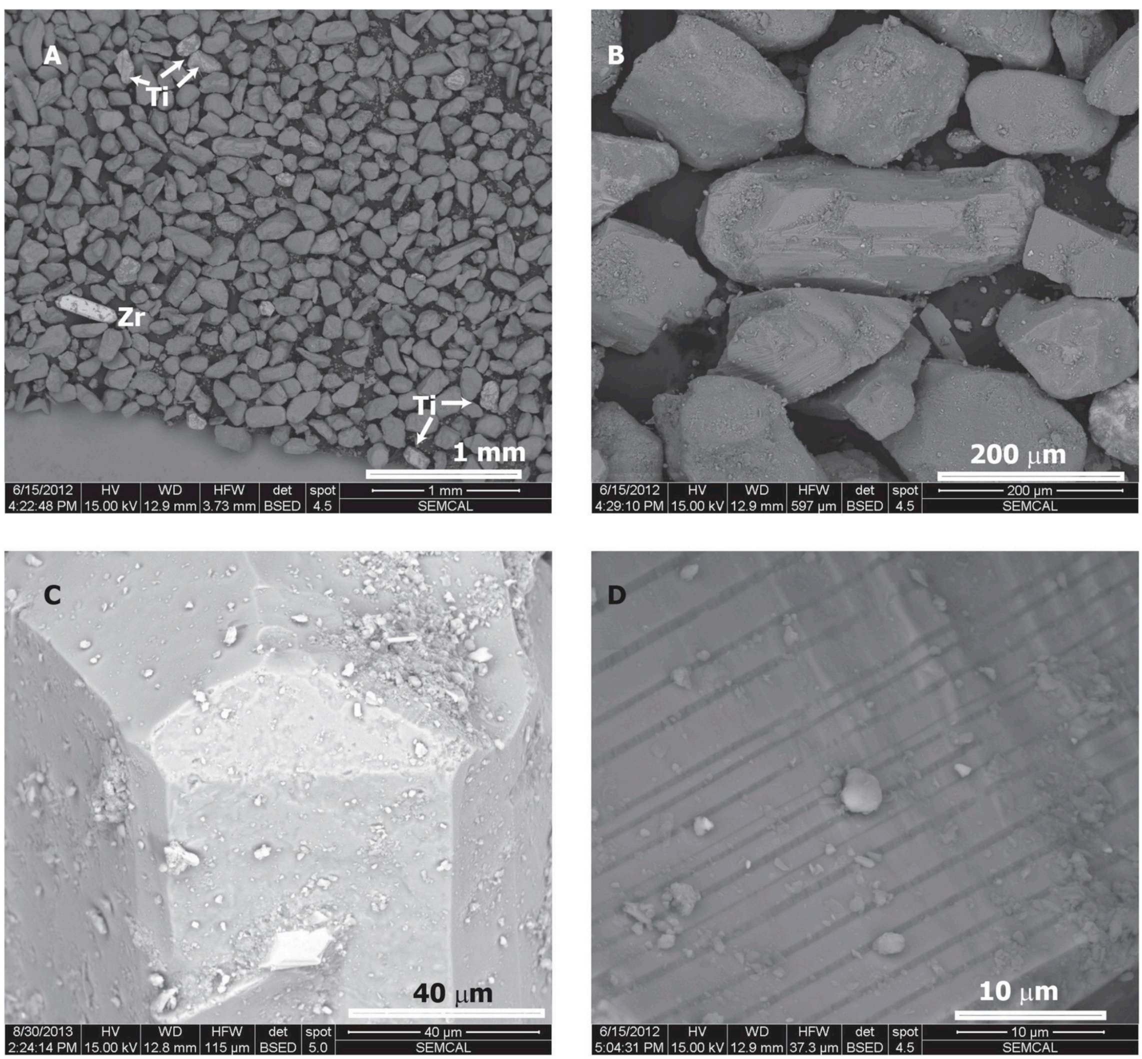

Fig. 4. SEM images from Crescent stream, Fryxell basin. (a) Low magnification image showing angular euhedral mineral grains. Brighter (high BSE) minerals are zircon or Fe–Ti-rich (ilmentite or rutile) grains. (b) Higher magnification image showing broken angular grains and slightly rounded grains with clay-sized grains observed on surfaces. EDX spot analysis on these phases suggest pyroxene/amphibole, quartz, Na rich plagioclase, K feldspar, Fe–Ti phase (ilmenite), and biotite. (c) Euhedral olivine. (d) Ca–Mg–Fe–Si bearing mineral (pyroxene) exhibiting linear etched features.

4.3. Chemical weathering

Because chemical weathering affects the geochemistry and mineralogy of siliciclastic sediments, the Chemical Index of Alteration (CIA) was calculated to quantify the amount of weathering that rocks and sediments have undergone by using molar proportions:

$$CIA = [(Al_2O_3)/(Al_2O_3 + K_2O + Na_2O + CaO^*)] \times 100$$

(Nesbitt and Young, 1982, 1984; Fedo et al., 1995). CaO* represents the Ca in silicate minerals by correcting for carbonates and phosphates. It is a dimensionless number that can range from 0 (fresh surfaces; no weathering) to 100 (residual clays from extensive weathering) (Nesbitt and Young, 1982; Young and Nesbitt, 1998). Taylor and McLennan (1985) calculated the CIA for the average UCC to be 50. High CIA numbers reflect chemical weathering where the soluble ions (e.g., Ca^{2+}, Na^{+}, K^{+}) are removed and clay minerals are produced. With a large proportion of secondary minerals, shales typically have CIA values ranging from 70 to 75, indicating higher rates of chemical weathering (Nesbitt and Young, 1982; Young and Nesbitt, 1998). Conversely, low CIAs (less than 50) suggest little or no chemical weathering. Values for primary minerals are commonly 50 or less with unaltered basalts ranging between 30 and 45 and granitic rocks between 45 and 55 (Nesbitt and Young, 1982; Nesbitt and Wilson, 1992). Taylor and McLennan (1985) determined CIA ranges of 50–55 and 60–65 for a Pleistocene till (matrix) and Pleistocene glacial clays, respectively. Taylor and McLennan (1985) listed a CIA range of 55–70 for loess, which is corroborated by Gallet et al. (1998)'s average CIA calculations (average: 62 ± 4; range: 54 to 68) for a series of worldwide glacial loess deposits. Canil and Lacourse (2011) calculated an average CIA of 54 ± 4 (range: 48–59) for the glacial till in the North American Cordillera (British Columbia, Canada).

Table 1 gives the CIA ratios calculated for the Dry Valley samples. The values suggest that these stream sediments have undergone little or no chemical weathering, with CIA ratios ranging from 39.0 to 48.3 with a mean of 45.0 ± 2.1 (Table 1), which are overall lower than any published values (CIA: 48–70) for the UCC or glacial material (Taylor and McLennan, 1985; Gallet et al., 1998; Canil and Lacourse, 2011). The North American Cordillera glacial till (Canil and Lacourse, 2011) values slightly overlap but are still overall more weathered than the Dry Valley samples. The hypothesis that little or no chemical weathering in occurring in the Dry Valley is corroborated by Gooseff et al. (2002) and the SEM observations of the sediments in addition the very low CIA ratios. The bulk of the sand-sized fraction images show mineral grains that are angular (sometimes euhedral) to slightly rounded (Fig. 4). The majority of the clay-sized mineral grains associated with the sand-sized fraction appear to be comprised of broken mineral fragments (e.g., Fig. 4C).

Molar proportions of Al_2O_3 (A), $CaO^* + Na_2O$ (CN), and K_2O (K) of our samples are graphed on the A–CN–K ternary diagram, which is useful for examining weathering trends and rock compositions (Fedo et al., 1995; Nesbitt et al., 1996). Plagioclase (Pl), K-feldspar (Ks), Smectite (Sm), Illite (Il), Kaolinite (Ka), Chlorite (Chl), and Gibbsite (Gi) are labeled as well (Nesbitt et al., 1996). The “feldspar join” is an imaginary line that connects plagioclase and K-feldspar plotting at 50% Al_2O_3 on both edges of a A–CN–K ternary diagram. Smectite and illite are positioned at 75% Al_2O_3, and the other aluminous minerals (kaolinite, chlorite, and gibbsite) are located at Al_2O_3 apex. As observed on the A–CN–K ternary plot (Fig. 5), our samples plot between the McMurdo Volcanic Group (MVG), Ferrar Dolerite (FD), and the upper continental crust (UCC). The MVG and FD rocks exert important controls on the geochemistry of the sediments, and the occurrence of these mafic minerals in the Taylor Valley tills results from the reduced rate of weathering, as the CIA values indicate. Our SEM observations of the angular nature of the Taylor Valley sediments themselves and the presence of seemingly fresh olivine, pyroxenes and amphiboles provide further confirmation of this idea. This evidence supports the notion that lower chemical weathering rates lead to the persistence of these more weathering susceptible minerals, which may significantly influence our upper continental crust calculations.

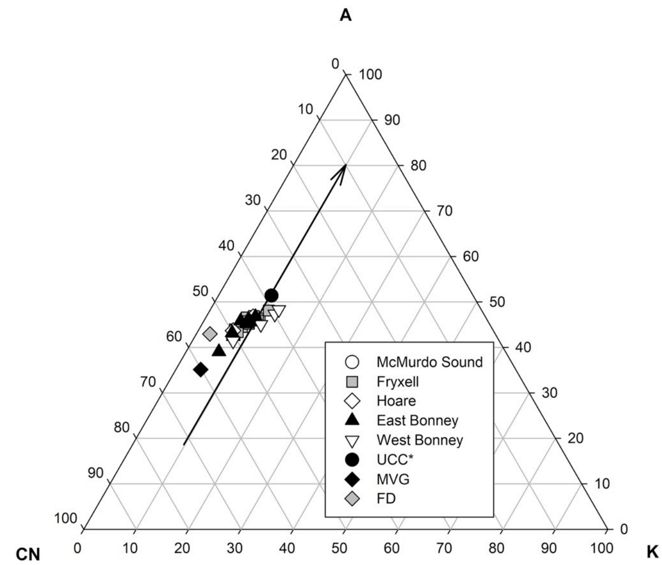

Fig. 5. A–CN–K Ternary Diagram. The Taylor Valley samples plot in the space between the UCC, MVG, and FD values. Plagioclase (Pl), K-feldspar (Ks), Smectite (Sm), Illite (Il), Kaolinite (Ka), Chlorite (Chl), and Gibbsite (Gi) are labeled (Nesbitt et al., 1996). The solid black arrow shows the predicted weathering trend of the crust (Fedo et al., 1995). The UCC, MVG, and FD values are based on the Rudnick/Gao composite, Cooper et al. (2007) and Gunn (1966), respectively.

The results of investigations into the formation of clay minerals in the Dry Valley soils are quite diverse. For example, Bockheim (1997) suggests minimal alteration of primary minerals in Dry Valley soils, consistent with the observations of our study. Ugolini and Jackson (1982), on the other hand, demonstrated that montmorillonite, vermiculite, and chlorite can be observed in these soils, produced from in situ chemical weathering. Others have demonstrated that the formation of weathering products include zeolites, iron oxides, and evaporates, and that authigenic clay minerals are present although not very abundant (Gibson et al., 1983).

Less is known about the clay mineralogy of the stream sediments. In an investigation on creek sediments in Huey and Greek Creeks in Taylor Valley, Gooseff et al. (2002) reported that the coarser fraction was composed mostly of primary minerals with some kaolinite and muscovite/illite/smectite. Forty to sixty-five percent of the $< 2\,\mu m$ size fraction consisted of amorphous weathering products; however, this only made up $< 0.3\%$ of the bulk sediment. This study (Figs. 4a and 5) and Gooseff et al. (2002)'s work on creek sediments indicate that the measured Mg, Fe, and Ti concentrations in our samples are not likely to be strongly influenced by smectite/vermiculite/montmorillonite formation but rather by the presence of MVG and FD detritus.

4.4. Chemical weathering and hydraulic sorting

However, the CIA values or the A–CN–K plots do not take into account other influences such as sedimentary sorting or transport. Fig. 6 illustrates the relations between Th/U and Th, which can also indicate weathering and sorting trends. Excluding one stream (Bo-1), Th/U ranges from 3.9 to $8.0\,\mu g g^{-1}$ with an average of $5.6 \pm 1.0\,\mu g g^{-1}$, mostly plotting above the UCC, MVG, and FD. The Th values vary between $3.6\,\mu g g^{-1}$ and $11\,\mu g g^{-1}$ with an average of 6.5 ± 1.7, with all but one lying below the UCC average. It is likely that the initial abundances of U and Th in Taylor Valley are lower than UCC, as

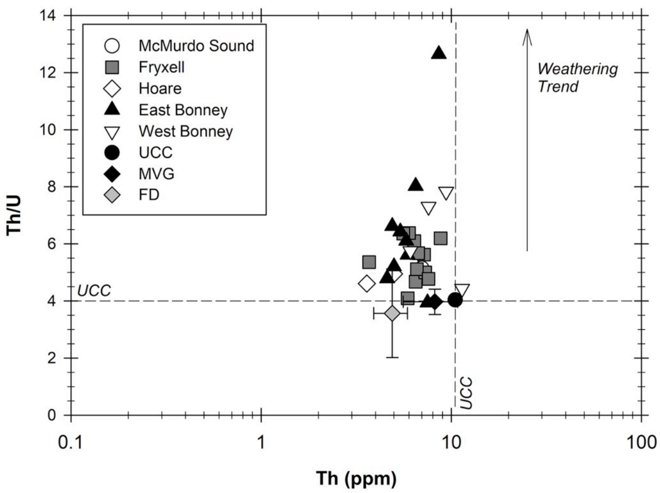

Fig. 6. Th/U vs. Th. The Taylor Valley Th/U values trend directly upwards, above the UCC, MVG, and FD. Most of the samples' Th concentrations vary between the UCC and FD. The error bars are either the same size or smaller than the data symbols. The UCC, MVG, and FD values are based on the Rudnick/Gao composite, Cooper et al. (2007) and Gunn (1966), respectively.

indicated by the elemental rock data of MVG and FD (Gunn, 1966; Cooper et al., 2007). U and Th are grouped with four other elements (Zr, Cs, Hf, Li) that have concentrations 25% lower than the Rudnick/Gao composite. Our mean U concentration is 1.2 ± 0.4 $\mu g g^{-1}$, which is well below UCC (2.6 $\mu g g^{-1}$) but overlaps with MVG (2.1 ± 0.7 $\mu g g^{-1}$) and FD (1.5 ± 0.4 $\mu g g^{-1}$) values. The Th values (6.5 ± 1.7 $\mu g g^{-1}$) are also lower than the UCC values (10.5 $\mu g g^{-1}$) but again overlap with MVG (9.0 ± 4.8 $\mu g g^{-1}$) and FD (4.9 ± 1.0 $\mu g g^{-1}$).

Th/U ratios will increase due to the loss of U from weathering and sedimentary sorting. Both McLennan et al. (1993) and Roser et al. (2002) explain upward trends in Th/U greater than UCC values through the loss of U from weathering and sediment recycling. Uranium will oxidize from U^{4+} to the more soluble U^{6+}, which can be lost through dissolution or sedimentation (McLennan et al., 1993). For the most part, our samples trend directly upwards, below the UCC Th and above the Th/U averages for UCC, MVG, and FD. A small amount of weathering or sorting may be indicated by the increasing Th/U ratios.

Most of the higher Th/U values are from the western portion of Taylor Valley (Bonney basin). When reviewing the data from East Bonney, there is a sizeable data range for Th/U (3.9–12.6), as compared to Eastern Taylor Valley. This most likely results from certain East Bonney sediments having undergone some alumino-silicate weathering as indicated from the stream water $^{87}Sr/^{86}Sr$ analyses (Dowling et al., 2013).

Binary Th/Sc–Zr/Sc plots (Fig. 7) are also useful for provenance studies. Typically, Th is an incompatible element in igneous rocks, Sc is compatible and reflects the original source rock geochemistry, and Zr is strongly enriched in zircon, a heavy mineral, which can be concentrated by sedimentary sorting. Therefore, the Th/Sc ratios preserve signatures of the original source rock compositions and Zr/Sc values reflect both the petrogenetic evolution and sedimentary zircon concentration (McLennan et al., 1993; Roser and Korsch, 1999; Roser et al., 2002). In our samples, the Th/Sc ratios do not vary much (range: 0.2–0.7 $\mu g g^{-1}/\mu g g^{-1}$; average = 0.4 ± 0.1), suggesting that igneous differentiation is not the primary control.

As shown in Fig. 7, the Zr/Sc ratios have a larger variation. Most of the data lie below the UCC and volcanic rock average (VRA) ratios (Taylor, 1965, 1969), overlap with the MVG (Th/Sc: 0.4 ± 0.2; Zr/Sc: 14.5 ± 7.3; Cooper et al., 2007) and do not intersect with FD (Th/Sc: 0.1 ± 0.0; Zr/Sc 3.0 ± 1.2; Gunn, 1966). McLennan et al. (1993) suggest that any elemental ratios higher than UCC are likely related to heavy mineral enrichments due to sedimentary sorting and recycling.

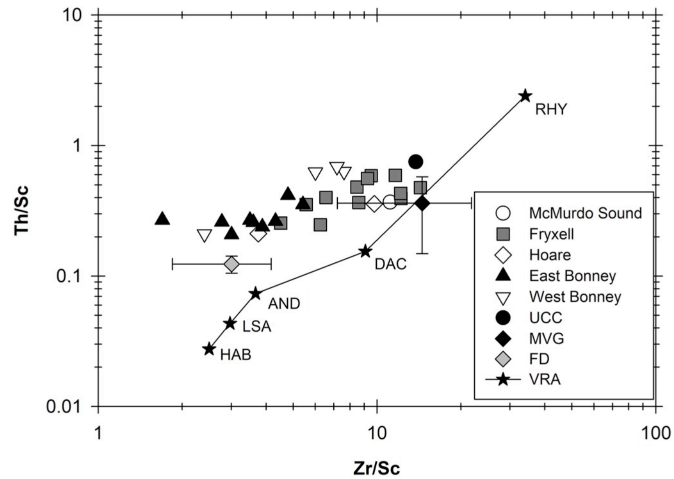

Fig. 7. Th/Sc vs. Zr/Sc. The Th/Sc ratios do not fluctuate much while Zr/Sc ratios have a larger variation. The majority of the data lie below the UCC, MVG, and volcanic rock averages (VRA) but above the FD. The error bars for the samples are either the same size or smaller than the data symbols. The data points labeled HAB (high-Al basalt), LSA (low-silica andesite), AND (andesite), DAC (dacite) and RH (rhyolite) are volcanic rock averages (Taylor, 1965, 1969). The UCC, MVG, and FD values are based on the Rudnick/Gao composite, Cooper et al. (2007) and Gunn (1966), respectively.

However, in this geologic setting, it is more likely that the lower initial composition of Zr in the FD and MVG causes the data to be lower than UCC. Zr is similar to U and Th in that it has values lower than 25% of the Rudnick/Gao composite. The more eastern samples may be disproportionately affected by the MVG while the FD may influence the more western samples.

In Fig. 8, the majority of the Al_2O_3 sediment data (concentrated in Trend 1) are similar to or lower than the UCC average, suggesting that few aluminum-rich products (i.e., clay minerals) are present. This, in turn, indicates either that these tills have not been exposed to intense chemical weathering or that the weathering products have been lost via transport. Trend 1, decreasing Al_2O_3 with static TiO_2 concentrations,

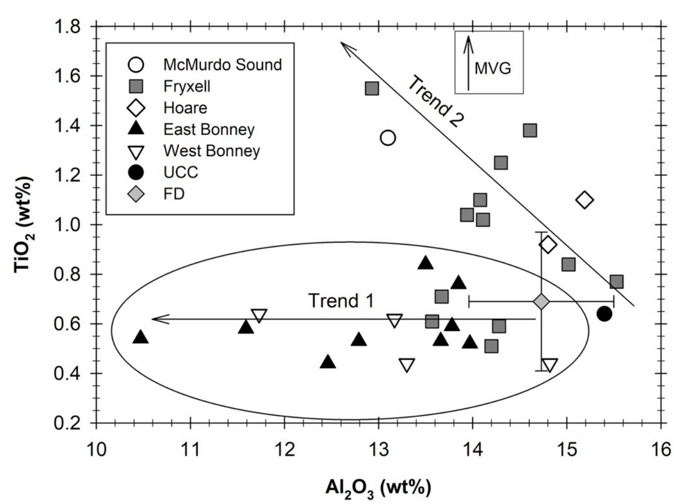

Fig. 8. Al2O3 vs. TiO2. There are two trends that move away from the mean UCC concentrations. The first trend (Trend 1) is horizontal, as the samples have similar TiO2 UCC and FD values but decreasing Al2O3 concentrations. The samples in Trend 2 have increasing TiO2 increasing towards to the MVG (Al2O3:13.7 ± 2.1 ppm; TiO2:3.7 ± 0.7 ppm) and decreasing Al2O3 values as compared to the UCC and FD. The error bars for the samples are either the same size or smaller than the data symbols. The UCC, MVG, and FD values are based on the Rudnick/Gao composite, Cooper et al. (2007) and Gunn (1966), respectively.

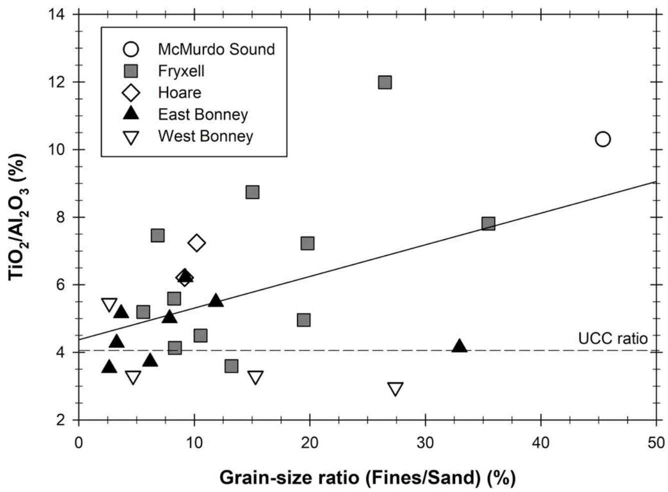

Fig. 9. TiO2:Al2O3 vs. Grain-size Ratios. There is a weak correlation (r2 = 0.22) between TiO2:Al2O3 and grain-size ratios.

follows the weathering and sorting pathway demonstrated by Young and Nesbitt (1998) and may indicate that these samples have been sorted and become more coarse-grained by losing their Al_2O_3-rich fines. This is supported by the fact that the fine-grained fraction comprises less than 15% of the samples. However, there is no strong correlation between the TiO_2:Al_2O_3 and grain-size ($r^2 = 0.22$), indicating that the bulk geochemistry is not strongly controlled by grain size (Fig. 9). Therefore, we interpret these data to suggest that the sediments have experienced a minimal amount of chemical weathering, corroborating the CIA calculations, A–CN–K plot, and SEM analyses.

In Fig. 8, the most probable explanation of Trend 2 relates to the higher TiO_2 values of McMurdo Volcanic Group rocks, as demonstrated by the MVG (TiO_2: 3.7 ± 0.7 ppm) plotting above Trend 2. Thus, Trend 2 may be due to an enhanced amount of MVG in these sediments (Gunn, 1966; Kyle, 1981; Allibone et al., 1993; Cooper et al., 2007). Ti-bearing minerals are notable in sediments from streams from the Fryxell basin (e.g., Fig. 4a). As noted above, there is a weak correlation between TiO_2:Al_2O_3 and grain-size (Fig. 9); therefore, the enrichment of mafic debris, such as from the McMurdo Volcanic Group, in the glacial tills may be an important control. Due to lower rates of chemical weathering in dry-based glacial systems, the presence of mafic minerals is not only possible, it is probable that they have a significant influence on the sediment geochemistry. Dry-based glacial tills where these minerals exist may provide a better representative composition and need to be included in upper continental crust calculations.

4.5. Presence of mafic volcanic rocks: McMurdo Volcanic Group and Ferrar Dolerite

Geochemical knowledge of the McMurdo Volcanic Group is extensive. Many of the basanites have compositions of near-primary magmas that contain Cr diopside, a major mantle nodule phase (Cooper et al., 2007). There is a strong correlation ($r^2 = 0.68$) between Ni and Cr in our samples (Fig. 10). The two samples that fall off the correlation line with very high Ni concentrations are the two eastern-most samples collected that have a larger percentage of mafic material, as they plot near closer to the MVG and FD. The basanites also contain more Ti, Ca, Cu, Mg, Ni, Sc, and V than the more fractionated rock types, such as phonolite (Cooper et al., 2007). In addition, sills within the Ferrar Dolerite in Western Taylor Valley have high concentrations of Mg, Cr, and Ni (Gunn, 1966).

These data confirm that the geochemistry of these tills is greatly influenced by the presence of mafic sources, such as the McMurdo Volcanic Group or the Ferrar Dolerite. As noted above, Canil and Lacourse (2011) have noted similar occurrences in the Canadian Cordillera where mafic fragments greatly influence the bulk geochemistry of the tills. The abundance of these mafic components is probably also enhanced by the nature of the glaciers that deposited these tills. Although there is still much debate over whether or not cold-based Antarctic glaciers are effective geomorphological agents (Hambrey and Fitzsimons, 2010), there is a clear agreement that the Dry Valley glaciers are entirely frozen to their beds and do not produce subglacial meltwater (Fountain et al., 1998; Atkins and Dickinson, 2007). Liquid water does not make contact with sediment at the glacier base and subglacial weathering is minimal (Tranter, 2004). Chemical weathering does exist when these materials are exposed to liquid water but the enhanced weathering rates occur in the hyporheic zones where the rock-water ratios are much higher (Nezat et al., 2001; Tranter, 2004). However, this study and Gooseff et al. (2002) demonstrate that the chemical weathering of the surface channel sediments is minimal.

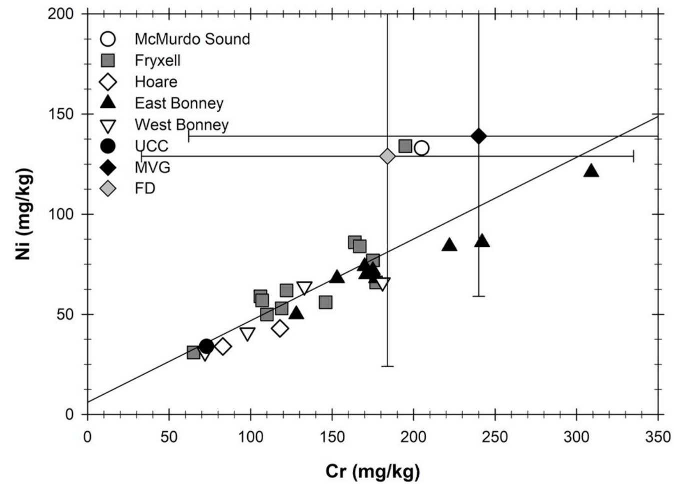

Fig. 10. Ni vs. Cr. There is a strong correlation (r2 = 0.68) between Ni and Cr. The two samples that plot off the regression line (high Ni values) are from the eastern-most portion of Taylor Valley. The error bars are either the same size or smaller than the data symbols. The UCC, MVG, and FD values are based on the Rudnick/Gao composite, Cooper et al. (2007) and Gunn (1966), respectively.

5. Conclusions

There is little indication that chemical weathering occurs in the stream sediment of the McMurdo Dry Valleys. The Chemical Index of Alteration calculations and A–CN–K plot suggest that these sediments have undergone minimal chemical weathering. In combination with these, the binary Th/Sc–Zr/Sc and Al_2O_3:TiO_2 plots imply that a small amount of mafic minerals influences the overall composition of the tills. Mafic materials in a glacial environment, as demonstrated by Nesbitt and Young (1996) and Canil and Lacourse (2011), may be better preserved in tills where cold-based glaciers exist. This notion is further supported by work done in the Arctic where in dry-based glacial systems chemical weathering (160 meq/m^2/yr) is significantly slower than the rates in wet-based glacier systems, such as the Haut Glacier D'Arolla, Switzerland (660 meq/m^2/yr) or Beredon Glacier, Canada (947 meq/m^2/yr) (Eyles et al., 1982; Hodgkins et al., 1997).

When taken all together, the data confirm that the geochemistry of these tills is greatly influenced by the presence of a mafic component, most likely from McMurdo Volcanic Group or Ferrar Dolerite. The presence of this constituent results from the reduced rate of weathering found in dry-based glaciers. Geochemical analyses of the dry-based glacial tills in polar deserts, such as those found in Taylor Valley, may provide a better representative composition of the original material and need to be incorporated into upper continental crust calculations.

Declarations of interest

none

Acknowledgements

This work was supported by NSF grants OPP-9813061 and ANT-0423595. We thank Ms. J. Gudding Martin for help in collecting the samples, Ms. Kathleen Welch for completing the grain size analysis, Dr. C. Gardner and Ms. A. Balakrishnan for their assistance with the graphics, and Dr. K. Neumann for his reviews of the original paper. We are especially indebted to Dr. B. P. Roser and the anonymous reviewers of the original manuscript whose comments and ideas greatly improved the manuscript. SEM analysis were conducted in the SEMCAL laboratory at the Ohio State University.

APPENDIX 1. Elemental concentrations ranked according to compatibility (mg/kg).

Sample	Map Label	Watershed	Cs	Rb	Tl	U	Th	Pb	K	Ba	La	Ce	Ta	Pr	Hf	Zr	Sr	Nd	Na
Eastern Taylor Valley																			
Commonwealth-1	Co1	McMurdo Sound	1.1	60	BDL*	1.4	7.0	18	17600	529	44	86	2.5	9.6	5.0	212	566	37	21440
Canada-1	C1	Fryxell	1.5	75	BDL	1.1	6.4	21	20900	688	33	65	1.2	7.5	3.0	105	529	30	20330
Canada-2	C2	Fryxell	1.2	68	BDL	0.7	3.7	16	18700	644	20	37	0.6	4.2	2.0	94	478	17	21960
Lost Seal-1	LS1	Fryxell	2.2	111	0.7	1.4	6.5	19	28500	812	30	59	1.2	6.6	3.0	128	486	26	25520
Lost Seal-2	LS2	Fryxell	1.5	85	0.5	1.4	5.9	17	22200	672	33	64	1.5	7.4	5.0	183	540	29	23290
Lost Seal-3	LS3	Fryxell	2.2	93	0.5	1.4	8.8	23	21500	632	40	75	1.7	8.4	4.0	143	486	32	23370
McKnight-A	McA	Fryxell	1.1	60	BDL	1.5	7.3	15	17300	520	45	87	2.9	9.7	5.0	207	581	38	22480
Crescent-1	Cr1	Fryxell	1.3	73	BDL	1.3	6.6	17	20200	659	37	71	1.9	8.0	4.0	155	571	31	24480
Crescent-2B	Cr2B	Fryxell	2.0	101	0.6	1.3	7.2	21	25200	1000	39	74	1.6	8.5	4.0	127	554	34	24930
Delta-1	D1	Fryxell	1.4	79	0.5	0.9	6.0	23	20200	613	30	56	1.0	6.2	2.0	95	486	25	22700
Delta-2	D2	Fryxell	1.3	65	BDL	0.9	5.6	20	17400	508	28	53	0.8	6.3	3.0	99	391	24	19510
Von Guerard-1	VG1	Fryxell	1.4	76	BDL	1.6	7.6	19	21300	667	47	90	5.0	10	6.0	229	600	38	25150
Von Guerard-2	VG2	Fryxell	1.6	95	0.6	1.2	6.7	16	24700	870	32	60	1.0	6.6	3.0	111	584	26	24110
Anderson-1	A1	Hoare	1.6	82	BDL	1.0	5.0	49	22500	753	29	59	1.2	6.8	4.0	137	633	28	23220
Anderson-2	A2	Hoare	1.3	61	BDL	0.8	3.6	20	16900	685	24	50	0.9	6.2	2.0	64	601	26	20330
Western Taylor Valley																			
LaCroix-1	LaC1	East Bonney	1.4	90	0.6	1.0	4.6	23	21300	673	22	41	0.7	4.5	2.0	71	482	17	23070
Barlette-1	Ba1	East Bonney	1.8	101	0.7	1.0	5.0	18	21200	635	21	41	0.6	4.7	2.0	81	395	19	20990
Barlette-2	Ba2	East Bonney	1.2	69	BDL	0.8	6.5	28	15300	514	26	50	BDL	5.4	2.0	69	317	21	18250
Bohner-1	Bo1	East Bonney	1.0	54	BDL	0.7	8.6	20	12700	398	33	63	BDL	6.9	2.0	54	269	26	15430
Priscu-1	P1	East Bonney	1.2	84	0.5	0.7	4.9	25	19500	647	24	45	15	5.0	2.0	68	419	20	22330
Priscu-2	P2	East Bonney	1.8	92	0.6	1.9	7.5	24	18500	575	30	58	1.0	6.3	2.0	86	545	24	21590
Priscu-3	P3	East Bonney	1.2	66	BDL	1.1	5.9	23	14700	408	22	44	0.7	5.0	2.0	77	273	19	15580
Vincent-1	V1	East Bonney	1.2	68	BDL	0.8	5.4	20	15300	461	21	42	12	4.7	2.0	78	289	19	16540
Vincent-2	V2	East Bonney	1.3	69	BDL	1.0	5.8	18	16100	574	26	50	0.9	5.8	2.0	95	375	23	20330
Blood Falls	BF	West Bonney	2.2	118	0.8	1.2	9.4	43	25600	673	42	64	0.7	7.3	3.0	90	304	26	20700
Lawson-1	La1	West Bonney	1.6	78	0.6	1.1	6.1	26	16000	438	21	43	0.5	4.7	2.0	70	205	19	16320
Lyons-1	Ly1	West Bonney	3.0	136	1.1	2.6	11	26	23800	626	37	70	1.0	7.6	4.0	137	360	29	21880
Santa Fe-1	SF1	West Bonney	2.3	125	0.9	1.0	7.6	35	28700	989	28	54	0.7	5.5	2.0	79	368	21	23520
McMurdo Volcanic Group (MVG) and Ferrar Dolerite (FD)																			
McMurdo Volcanic Group			0.4	46	NR	2.1	9.0	4	14889	603	69	133	5.8	NR	8.2	358	1056	59	30851
Ferrar Dolerite			NR	32	NR	1.3	5.1	NR	7869	237	NR	NR	NR	NR	NR	103	133	NR	14291
Upper Continental Crust (UCC)																			
Rudnick/Gao Composite			4.9	94	0.55	2.6	10.5	17	23244	628	31	63	0.92	7.1	5.3	193	320	27	24259

sample	Sm	Gd	Tb	Eu	Ho	Y	Er	Dy	Yb	Tm	Lu	Al	Ti	Si	Ca	Cu	Fe	Co	Mg	Cr	Ni
Eastern Taylor Valley																					
Commonwealth-1	7.2	6.2	0.9	2.0	0.9	24	2.5	5.1	2.4	0.4	0.4	70900	8000	270200	49500	19	54200	32	42900	205	133
Canada-1	5.7	5.1	0.8	1.6	0.8	20	2.2	4.2	2.0	0.3	0.3	77200	5700	281130	48300	20	43500	21	29300	119	53
Canada-2	3.4	3.2	0.5	1.2	0.6	14	1.5	2.7	1.4	0.2	0.2	76900	3100	303850	42400	16	32600	18	23800	146	56
Lost Seal-1	5.2	4.4	0.7	1.4	0.7	19	2.1	4.0	2.0	0.3	0.4	80200	4300	293470	34800	18	35200	15	15400	65	31
Lost Seal-2	5.4	4.8	0.8	1.6	0.8	21	2.3	4.2	2.1	0.3	0.3	75600	6400	273190	48600	16	45800	22	24700	106	59
Lost Seal-3	5.8	5.3	0.8	1.5	0.8	22	2.3	4.3	2.1	0.3	0.3	72800	5700	284360	40600	16	42600	21	25100	107	57
McKnight-A	6.9	5.9	0.9	2.1	0.9	23	2.4	4.8	2.3	0.4	0.3	66800	8600	265660	46700	17	54500	33	41700	195	134
Crescent-1	5.9	5.1	0.8	1.7	0.8	21	2.2	4.4	2.0	0.3	0.3	75300	6000	282540	46100	19	46500	24	31000	164	86
Crescent-2B	6.3	5.5	0.9	1.6	0.9	23	2.5	4.8	2.3	0.4	0.3	78800	4700	287210	40300	24	41400	20	20100	122	62
Delta-1	4.6	4.1	0.7	1.4	0.7	17	1.8	3.5	1.7	0.3	0.3	73500	4100	292030	42600	15	39000	22	27900	177	66
Delta-2	4.6	4.1	0.7	1.3	0.7	19	2.1	3.7	2.0	0.3	0.3	73700	3600	291560	49100	35	42500	26	30100	175	77
Von Guerard-1	7.2	6.4	1.0	2.1	1.0	25	2.6	5.1	2.5	0.4	0.4	76800	8000	271500	42900	17	49000	75	27600	167	84
Von Guerard-2	4.7	4.1	0.7	1.5	0.7	17	1.9	3.4	1.7	0.3	0.3	76900	3600	297590	42200	12	31600	17	22200	110	50
Anderson-1	5.5	5.2	0.8	1.7	0.8	21	2.3	4.3	2.1	0.3	0.3	81700	6500	282160	47700	31	43800	18	22100	83	34
Anderson-2	5.5	5.0	0.8	1.5	0.8	21	2.2	4.3	1.9	0.3	0.3	80300	5300	270570	61800	15	47300	20	33600	118	43

Western Taylor Valley																					
LaCroix-1	3.3	3.2	0.5	1.2	0.5	14	1.5	2.7	1.3	0.2	0.2	74200	2900	303950	39600	14	29900	18	20400	128	50
Barlette-1	3.9	3.6	0.6	1.3	0.7	18	1.8	3.4	1.8	0.3	0.3	74400	3200	290300	43700	23	43400	26	31800	177	68
Barlette-2	4.2	3.7	0.6	1.0	0.7	18	2.0	3.5	1.9	0.3	0.3	65800	2500	296190	45700	18	44000	30	36400	222	84
Bohner-1	4.7	4.2	0.7	1.0	0.8	20	2.2	3.9	2.2	0.3	0.3	55900	3100	288470	50800	18	55600	41	52100	309	121
Priscu-1	3.8	3.4	0.5	1.1	0.6	15	1.6	2.9	1.6	0.2	0.2	71000	3000	295480	40800	14	37800	72	31000	171	70
Priscu-2	4.6	4.1	0.7	1.3	0.7	19	2.1	3.8	1.9	0.3	0.3	71700	4200	276880	51100	30	43400	27	28100	153	68
Priscu-3	3.7	3.6	0.6	1.0	0.7	18	2.0	3.4	1.9	0.3	0.3	66900	3100	295530	50100	23	42100	28	31300	175	72
Vincent-1	3.7	3.6	0.6	1.0	0.7	18	1.9	3.3	1.9	0.3	0.3	62600	3400	291510	46800	19	48300	71	39600	242	86
Vincent-2	4.5	4.2	0.7	1.2	0.7	19	2.1	3.7	1.9	0.3	0.3	73700	5000	289830	45500	24	50300	28	30700	170	74
Blood Falls	4.5	3.8	0.6	1.1	0.6	17	1.9	3.4	1.9	0.3	0.3	67200	2300	309740	32300	25	33100	19	18000	98	41
Lawson-1	3.8	3.8	0.7	1.0	0.8	22	2.5	4.0	2.5	0.4	0.4	60600	3600	294360	47200	35	53100	33	30000	133	64
Lyons-1	5.3	4.9	0.8	1.2	0.9	22	2.3	4.2	2.4	0.3	0.3	68600	3600	291930	36700	26	42900	25	30100	181	66
Santa Fe-1	4.0	3.6	0.6	1.2	0.6	18	1.8	3.3	1.8	0.3	0.2	74500	2300	297590	34100	20	29000	14	16200	72	31
McMurdo Volcanic Group (MVG) and Ferrar Dolerite (FD)																					
MGV	11	9.5	1.3	3.3	NR	32	NR	NR	2.5	0.4	0.3	72339	22606	201193	73355	57	88035	50	51975	240	134
FD	NR	NR	NR	NR	NR	24	NR	NR	NR	NR	NR	74932	5009	256642	69187	94	133215	68	41186	213	130
Upper Continental Crust (UCC)																					
RG	4.7	4.0	0.7	1.0	0.83	21	2.3	3.9	2.34	0.37	0.36	81416	3836	311332	25657	27	35252	15	14956	73	34

*BDL = Below Detection Limit.
*NR = Not Reported.

APPENDIX 2. Remaining elemental concentrations ranked according to atomic number (mg/kg).

Sample	Li	Be	P	Sc	V	Mn	Zn	Ga	Ge	As	Nb	Mo	Cd	In	Sn	W	Bi
Eastern Taylor Valley																	
Commonwealth-1	12	BDL*	1500	19	134	1100	63	15	2.0	BDL	37	2.0	0.3	BDL	2.0	2.0	BDL
Canada-1	15	BDL	1100	16	112	800	64	17	1.0	BDL	18	BDL	0.6	BDL	1.0	1.0	BDL
Canada-2	11	BDL	600	15	91	600	46	15	1.0	BDL	9	BDL	BDL	BDL	1.0	1.0	0.2
Lost Seal-1	22	BDL	900	11	75	700	58	18	1.0	BDL	21	BDL	0.4	BDL	2.0	1.0	BDL
Lost Seal-2	20	BDL	1000	15	120	900	64	17	1.0	BDL	23	BDL	BDL	BDL	2.0	1.0	BDL
Lost Seal-3	20	BDL	1100	15	105	800	60	17	1.0	BDL	24	BDL	BDL	BDL	2.0	BDL	BDL
McKnight-A	11	BDL	1600	17	133	1100	64	16	1.0	BDL	43	2.0	BDL	BDL	2.0	2.0	BDL
Crescent-1	14	BDL	1200	18	126	900	66	16	1.0	BDL	27	BDL	0.2	BDL	2.0	BDL	BDL
Crescent-2B	18	BDL	1100	15	99	800	65	18	1.0	BDL	18	BDL	BDL	BDL	2.0	1.0	BDL
Delta-1	13	BDL	700	17	112	800	50	15	1.0	BDL	13	BDL	BDL	BDL	1.0	BDL	BDL
Delta-2	11	BDL	600	22	133	800	53	14	1.0	BDL	12	BDL	0.2	BDL	1.0	1.0	BDL
Von Guerard-1	12	BDL	1800	16	117	900	62	18	1.0	BDL	51	3.0	BDL	BDL	2.0	720	BDL
Von Guerard-2	14	BDL	800	12	80	600	53	17	1.0	BDL	14	BDL	0.2	BDL	2.0	4.0	BDL
Anderson-1	16	BDL	1200	14	104	700	221	19	1.0	BDL	18.0	BDL	0.5	0.5	21.0	5.0	0.8
Anderson-2	15	BDL	900	17	117	800	74	17	1.0	BDL	8.0	2.0	BDL	BDL	3.0	17.0	0.5
Western Taylor Valley																	
LaCroix-1	11	BDL	600	13	82	600	43	16	1.0	BDL	12.0	BDL	BDL	BDL	1.0	1.0	BDL
Barlette-1	14	BDL	600	21	121	900	58	16	1.0	BDL	8.0	BDL	BDL	BDL	2.0	2.0	BDL
Barlette-2	11	BDL	400	25	138	900	85	14	1.0	BDL	7.0	BDL	0.2	BDL	1.0	1.0	0.1
Bohner-1	BDL	BDL	400	32	186	1200	95	12	2.0	BDL	8.0	BDL	0.3	BDL	1.0	1.0	BDL
Priscu-1	BDL	BDL	500	19	110	700	55	15	1.0	BDL	10	BDL	BDL	BDL	1.0	491	BDL
Priscu-2	17	BDL	700	18	114	800	69	16	1.0	BDL	13	BDL	BDL	BDL	2.0	8.0	0.1
Priscu-3	11	BDL	400	22	134	800	69	14	2.0	BDL	10	BDL	0.2	BDL	1.0	3.0	BDL
Vincent-1	11	BDL	400	26	158	1000	62	13	1.0	BDL	10	BDL	BDL	BDL	3.0	447	0.3
Vincent-2	13	BDL	700	22	141	900	70	15	1.0	BDL	10	3.0	BDL	BDL	4.0	6.0	0.8
Blood Falls	12	BDL	400	15	90	600	167	16	2.0	BDL	9.0	BDL	0.5	BDL	2.0	2.0	0.2
Lawson-1	11	BDL	500	29	176	1000	64	14	1.0	BDL	8.0	BDL	BDL	BDL	2.0	2.0	0.2
Lyons-1	16	BDL	600	18	113	900	108	16	1.0	BDL	14	BDL	BDL	BDL	5.0	2.0	0.2
Santa Fe-1	15	BDL	500	11	64	500	78	16	1.0	BDL	9.0	BDL	BDL	BDL	2.0	1.0	0.2
McMurdo Volcanic Group (MVG) and Ferrar Dolerite (FD)																	
McMurdo Volcanic Group	NR	NR	3872	25	249	1562	89	18	NR	1.7	79.0	NR	NR	NR	NR	NR	NR
Ferrar Dolerite	NR	NR	648	37	169	1372	88	NR	NR	NR	6.8	NR	NR	NR	NR	NR	NR
Upper Continental Crust (UCC)																	
Rudnick/Gao Composite	41	1.9	655	14	106	774	75	18.6	1.3	5.7	11.6	0.6	0.06	0.066	2.2	1.4	0.23

*BDL = Below Detection Limit.
*NR = Not Reported.

APPENDIX 3. Samples normalized to Upper Continental Crust and ranked according to compatibility.

Sample	Map Label	Watershed	Cs	Rb	Tl	U	Th	Pb	K	Ba	La	Ce	Ta	Pr	Hf	Zr	Sr	Nd	Na
Eastern Taylor Valley																			
Commonwealth-1	Co1	McMurdo Sound	0.22	0.63	BDL*	0.52	0.67	1.06	0.76	0.84	1.41	1.37	2.72	1.35	0.94	1.10	1.77	1.37	0.88
Canada-1	C1	Fryxell	0.31	0.79	BDL	0.40	0.61	1.24	0.90	1.10	1.06	1.03	1.30	1.05	0.57	0.54	1.65	1.11	0.84
Canada-2	C2	Fryxell	0.24	0.72	BDL	0.27	0.35	0.94	0.80	1.03	0.64	0.58	0.65	0.60	0.38	0.49	1.49	0.64	0.91
Lost Seal-1	LS1	Fryxell	0.45	1.18	1.27	0.53	0.62	1.12	1.23	1.29	0.97	0.94	1.30	0.92	0.57	0.66	1.52	0.95	1.05
Lost Seal-2	LS2	Fryxell	0.31	0.90	0.91	0.55	0.56	1.00	0.96	1.07	1.08	1.02	1.63	1.04	0.94	0.95	1.69	1.08	0.96
Lost Seal-3	LS3	Fryxell	0.45	0.99	0.91	0.55	0.84	1.35	0.92	1.01	1.28	1.20	1.85	1.18	0.75	0.74	1.52	1.19	0.96
McKnight-A	McA	Fryxell	0.22	0.64	BDL	0.56	0.70	0.88	0.74	0.83	1.46	1.38	3.15	1.36	0.94	1.07	1.82	1.39	0.93
Crescent-1	Cr1	Fryxell	0.27	0.78	BDL	0.50	0.63	1.00	0.87	1.05	1.19	1.13	2.07	1.13	0.75	0.80	1.78	1.16	1.01
Crescent-2B	Cr2B	Fryxell	0.41	1.07	1.09	0.49	0.69	1.24	1.08	1.59	1.26	1.17	1.74	1.20	0.75	0.66	1.73	1.25	1.03
Delta-1	D1	Fryxell	0.29	0.84	0.91	0.36	0.57	1.35	0.87	0.98	0.97	0.89	1.09	0.87	0.38	0.49	1.52	0.91	0.94
Delta-2	D2	Fryxell	0.27	0.69	BDL	0.34	0.53	1.18	0.75	0.81	0.89	0.84	0.87	0.88	0.57	0.51	1.22	0.89	0.80
Von Guerard-1	VG1	Fryxell	0.29	0.81	BDL	0.61	0.72	1.12	0.92	1.06	1.52	1.42	5.43	1.40	1.13	1.19	1.88	1.39	1.04
Von Guerard-2	VG2	Fryxell	0.33	1.01	1.09	0.45	0.64	0.94	1.06	1.39	1.03	0.95	1.09	0.94	0.57	0.58	1.83	0.96	0.99
Anderson-1	A1	Hoare	0.33	0.87	BDL	0.39	0.48	2.88	0.97	1.20	0.92	0.93	1.30	0.95	0.75	0.71	1.98	1.03	0.96
Anderson-2	A2	Hoare	0.27	0.65	BDL	0.30	0.34	1.18	0.73	1.09	0.78	0.80	0.98	0.87	0.38	0.33	1.88	0.97	0.84
Average			0.31	0.84	1.03	0.46	0.60	1.23	0.90	1.09	1.10	1.04	1.81	1.05	0.69	0.72	1.68	1.09	0.94
Standard Deviation			0.07	0.17	0.15	0.11	0.13	0.48	0.14	0.21	0.25	0.24	1.21	0.22	0.23	0.25	0.20	0.21	0.08
Western Taylor Valley																			
LaCroix-1	LaC1	East Bonney	0.29	0.96	1.09	0.37	0.44	1.35	0.92	1.07	0.70	0.64	0.76	0.64	0.38	0.37	1.51	0.63	0.95
Barlette-1	Ba1	East Bonney	0.37	1.07	1.27	0.37	0.48	1.06	0.91	1.01	0.68	0.65	0.65	0.66	0.38	0.42	1.23	0.71	0.87
Barlette-2	Ba2	East Bonney	0.24	0.73	BDL	0.31	0.62	1.65	0.66	0.82	0.82	0.79	BDL	0.76	0.38	0.36	0.99	0.77	0.75
Bohner-1	Bo1	East Bonney	0.20	0.58	BDL	0.26	0.82	1.18	0.55	0.63	1.07	1.00	BDL	0.97	0.38	0.28	0.84	0.95	0.64
Priscu-1	P1	East Bonney	0.24	0.89	0.91	0.28	0.47	1.47	0.84	1.03	0.76	0.72	15.87	0.70	0.38	0.35	1.31	0.72	0.92
Priscu-2	P2	East Bonney	0.37	0.98	1.09	0.73	0.71	1.41	0.80	0.92	0.96	0.91	1.09	0.88	0.38	0.45	1.70	0.90	0.89
Priscu-3	P3	East Bonney	0.24	0.71	BDL	0.40	0.56	1.35	0.63	0.65	0.72	0.70	0.76	0.70	0.38	0.40	0.85	0.71	0.64
Vincent-1	V1	East Bonney	0.24	0.72	BDL	0.32	0.51	1.18	0.66	0.73	0.68	0.66	13.15	0.67	0.38	0.41	0.90	0.69	0.68
Vincent-2	V2	East Bonney	0.27	0.73	BDL	0.37	0.55	1.06	0.69	0.91	0.83	0.79	0.98	0.81	0.38	0.49	1.17	0.84	0.84
Blood Falls	BF	West Bonney	0.45	1.26	1.45	0.46	0.90	2.53	1.10	1.07	1.35	1.02	0.76	1.02	0.57	0.47	0.95	0.98	0.85
Lawson-1	La1	West Bonney	0.33	0.83	1.09	0.41	0.58	1.53	0.69	0.70	0.69	0.68	0.54	0.67	0.38	0.36	0.64	0.71	0.67
Lyons-1	Ly1	West Bonney	0.61	1.45	2.00	0.99	1.09	1.53	1.02	1.00	1.18	1.11	1.09	1.07	0.75	0.71	1.13	1.07	0.90
Santa Fe-1	SF1	West Bonney	0.47	1.33	1.64	0.40	0.72	2.06	1.23	1.57	0.91	0.86	0.76	0.77	0.38	0.41	1.15	0.78	0.97
Average			0.33	0.94	1.32	0.44	0.65	1.49	0.82	0.93	0.87	0.81	3.31	0.79	0.42	0.42	1.11	0.81	0.81
Standard Deviation			0.12	0.27	0.36	0.20	0.19	0.41	0.21	0.25	0.21	0.16	5.57	0.15	0.11	0.10	0.29	0.13	0.12

Sample	Sm	Gd	Tb	Eu	Ho	Y	Er	Dy	Yb	Tm	Lu	Al	Ti	Si	Ca	Cu	Fe	Co	Mg	Cr	Ni
Eastern Taylor Valley																					
Commonwealth-1	1.53	1.56	1.33	1.97	1.13	1.14	1.08	1.30	1.03	1.00	1.06	0.87	2.09	0.87	1.93	0.70	1.54	2.13	2.87	2.81	3.91
Canada-1	1.21	1.27	1.11	1.58	0.96	0.97	0.93	1.07	0.85	0.84	0.89	0.95	1.49	0.90	1.88	0.74	1.23	1.38	1.96	1.63	1.56
Canada-2	0.72	0.80	0.69	1.22	0.66	0.66	0.67	0.70	0.60	0.62	0.58	0.94	0.81	0.98	1.65	0.59	0.92	1.17	1.59	2.00	1.65
Lost Seal-1	1.11	1.09	1.01	1.36	0.89	0.92	0.92	1.02	0.85	0.76	1.00	0.99	1.12	0.94	1.36	0.67	1.00	0.99	1.03	0.89	0.91
Lost Seal-2	1.15	1.20	1.11	1.55	0.99	1.00	0.99	1.08	0.90	0.89	0.86	0.93	1.67	0.88	1.89	0.59	1.30	1.49	1.65	1.45	1.74
Lost Seal-3	1.23	1.31	1.14	1.52	0.99	1.03	1.02	1.11	0.90	0.89	0.92	0.89	1.49	0.91	1.58	0.59	1.21	1.41	1.68	1.47	1.68
McKnight-A	1.47	1.48	1.34	2.05	1.11	1.11	1.06	1.23	0.98	0.97	0.92	0.82	2.24	0.85	1.82	0.63	1.55	2.19	2.79	2.67	3.94
Crescent-1	1.26	1.28	1.19	1.70	0.98	1.00	0.97	1.14	0.85	0.84	0.89	0.92	1.56	0.91	1.80	0.70	1.32	1.61	2.07	2.25	2.53
Crescent-2B	1.34	1.37	1.24	1.64	1.11	1.10	1.07	1.22	0.98	0.97	0.94	0.97	1.23	0.92	1.57	0.89	1.17	1.31	1.34	1.67	1.82
Delta-1	0.98	1.02	0.94	1.41	0.80	0.80	0.80	0.89	0.73	0.78	0.75	0.90	1.07	0.94	1.66	0.56	1.11	1.45	1.87	2.42	1.94
Delta-2	0.98	1.02	0.96	1.27	0.87	0.90	0.90	0.95	0.85	0.81	0.78	0.91	0.94	0.94	1.91	1.30	1.21	1.71	2.01	2.40	2.26
Von Guerard-1	1.53	1.59	1.41	2.11	1.17	1.17	1.13	1.31	1.07	0.97	1.03	0.94	2.09	0.87	1.67	0.63	1.39	4.99	1.85	2.29	2.47
Von Guerard-2	1.00	1.03	0.94	1.46	0.78	0.81	0.81	0.88	0.73	0.68	0.72	0.94	0.94	0.96	1.64	0.44	0.90	1.10	1.48	1.51	1.47
Anderson-1	1.17	1.30	1.16	1.72	0.96	1.01	1.00	1.11	0.90	0.86	0.86	1.00	1.69	0.91	1.86	1.15	1.24	1.21	1.48	1.14	1.00
Anderson-2	1.17	1.25	1.14	1.53	1.00	1.00	0.97	1.11	0.81	0.86	0.81	0.99	1.38	0.87	2.41	0.56	1.34	1.35	2.25	1.62	1.26
Average	1.19	1.24	1.12	1.61	0.96	0.98	0.95	1.07	0.87	0.85	0.87	0.93	1.45	0.91	1.78	0.72	1.23	1.70	1.86	1.88	2.01
Standard Deviation	0.22	0.22	0.19	0.27	0.14	0.14	0.12	0.17	0.12	0.11	0.12	0.05	0.45	0.04	0.24	0.23	0.19	0.97	0.50	0.57	0.91
Western Taylor Valley																					
LaCroix-1	0.70	0.80	0.69	1.23	0.61	0.66	0.67	0.68	0.56	0.57	0.50	0.91	0.76	0.98	1.54	0.52	0.85	1.20	1.36	1.75	1.47
Barlette-1	0.83	0.90	0.84	1.25	0.80	0.84	0.79	0.86	0.77	0.73	0.72	0.91	0.83	0.93	1.70	0.85	1.23	1.73	2.13	2.42	2.00
Barlette-2	0.89	0.92	0.87	1.03	0.84	0.85	0.87	0.89	0.81	0.78	0.75	0.81	0.65	0.95	1.78	0.67	1.25	1.97	2.43	3.04	2.47
Bohner-1	1.00	1.06	1.00	0.95	0.94	0.97	0.95	0.99	0.94	0.86	0.86	0.69	0.81	0.93	1.98	0.67	1.58	2.71	3.48	4.23	3.56
Priscu-1	0.81	0.86	0.76	1.14	0.70	0.72	0.69	0.75	0.68	0.65	0.58	0.87	0.78	0.95	1.59	0.52	1.07	4.81	2.07	2.34	2.06
Priscu-2	0.98	1.04	0.96	1.34	0.88	0.91	0.92	0.97	0.81	0.81	0.86	0.88	1.09	0.89	1.99	1.11	1.23	1.81	1.88	2.10	2.00
Priscu-3	0.79	0.89	0.81	0.99	0.82	0.86	0.85	0.86	0.81	0.76	0.78	0.82	0.81	0.95	1.95	0.85	1.19	1.86	2.09	2.40	2.12
Vincent-1	0.79	0.91	0.81	0.95	0.78	0.85	0.84	0.85	0.81	0.76	0.72	0.77	0.89	0.94	1.82	0.70	1.37	4.75	2.65	3.32	2.53
Vincent-2	0.96	1.05	0.99	1.19	0.89	0.92	0.90	0.96	0.81	0.81	0.75	0.91	1.30	0.93	1.77	0.89	1.43	1.83	2.05	2.33	2.18
Blood Falls	0.96	0.94	0.84	1.05	0.77	0.82	0.81	0.86	0.81	0.76	0.75	0.83	0.60	0.99	1.26	0.93	0.94	1.23	1.20	1.34	1.21
Lawson-1	0.81	0.96	0.94	1.00	0.96	1.04	1.08	1.04	1.07	1.00	0.97	0.74	0.94	0.95	1.84	1.30	1.51	2.21	2.01	1.82	1.88
Lyons-1	1.13	1.21	1.14	1.17	1.05	1.06	1.00	1.09	1.03	0.92	0.94	0.84	0.94	0.94	1.43	0.96	1.22	1.69	2.01	2.48	1.94
Santa Fe-1	0.85	0.89	0.83	1.21	0.76	0.83	0.80	0.85	0.77	0.73	0.64	0.92	0.60	0.96	1.33	0.74	0.82	0.94	1.08	0.99	0.91
Average	0.88	0.95	0.88	1.12	0.83	0.87	0.86	0.90	0.82	0.78	0.76	0.84	0.85	0.94	1.69	0.82	1.21	2.21	2.04	2.35	2.02
Standard Deviation	0.12	0.11	0.12	0.13	0.12	0.11	0.12	0.11	0.13	0.11	0.13	0.07	0.20	0.03	0.24	0.22	0.24	1.23	0.63	0.84	0.65

*BDL = Below Detection Limit.

APPENDIX 4. Remaining elemental concentrations normalized to UCC and ranked according to atomic number.

Sample	Li	Be	P	Sc	V	Mn	Zn	Ga	Ge	As	Nb	Mo	Cd	In	Sn	W	Bi
Eastern Taylor Valley																	
Commonwealth-1	0.29	BDL*	2.29	1.36	1.26	1.42	0.84	0.81	1.54	BDL	3.19	3.33	5.00	BDL	0.91	1.43	BDL
Canada-1	0.37	BDL	1.68	1.14	1.06	1.03	0.85	0.91	0.77	BDL	1.55	BDL	10.00	BDL	0.45	0.71	BDL
Canada-2	0.27	BDL	0.92	1.07	0.86	0.77	0.61	0.81	0.77	BDL	0.78	BDL	BDL	BDL	0.45	0.71	0.87
Lost Seal-1	0.54	BDL	1.37	0.79	0.71	0.90	0.77	0.97	0.77	BDL	1.81	BDL	6.67	BDL	0.91	0.71	BDL
Lost Seal-2	0.49	BDL	1.53	1.07	1.13	1.16	0.85	0.91	0.77	BDL	1.98	BDL	BDL	BDL	0.91	0.71	BDL
Lost Seal-3	0.49	BDL	1.68	1.07	0.99	1.03	0.80	0.91	0.77	BDL	2.07	BDL	BDL	BDL	0.91	BDL	BDL
McKnight-A	0.27	BDL	2.44	1.21	1.25	1.42	0.85	0.86	0.77	BDL	3.71	3.33	BDL	BDL	0.91	1.43	BDL
Crescent-1	0.34	BDL	1.83	1.29	1.19	1.16	0.88	0.86	0.77	BDL	2.33	BDL	3.33	BDL	0.91	BDL	BDL
Crescent-2B	0.44	BDL	1.68	1.07	0.93	1.03	0.87	0.97	0.77	BDL	1.55	BDL	BDL	BDL	0.91	0.71	BDL
Delta-1	0.32	BDL	1.07	1.21	1.06	1.03	0.67	0.81	0.77	BDL	1.12	BDL	BDL	BDL	0.45	BDL	BDL
Delta-2	0.27	BDL	0.92	1.57	1.25	1.03	0.71	0.75	0.77	BDL	1.03	BDL	3.33	BDL	0.45	0.71	BDL
Von Guerard-1	0.29	BDL	2.75	1.14	1.10	1.16	0.83	0.97	0.77	BDL	4.40	5.00	BDL	BDL	0.91	514.3	BDL
Von Guerard-2	0.34	BDL	1.22	0.86	0.75	0.77	0.71	0.91	0.77	BDL	1.21	BDL	3.33	BDL	0.91	2.86	BDL
Anderson-1	0.39	BDL	1.83	1.00	0.98	0.90	2.95	1.02	0.77	BDL	1.55	BDL	8.33	7.58	9.55	3.57	3.48
Anderson-2	0.37	BDL	1.37	1.21	1.10	1.03	0.99	0.91	0.77	BDL	0.69	3.33	BDL	BDL	1.36	12.14	2.17
Average	0.36	NA†	1.64	1.14	1.04	1.06	0.94	0.89	0.82	NA	1.93	3.75	5.71	7.58	1.39	45.00	2.17
Standard Deviation	0.09	NA	0.54	0.19	0.17	0.19	0.56	0.08	0.20	NA	1.08	0.83	2.70	NA	2.27	148.0	1.30
Western Taylor Valley																	
LaCroix-1	0.27	BDL	0.92	0.93	0.77	0.77	0.57	0.86	0.77	BDL	1.03	BDL	BDL	BDL	0.45	0.71	BDL
Barlette-1	0.34	BDL	0.92	1.50	1.14	1.16	0.77	0.86	0.77	BDL	0.69	BDL	BDL	BDL	0.91	1.43	BDL
Barlette-2	0.27	BDL	0.61	1.79	1.30	1.16	1.13	0.75	0.77	BDL	0.60	BDL	3.33	BDL	0.45	0.71	0.43
Bohner-1	BDL	BDL	0.61	2.29	1.75	1.55	1.27	0.65	1.54	BDL	0.69	BDL	5.00	BDL	0.45	0.71	BDL
Priscu-1	BDL	BDL	0.76	1.36	1.04	0.90	0.73	0.81	0.77	BDL	0.86	BDL	BDL	BDL	0.45	350.7	BDL
Priscu-2	0.41	BDL	1.07	1.29	1.08	1.03	0.92	0.86	0.77	BDL	1.12	BDL	BDL	BDL	0.91	5.71	0.43
Priscu-3	0.27	BDL	0.61	1.57	1.26	1.03	0.92	0.75	1.54	BDL	0.86	BDL	3.33	BDL	0.45	2.14	BDL
Vincent-1	0.27	BDL	0.61	1.86	1.49	1.29	0.83	0.70	0.77	BDL	0.86	BDL	BDL	BDL	1.36	319.3	1.30
Vincent-2	0.32	BDL	1.07	1.57	1.33	1.16	0.93	0.81	0.77	BDL	0.86	5.00	BDL	BDL	1.82	4.29	3.48
Blood Falls	0.29	BDL	0.61	1.07	0.85	0.77	2.23	0.86	1.54	BDL	0.78	BDL	8.33	BDL	0.91	1.43	0.87
Lawson-1	0.27	BDL	0.76	2.07	1.66	1.29	0.85	0.75	0.77	BDL	0.69	BDL	BDL	BDL	0.91	1.43	0.87
Lyons-1	0.39	BDL	0.92	1.29	1.07	1.16	1.44	0.86	0.77	BDL	1.21	BDL	BDL	BDL	2.27	1.43	0.87
Santa Fe-1	0.37	BDL	0.76	0.79	0.60	0.65	1.04	0.86	0.77	BDL	0.78	BDL	BDL	BDL	0.91	0.71	0.87
Average	0.31	NA	0.79	1.49	1.18	1.07	1.05	0.80	0.95	NA	0.85	5.00	5.00	NA	0.94	53.13	1.14
Standard Deviation	0.06	NA	0.17	0.44	0.34	0.25	0.42	0.07	0.34	NA	0.18	NA	2.36	NA	0.57	125.3	0.98

*BDL = Below Detection Limit; †NA = Not Applicable.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeochem.2019.05.006.

References

Allibone, A.H., Cox, S.C., Smillie, R.W., 1993. Granitoids of the dry valleys area, southern Victoria Land: geochemistry and evolution along the paleozoic antarctic craton margin. N. Z. J. Geol. Geophys. 36, 299–316.
Atkins, C.B., Dickinson, W.W., 2007. Landscape modification by meltwater channels at margins of cold-based glaciers, Dry Valleys, Antarctica. Boreas 36, 47–55.
Bisson, K.M., Welch, K.A., Welch, S.A., Sheets, J.M., Lyons, W.B., Levy, J.S., Fountain, A.G., 2015. Patterns and processes of salt efflorescences in the McMurdo Region, Antarctica. Arctic Antarct. Alpine Res. 47, 407–425.
Bockheim, J.G., 1997. Properties and classification of cold desert soils from Antarctica. Soil Sci. Soc. Am. J. 61 (1), 224–231.
Canil, D., Lacourse, T., 2011. An estimate for the bulk composition of juvenile upper continental crust derived from glacial till in the North American Cordillera. Chem. Geol. 284 (3–4), 229–239.
Clarke, F.W., Washington, H.S., 1924. The Composition of the Earth's Crust. USGS Professional Paper 127, Washington, DC.
Conovitz, P.A., McKnight, D.M., MacDonald, L.H., Fountain, A.G., House, H.R., 1998. Hydrologic processes influencing streamflow variation in Fryxell Basin, Antarctica. In: Priscu, J.C. (Ed.), Ecosystem Dynamics in a Polar Desert: the McMurdo Dry Valleys, Antarctica. American Geophysical Union, Washington, DC.
Cooper, A.F., Adam, L.J., Coulter, R.F., Eby, G.N., McIntosh, W.C., 2007. Geology, geochronology, and geochemistry of a basanitic volcano, white Island, Ross Sea, Antarctica. J. Volcanol. Geotherm. Res. 165 (3–4), 189–216.
Daly, R.A., 1914. Igneous Rocks and Their Origin. McGraw-Hill, New York.
Dowling, C.B., Lyons, W.B., Welch, K.A., 2013. Strontium isotopic signatures of streams, Taylor Valley, Antarctica, revisited: the role of carbonate mineral dissolution. Aquat. Geochem. 19 (3), 231–240. https://doi.org/10.1007/s10498-013-9189-4.
Eyles, N., Sasseville, D.R., Slatt, R.M., Rogerson, R.J., 1982. Geochemical denudation rates and solute transport mechanism in a maritime temperature glacier basin. Can. J. Earth Sci. 19, 1570–1581.
Faure, G., 1998. Principles and Applications of Geochemistry, second ed. Prentice Hall, Upper Saddle, NJ.
Fedo, C.M., Nesbitt, H.W., Young, G.M., 1995. Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. Geology 10, 921–924.
Fortner, S.K., Tranter, M., Fountain, A., Lyons, W.B., Welch, K.A., 2005. The geochemistry of supraglacial streams of Canada glacier, Taylor Valley (Antarctica), and their evolution into proglacial waters. Aquat. Geochem. 11https://doi.org/10.1007/s10498-004-7373-2. 391–41.
Fountain, A.G., Dana, G.L., Lewis, K.J., Vaughn, B.H., McKnight, D.M., 1998. Glaciers of the McMurdo dry valleys, southern Victoria Land, Antarctica. In: Priscu, J.C. (Ed.), Ecosystem Dynamics in a Polar Desert: the McMurdo Dry Valleys, Antarctica. American Geophysical Union, Washington, D. C.
Fountain, A.G., Lyons, W.B., Burkins, M.B., Dana, G.L., Doran, P.T., Lewis, K.J., McKnight, D.M., Moorhead, D., Parsons, A.N., Priscu, J.C., Wall, D.H., Wharton Jr., R.A., Virginia, R.A., 1999. Physical controls on the Taylor Valley ecosystem, Antarctica. Bioscience 49, 961–971.
Gaillardet, J., Dupre, B., Allegre, C.J., 1999. Geochemistry of large river suspended sediments: silicate weathering or recycling tracer? Geochmicia et Cosmochimica Acta 63 (23/24), 4037–4051.
Gallet, S., Jahn, B., Van Vliet Lanoë, B., Dia, A., Rossello, E., 1998. Loess geochemistry and its implications for particle origin and composition of the upper continental crust. Earth Planet. Sci. Lett. 156, 157–172.
Gibson, E.K., Wentworth, S.J., McKay, D.S., 1983. Chemical weathering and diagenesis of a cold desert soil from Wright Valley, Antarctica: an analog of Martian weathering processes. J. Geophys. Res. 88, A912–A928. https://doi.org/10.1029/JB088iS02p0A912.
Goldschmidt, V.M., 1933. Grundlagen der quantitaven Geochemie (Fundamentals of quantitative Geochemistry). Fortschritte der Mineralogie, Kristallographie und Petrographie 17, 495–530.
Gooseff, M.N., McKnight, D.M., Lyons, W.B., Blum, A., 2002. Weathering reactions and hyporheic exchange controls on stream water chemistry in a glacial meltwater stream in the McMurdo Dry Valleys. Water Resour. Res. 38 (12) 15-1-15-7.
Gunn, B.M., 1966. Model and element variation in Antarctic tholeiites. Geochem. Cosmochim. Acta 30, 881–920.
Hall, B.L., Denton, G.H., Hendy, C.H., 2000. Evidence from Taylor Valley for a grounded ice sheet in the Ross Sea, Antarctica. Geogr. Ann. 82A (2–3), 275–303.
Hambrey, M.J., Fitzsimons, S.J., 2010. Development of sediment-landform associations at cold glacier margins, Dry Valleys, Antarctica. Sedimentology 57 (3), 857–882.
Haskell, T.R., Kennett, J.P., Smith, G., Willis, I.A.G., 1965. The geology of the middle and lower Taylor Valley of south Victoria Land, Antarctica. Trans. R. Soc. N. Z. Geol. 2 (12), 169–186.
Higgins, S.M., Denton, G.H., Hendy, C.H., 2000. Glacial geomorphology of Bonney drift, Taylor Valley, Antarctica. Geogr. Ann. 82A (2–3), 365–389.
Hodgkins, R., Tranter, M., Dowdeswell, J.A., 1997. Solute provenance, transport, and denudation in a high Arctic glacierized catchment. Hydrol. Process. 11, 1813–1832.
Hu, Z., Gao, S., 2008. Upper crustal abundances of trace elements: a revision and update. Chem. Geol. 253, 205–221. https://doi.org/10.1016/j.chemgeo.2008.05.010.
Kyle, P.R., 1981. Mineralogy and geochemistry of a basanite to phonolite sequence at Hut Point Peninsula, Antarctica, based on cores from Dry Valley Drilling Project drill holes 1, 2 and 3. J. Petrol. 22 (4), 451–500.
McLennan, S.M., Hemming, S., McDaniel, D.K., Hanson, G.N., 1993. Geochemical approaches to sedimentation, provenance and tectonics. In: Geological Society of America Special Paper 284, pp. 21–40.
Mosley, M.P., 1988. Bedload transport and sediment yield in the Onyx River, Antarctica. Earth Surf. Process. Landforms 13 (1), 51–67.
Nesbitt, H.W., Wilson, R.E., 1992. Recent chemical weathering of basalts. Am. J. Sci. 292, 740–777.
Nesbitt, H.W., Young, G.M., 1982. Early Proterozic climates and plate motions inferred from major element chemistry of lutites. Nature 299, 715–717.
Nesbitt, H.W., Young, G.M., 1984. Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. Geochimica et Cosmochimica Acts 48, 1523–1534.
Nesbitt, H.W., Young, G.M., 1996. Petrogenesis of sediments in the absence of chemical weathering: effects of abrasion and sorting on bulk composition and mineralogy. Sedimentology 436, 341–358.
Nesbitt, H.W., Young, G.M., McLennan, S.M., Keays, R.R., 1996. Effects of Chemical Weathering and sorting on the petrogenesis of siliciclastic sediments with implications for provenance studies. J. Geol. 104 (5), 525–542.
Nezat, C.A., Lyons, W.B., Welch, K.A., 2001. Chemical weathering in streams of a polar desert (Taylor Valley, Antarctica). GSA Bulletin 113 (11), 1401–1408.
Roser, B.P., Korsch, R.J., 1999. Geochemical characterization, evolution and source of a Mesozoic accretionary wedge: the Torlesse terrance, New Zealand. Geol. Mag. 136 (5), 493–512.
Roser, B.P., Coombs, D.S., Korsch, R.J., Campbell, J.D., 2002. Whole-rock geochemical variations and evolution of the arc-derived Murihiku Terrane, New Zealand. Geol. Mag. 139 (6), 665–685.
Rudnick, R.L., Gao, S., 2005. Composition of the continental crust. In: In: Rudnick, R.L. (Ed.), Treatise on Geochemistry, vol. 3 Elsevier, Boston.
Stuiver, M., Denton, G.H., Hughes, T.J., Fastook, J.L., 1981. History of the marine ice sheet in West Antarctica during the last glaciation; a working hypothesis. In: Denton, G.H., Hughes, T.J. (Eds.), The Last Great Ice Sheets. John Wiley and Sons, New York.
Taylor, S.R., 1965. The Application of Trace Element Data to Problems in Petrology. In: In: Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C. (Eds.), Physics and Chemistry of the Earth, vol. 6 Pergamon, Oxford.
Taylor, S.R., 1969. Trace element chemistry of andesites and associated calc-alkaline rocks. In: McBirney, A.R. (Ed.), Proceedings of the Andesite Conference. Department of Geology and Mineral Industries: Oregon.
Taylor, S.R., McLennan, S.M., 1985. The Continental Crust: its Composition and Evolution. Wiley, Oxford.
Toner, J.D., Sletten, R.S., Prentice, M.L., 2013. Soluble salt accumulations in Taylor Valley, Antarctica: implications for paleolakes and Ross Sea ice sheet dynamics. J. Geophys. Res.: Earth Surface 118, 1–18. https://doi.org/10.1029/2012JF002467.
Tranter, M., 2004. Geochemical weathering in glacial and proglacial environments. In: In: Drever, J. (Ed.), Treatise on Geochemistry, vol. 5 Elsevier, Amsterdam.
Ugolini, F.C., Jackson, M.L., 1982. Weathering and mineral synthesis in Antarctic soils. In: Craddock, C. (Ed.), *Antarctic Geoscience* (IUGS Series B No 4). University of Madison Press, Wisconsin.
Wedepohl, K.H., 1995. Ingerson Lecture: the composition of the continental crust. Geochem. Cosmochim. Acta 59 (7), 1217–1232.
Welch, S.A., Welch, K.A., Bisson, K.M., Doran, P., Dowling, C.B., Lyons, W.B., 2013. Chemical weathering and mineral reaction textures in a polar desert—examples from the McMurdo Dry Valleys, Antarctica. Geol. Soc. Am. Abstr. Progr. 45 (7), 550.
Wilch, T.I., Lux, D.R., Denton, G.H., McIntosh, W.C., 1993. Minimal Pliocene-Pleistocene uplift of the dry valleys sector of the Transantarctic Mountains: a key parameter in ice sheet reconstructions. Geology 21, 841–844.
Wright, A.C., Kyle, P.R., 1990. Taylor and wright valleys. In: LeMasurier, W.E., Thomson, J.W. (Eds.), Volcanoes of the Antarctic Plate and Southern Oceans. American Geophysical Union, Washington, DC.
Young, G.M., Nesbitt, H.W., 1998. Processes controlling the distribution of Ti and Al in weathering profiles, siliciclastic sediments and sedimentary rocks. J. Sediment. Res. 68 (3), 448–455.