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Strontium Isotopic Signatures of the Streams and Lakes of Taylor Valley, Southern Victoria Land, Antarctica: Chemical Weathering in a Polar Climate

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Abstract. We have collected and analyzed a series of water samples from three closed-basin lakes (Lakes Bonney, Fryxell, and Hoare) in Taylor Valley, Antarctica, and the streams that flow into them. In all three lakes, the hypolimnetic waters have different $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than the surface waters, with the deep water of Lakes Fryxell and Hoare being less radiogenic than the surface waters. The opposite occurs in Lake Bonney. The Lake Fryxell isotopic ratios are lower than modern-day ocean water and most of the whole-rock ratios of the surrounding geologic materials. A conceivable source of Sr to the system could be either the Cenozoic volcanic rocks that make up a small portion of the till deposited in the valley during the Last Glacial Maximum or from marble derived from the local basement rocks. The more radiogenic ratios from Lake Bonney originate from ancient salt deposits that flow into the lake from Taylor Glacier and the weathering of minerals with more radiogenic Sr isotopic ratios within the tills. The Sr isotopic data from the streams and lakes of Taylor Valley strongly support the notion documented by previous investigators that chemical weathering has been, and is currently, a major process in determining the overall aquatic chemistry of these lakes in this polar desert environment.

Introduction

The role of chemical weathering in cold climatic regions where both glaciers and/or cryogenic processes occur has received much attention in the past few years due to two important questions: 1) do colder temperatures result in lower chemical weathering rates, and 2) does atmospheric CO_2 drawdown take place during glacial times and/or times of tectonic uplift where mechanical weathering by glaciers is coupled with chemical weathering? Authors have speculated that chemical weathering rates in glaciated watersheds have a profound effect on carbon fluxes and turnover rates, and have been responsible for the increase in the Sr isotopic signature of the oceans (Munhoven and Francois, 1994; Hodell et al., 1991). On the other hand, other

researchers have suggested that weathering rates were not enhanced during the last glacial period, but rather were enhanced during the relatively short period of deglaciation, when surface water flows increased (Gibbs and Kump, 1994). Clearly, the role of glaciers, especially polar ones, in global chemical weathering processes is not agreed upon and definitely not well understood.

Although a number of excellent studies evaluating weathering in glaciated watersheds have been published in the past few years (e.g., Anderson et al., 1997), only two involved a “cold-based” glacier (Hodgkins et al., 1997, 1998). Most investigations of chemical weathering in glaciated regions have involved temperate or “warm-based” glaciers. These studies have indicated that solute fluxes are above the global average, have unique geochemical signatures (i.e., higher Ca^{2+} and K^+ and lower H_4SiO_4), and are derived largely from non-silicate sources (Anderson et al., 1997). Recent work by our group (e.g., Lyons et al., 1997; Nezat et al., 2001) and others (Maurice et al., 2002) has shown that within the channels and hyporheic zones of the streams in McMurdo Dry Valleys, Antarctica, chemical weathering does occur and that the rates per unit area can be as high as rates in temperate systems. In glaciated environments, where till and morainal material can be a mixture of many rock types, discerning what minerals are being weathered can be difficult. In a general way, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of water reflects the lithologic components with which it has been in contact. Felsic rocks are enriched in K^+ and Rb^+ relative to mafic rocks and, therefore, have higher (more radiogenic) ^{87}Sr concentrations from the decay of ^{87}Rb . Rocks and minerals enriched in Ca^{2+} relative to K^+ tend to have lower (less radiogenic) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Several types of igneous, metamorphic and sedimentary rocks can be found in the till that covers the floor of Taylor Valley. It was hoped that strontium isotopes could be used as a tool to help discern the proportions of the geologic material undergoing chemical weathering within the stream channels and their hyporheic zones.

McMurdo Dry Valleys

We present data from the McMurdo Dry Valleys (MCM) region of Southern Victoria Land; specifically, Taylor Valley (TV) at $\sim 78^\circ\text{S}$ and $160\text{--}164^\circ\text{E}$ (Figure 1). The MCM comprise the largest ice-free area in Antarctica ($\sim 4800\text{ km}^2$). They are located on the western coast of the Ross Sea $\sim 100\text{ km}$ west of the USA scientific base, McMurdo Station. The MCM are considered to be a polar desert with a mean annual temperature of $\sim -20^\circ\text{C}$, and a precipitation rate of $<10\text{ cm yr}^{-1}$. Taylor Valley is a mosaic of ice-covered lakes, ephemeral streams, soils and surrounding glaciers (Figure 1). Since 1993, it has been the site of a Long Term Ecological Research (LTER) study. The geology of TV consists of four primary rock types: Precambrian to Cambrian metasediments including schists, argillites, quartzites, and marbles; Paleozoic age intrusive rocks (i.e., granites and granodiorites); the Jurassic age Ferrar Dolerite; and Cenozoic age McMurdo Volcanics. An additional rock type, the Beacon Supergroup is also present at higher elevations in the sur-

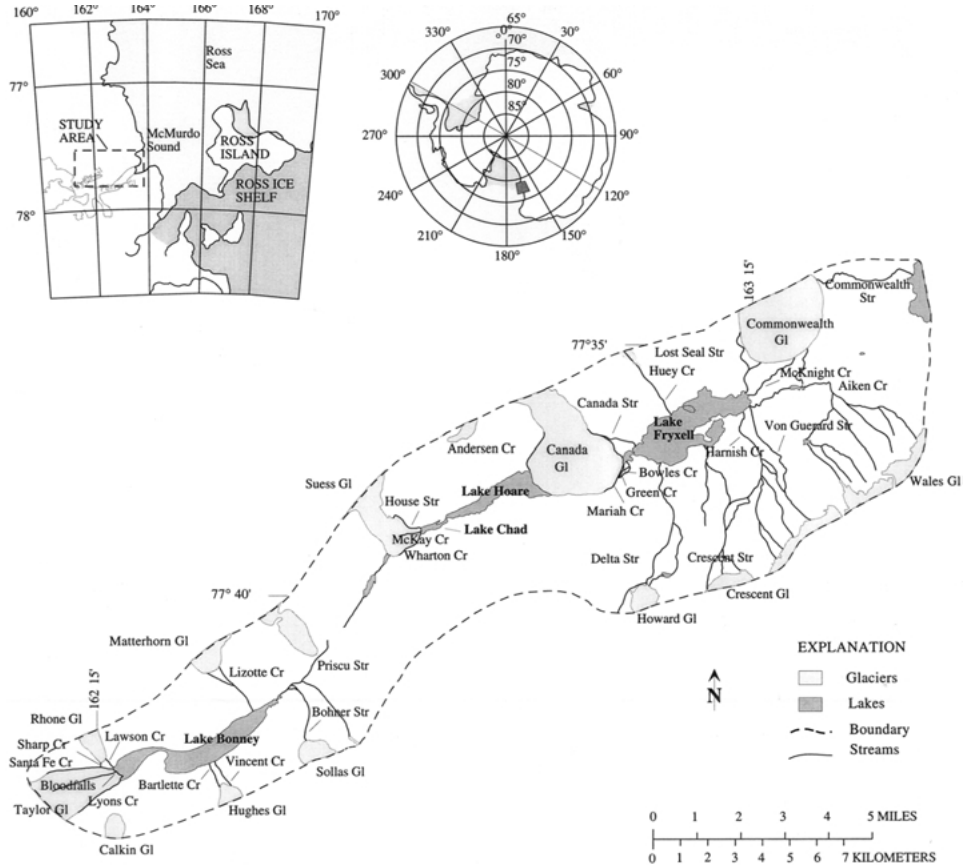


Figure 1. Map of Taylor Valley, southern Victoria Land, Antarctica (adapted from Lyons et al., 1998a).

rounding valleys. The first two types are collectively referred to as the “Basement Complex”. In addition, the valley floor is covered with Quaternary glacial, alluvial, and lacustrine deposits. The glacial deposits have been produced by 1) the intrusion of the West Antarctic Ice Sheet (i.e., the Ross Glaciation) into the valley entrance during the Last Glacial Maximum, and 2) the advance and retreat of Taylor Glacier, a terminal glacier of the East Antarctic Ice Sheet, and the alpine glaciers during interglacial times (Hendy et al., 1977). Therefore, the glacial tills and moraines on the valley floor are a complex mix of material from the greater McMurdo region that includes debris of the four primary rock types outlined above plus sandstones and shales of the Beacon Formation.

Glacier melt occurs intermittently from late November into late January (Conovitz et al., 1998). The glacier melt water flows via stream channels to the lakes. Flow is highly variable, on daily, seasonal, and inter-annual time scales. Stream flow during the 1980s was, in general, much higher than during the 1990s (McKnight et al., 1999). Because of this great variability in stream flow into the lakes, it

is extremely difficult to establish long-term mass fluxes of chemicals into the lakes (Lyons et al., 1998a). The lakes are perennially ice covered, chemically stratified, closed-basin lakes. Lake Bonney has two distinct lobes separated by a sill at ~13 m depth. The hypolimnia of the lakes are chemically distinct, with the hypolimnion waters of Lake Bonney being hypersaline, Lake Fryxell being brackish, and Lake Hoare being fresh. It is believed that the differences are due to their relative ages and past climatic histories (Matsubaya et al., 1979; Lyons et al., 1998b). Because of their chemical stratification and their ice covers, the lakes are dominated by diffusive mixing and little advection is thought to occur in these lakes (Spigel and Priscu, 1998). As a result, the solutes in the hypolimnia of Lake Fryxell and Lake Bonney represent input from 700–2400 yrs BP (Matsubaya et al., 1979; Lyons et al., 1998b). The differences between the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the surface and bottom waters therefore, represent changes in the Sr isotopic input into these lakes over that time period.

Numerous authors over the past two decades have either argued explicitly or implicitly that chemical weathering occurs in the McMurdo Dry Valleys (e.g., Jones and Faure, 1978; Keys and Williams, 1981; Green et al., 1988). For example, earlier Sr isotope work by Jones and Faure (1978) demonstrated the input of radiogenic Sr (compared to marine aerosol) into the surface waters of these lakes. On the other hand, abundant evidence exists delineating the “ancient” ages of many of the surface features within the dry valleys, particularly in areas inland and/or at higher elevation (>100 m above sea level) (Marchant et al., 1993). In the MCM, abundant liquid water, where chemical weathering can occur, exists only in a very few locations for more than a few hours at a time – the streambeds, floodplains and hyporheic zones of the streams draining the alpine and piedmont glaciers in the valleys. Hence, we have focused on these streams and their floodplains during the few weeks of the austral summer when glacier melt occurs.

Sample Collection and Analysis

Samples were collected in the 1994–95 austral summer from Lake Fryxell, Lake Hoare and both lobes of Lake Bonney using standard limnological techniques (Welch et al., 1996). The samples were filtered through 0.4 μm NucleoporeTM filters and acidified soon after collection. Stream water samples were collected by hand by submerging a wide mouth bottle into the deepest part of the stream channel and samples were processed in the same manner as the lake waters, except that the stream samples for Sr isotope analysis were filtered after return to the United States. The Sr isotopic analyses were performed at the USGS facility at Menlo Park, California, using a Finnigan MAT 261 multi-collector mass spectrometer (Bullen et al., 1996). The one exception was the sample from Blood Falls which was analyzed by Geochron Laboratories, Cambridge, MA. All reported values of $^{87}\text{Sr}/^{86}\text{Sr}$ have been corrected for natural and analytical stable isotope fractionation to $^{87}\text{Sr}/^{86}\text{Sr} = 8.37521$ and the measurements are precise to 0.00002 at the 95%

confidence level, which is better than the older work of Jones and Faure (1978). The mass spectrometer typically reports a value of 0.71024 for NBS987 Sr metal standard (Bullen et al., 1996). A number of lake water sample aliquots were analyzed in replicate. They yielded $^{87}\text{Sr}/^{86}\text{Sr}$ variations of 0.01% or less. Additional samples were collected from streams in 1994–95 and 1995–96, and from the lakes in 1997–98. Major element concentrations were analyzed by ion chromatography using the procedure outlined in Welch et al. (1996) with the analytical precision being better than $\pm 5\%$. Rb and Sr in stream waters were analyzed using a Perkin-Elmer Elan 6000 Inductively Coupled Plasma-Mass Spectrometer (ICP-MS). The difference between certified and measured concentrations of SLRS-3 reference water was better than 5% for Rb and 3% for Sr.

Results

Profiles of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the three lakes are shown in Figure 2 and lake surface and stream $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from Taylor Valley are presented in Table I. Modern-day seawater (and recent marine aerosol) and average global runoff ratios are 0.70916 and 0.7119, respectively (Palmer and Edmond, 1989). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the majority of the rock types within the MCM area are summarized in Figure 3. These Sr isotopic ratios range from the relatively high ratios of the basement metamorphic and intrusive igneous rocks (0.7112–0.7442) to lower ratios of the volcanic rocks (0.7033–0.7043).

In Lake Fryxell and Lake Hoare, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios become less radiogenic with depth, while in both lobes of Lake Bonney, the ratios increase slightly with depth (Figure 2). In addition, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the surface waters of the lakes become more radiogenic with distance from the coast (Figure 1), with Lake Fryxell being 0.70895, Lake Hoare 0.71057, and Lake Bonney 0.71187–0.71204 (Table I). Jones and Faure (1978) previously recognized this increase in Sr isotopic ratios of the lake waters of Taylor Valley. There are also substantial variations in the stream data with ratios ranging from 0.70823 (McKay Creek) to 0.71333 (Priscu Stream). Another important result is that all the inflow waters to Lake Fryxell are more radiogenic than the surface water of the lake, with the exception of Harnish Creek (Table I). This implies that the present inflow of Sr into Lake Fryxell may not be reflective of the isotopic input of the past. In Lake Hoare, on the other hand, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the lake surface falls between the isotopic range of the various inflow waters. Lake Bonney's surface waters have an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio that falls between stream inflow and Blood Falls input. (Blood Falls is a frozen, saline discharge at the terminus of Taylor Glacier that contains abundant amounts of halite and aragonite (Black et al., 1965).) Blood Falls is thought to be trapped, frozen seawater dating back to before the Pleistocene Epoch when these valleys were fjords. We have previously estimated it to be the major contributor of Cl^- (and probably other solutes) to Lake Bonney (Lyons et al., 1998b, Lyons et al., 1998c).

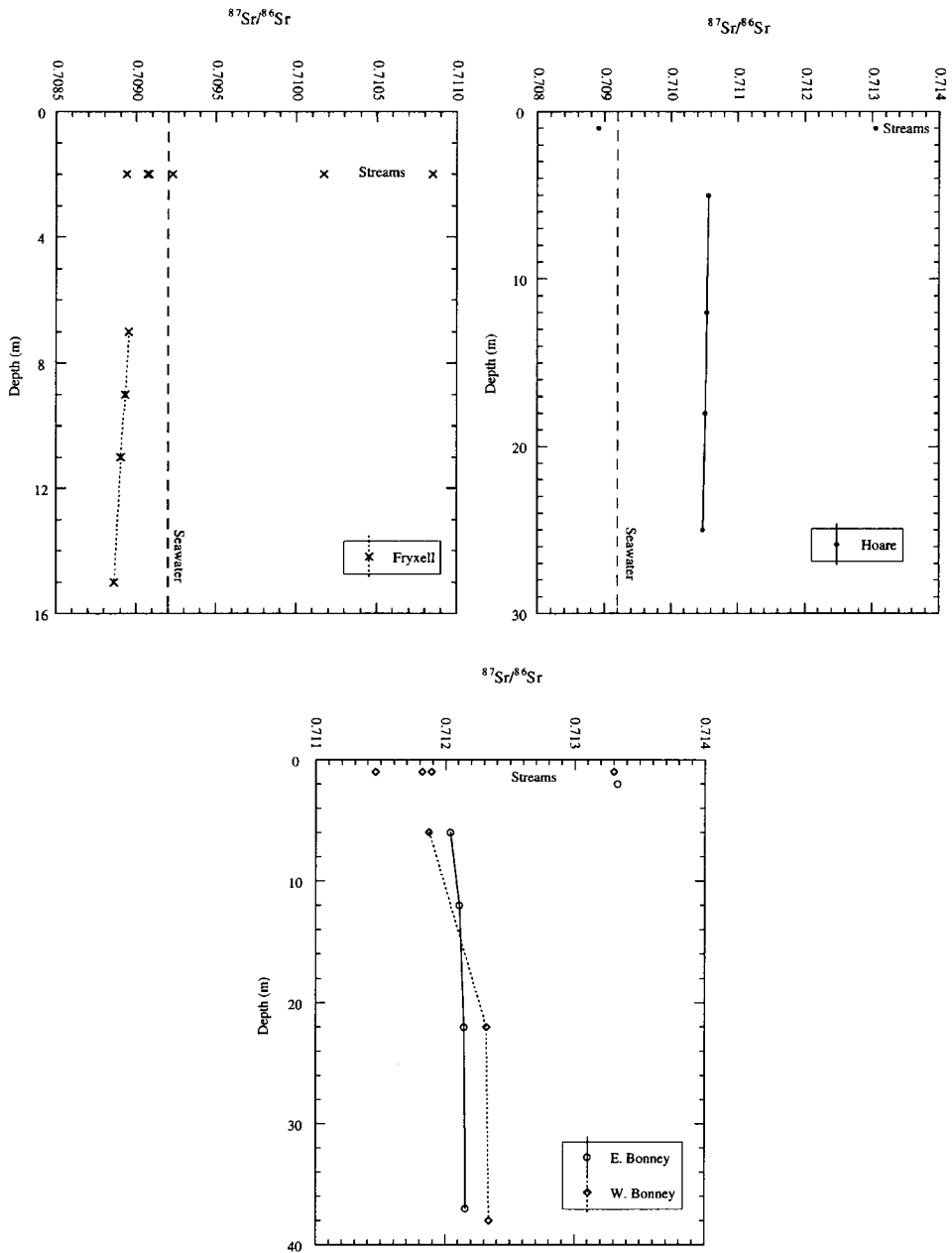


Figure 2. Sr isotope distribution in the Taylor Valley lakes versus depth. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the stream waters are also shown for comparison. The symbols correspond within each basin.

Table 1. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for Taylor Valley streams and surface waters from Lakes Bonney, Fryxell, and Hoare.

Lake Fryxell (7 m)	0.70895
Lost Seal Creek	0.70907
Green Creek	0.71017
Harnish Creek	0.70894
Delta Creek	0.70908
Canada Stream	0.71085
Von Guerard Stream	0.70923
Lake Hoare (5 m)	0.71057
Andersen Creek	0.71305
McKay Creek	0.70823
House Creek	0.70891
Wharton Creek	0.70902
Lake Bonney (East) (6 m)	0.71204
Priscu Stream	0.71333
Lake Bonney (West) (6 m)	0.71187
Lawson Creek	0.71330
Santa Fe Creek	0.71182
Lyons Creek	0.71189
Blood Falls	0.71146

Table II shows the dissolved Sr and Rb concentrations from streams from the various sub-basins in Taylor Valley collected primarily during 1995–96. Except for the streams that emanate from Blood Falls, the streams in the southeastern portion of the Fryxell Basin have the highest molar Sr:Rb ratios (Table II). The single value from the Onyx River, in Wright Valley, has the lowest Sr:Rb ratio (Table II). The overall trend reflected in the basins support the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the surface waters of the lakes, in that Lake Fryxell is the least radiogenic. The extremely high Sr:Rb ratio of the Taylor Glacier streams does not, however, fit this pattern, as the Sr in these streams is more radiogenic than both current seawater (0.70916) and Blood Falls (0.71146) (Figure 2). These data imply that there is an additional source of weathering- derived Sr in the Taylor Glacier streams besides Blood Falls. These data also suggest that the Sr has been derived from more radiogenic sources than the Sr currently entering from the Bonney basin streams.

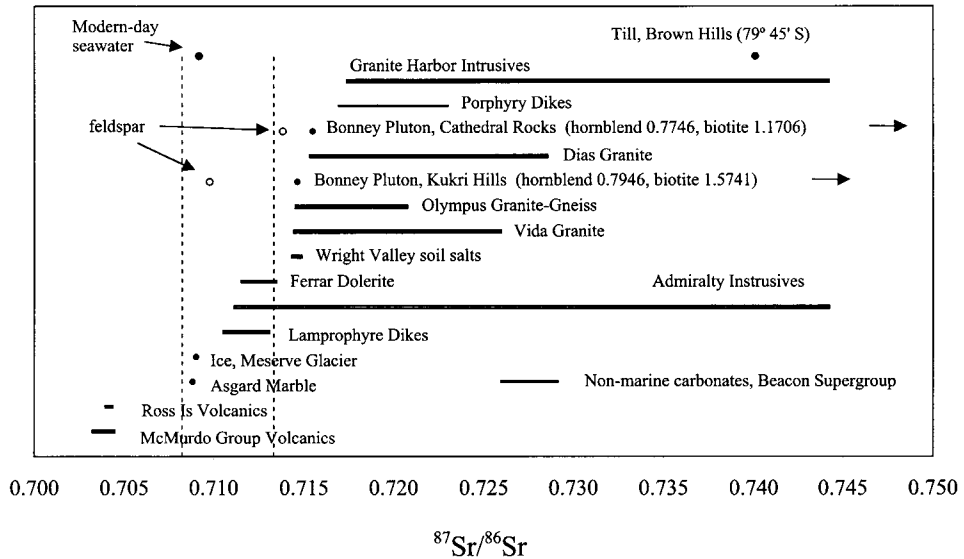


Figure 3. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for various geologic units in the McMurdo Dry Valleys region. The vertical lines represent the minimum and maximum ratios measured in the Taylor Valley streams. Sources of data are Allibone et al. (1993), Borg et al. (1987), Faure and Barrett (1973), Faure and Felder (1981), Faure et al. (1974), Hart and Kyle (1993), Jones and Faure (1967), and Jones and Faure as reported in Friedman et al. (1995).

Discussion

CHEMICAL WEATHERING AS A MAJOR SOURCE OF DISSOLVED STRONTIUM

As suggested by the earlier work of Jones and Faure (1978), chemical weathering is most likely the source of modern Sr^{2+} to the lakes in Taylor and Wright Valleys. Compared to present-day seawater, the surface waters of Lakes Fryxell, Hoare, and Bonney are enriched in Sr^{2+} relative to Cl^- (Figure 4). This strongly suggests that present-day marine-derived aerosol or glacier/snow melt cannot be the sole source of Sr^{2+} to the lakes. With the exception of the hypolimnetic waters of the east lobe of Lake Bonney, the lake waters also have Sr:Ca ratios that are less than seawater ratios (Figure 5). These ratios are well below the variability of Sr:Ca observed in the modern ocean (DeVilliers, 1999), and must reflect either a source of alkaline earths enriched in Ca^{2+} (relative to Sr^{2+}) or preferential solubilization of Ca^{2+} from the geologic material in the basins. The Sr:Ca ratios in the TV stream waters are also much higher than streams draining crystalline rocks where disseminated calcite is the major source of Ca^{2+} , suggesting perhaps that the Sr:Ca ratio is being controlled primarily by the dissolution of silicate minerals, such as plagioclase, rather than calcite (White et al., 1999). An evaluation of the potential sources follows.

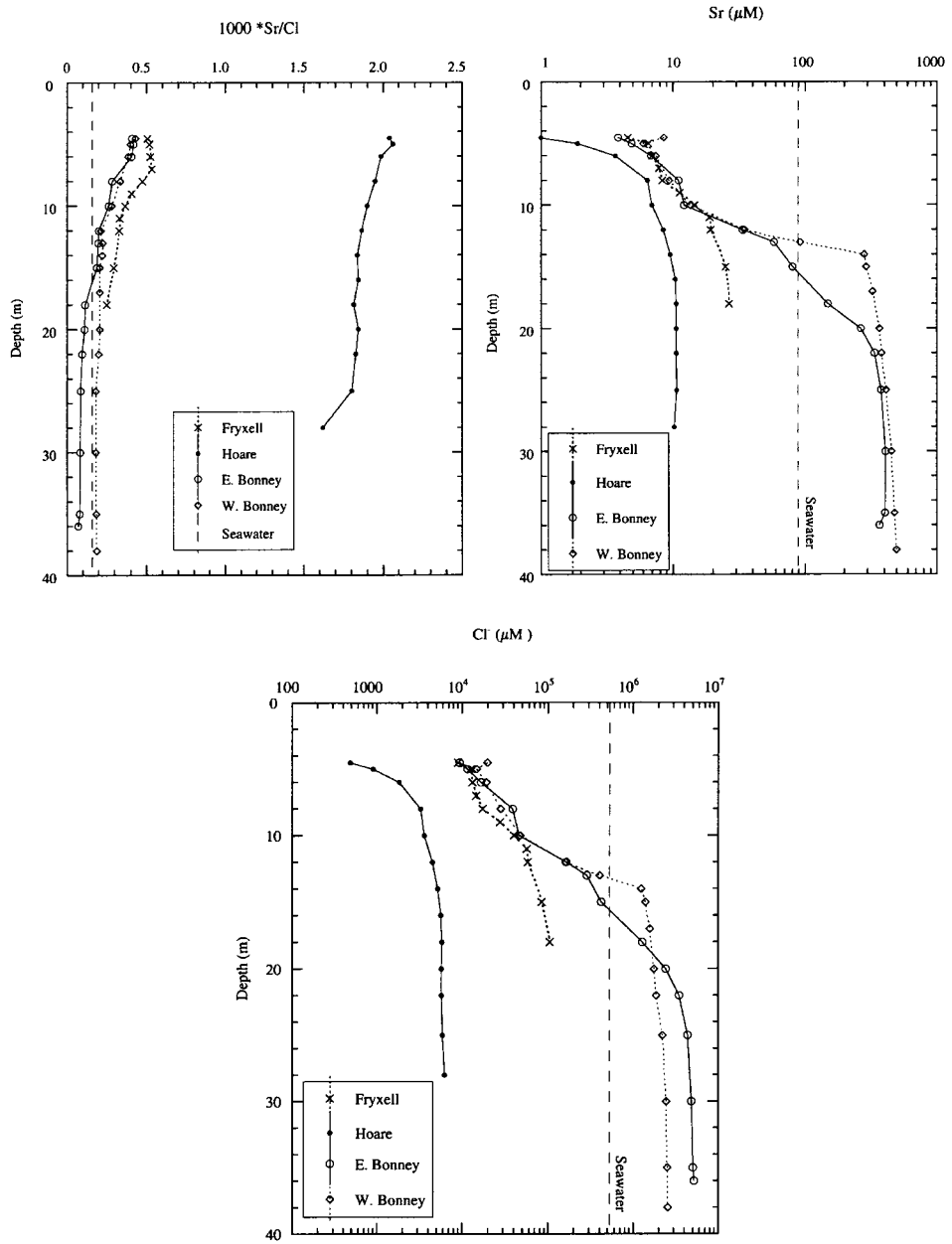


Figure 4. $Sr^{2+}:Cl^{-}$, Sr^{2+} , and Cl^{-} profiles in Taylor Valley lakes.

Table II. Sr, Rb, Ca and Cl data from McMurdo Dry Valley streams.

Basin/River		Rb (nM)	Sr (μ M)	Sr:Rb	Ca (mM)	Cl (mM)
W Bonney	(mean)*			(202)		
Lawson	6 Jan 1996	4.3	0.3	72	0.120	0.558
Lyons	10 Dec 1995	7.9	2.9	365	2.135	2.210
Santa Fe	1 Dec 1995	10.2	3.2	310	2.722	1.477
Sharp	17 Jan 1996	7.5	0.5	61	0.208	0.389
E Bonney	(mean)			(65)		
Bartlette	17 Jan 1996	9.8	0.4	41	0.128	0.189
Priscu	15 Dec 1994	23.1	2.4	102	0.626	1.225
Vincent	17 Jan 1996	10.6	0.6	52	0.181	0.079
Hoare	(mean)			(58)		
Andersen	22 Jan 1996	7.7	0.5	67	0.179	0.111
House	4 Dec 1995	9.4	0.5	49	0.186	0.068
NW Fryxell	(mean)			(59)		
Andrews	13 Jan 1996	6.6	0.3	46	0.109	0.065
Bowles	13 Jan 1996	9.4	0.6	61	0.205	0.086
Canada	13 Jan 1996	8.3	0.2	24	0.079	0.064
Green	13 Jan 1996	4.1	0.4	108	0.116	0.080
Huey	12 Jan 1996	16.6	1.3	78	0.504	0.393
Mariah	16 Dec 1995	6.2	0.2	35	0.079	0.109
SE Fryxell	(mean)			(107)		
Aiken	28 Dec 1995	10.2	0.7	70	0.237	0.546
Crescent	12 Jan 1996	11.5	1.5	128	0.562	0.479
Delta	13 Jan 1995	10	1.3	125	0.441	0.309
Lost Seal	23 Jan 1995	5	0.4	89	0.175	0.334
McKnight	17 Dec 1995	7.1	0.9	125	0.362	0.494
VonGuerard	12 Jan 1996	11.9	1.2	104	0.563	0.375
Wright Valley						
Onyx		27	0.3	11		

*Excluding Lyons and Santa Fe, the W Bonney mean is 67.

We have developed a simple model to quantify the relative contribution of each source of Sr in the streams of TV. There are only two primary sources of Sr to the streams: input from glacier melt, which is ultimately derived from aerosol/precipitation to the glaciers, and from the chemical weathering of the geologic materials within the stream bed and floodplains. Therefore, $Sr_{total} = Sr_{cw} + Sr_{precip}$, where the total Sr concentration is the sum of Sr derived from chemical weathering (Sr_{cw}) and that derived from glacier melt (Sr_{precip}). Strontium concentrations have not been determined in the glacier ice from the McMurdo region, but we can estim-

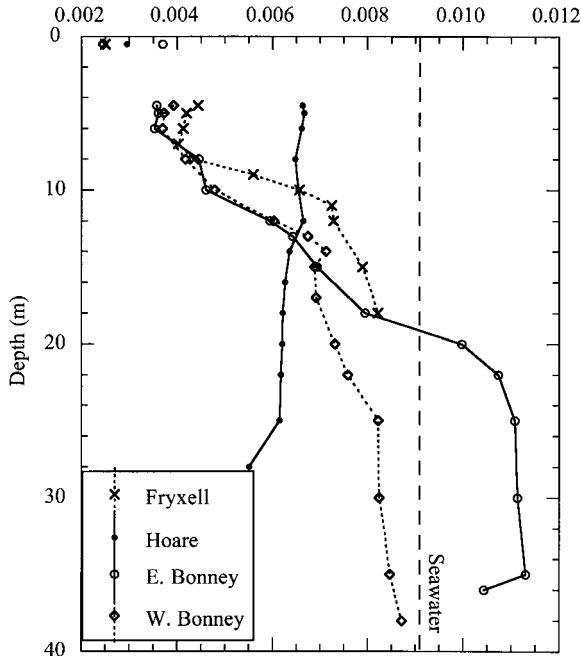


Figure 5. $\text{Sr}^{2+}:\text{Ca}^{2+}$ profiles in Taylor Valley lakes.

ate the Sr input from this source by assuming that the source of Sr to the aerosol is the nearby ocean, and the Sr input is related to the Cl^- concentration of the sample in this manner: $\text{Sr}_{\text{precip}} = [\text{Sr}/\text{Cl}]_{\text{sw}} \cdot \text{Cl}_{\text{precip}}^-$, where Sr/Cl is the present-day ratio in seawater. Assuming that all the Cl^- in the streams has originated from a marine source, the $\text{Sr}_{\text{precip}}$ can be calculated using the Cl^- data from the streams (Table II). The Sr isotopic ratio of glacier ice does indeed reflect present-day marine aerosol input as Meserve Glacier in Wright Valley has a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7090 (Figure 3). This, in turn, can be compared to the total Sr concentrations. $\text{Sr}_{\text{precip}}$ accounts for no more than 29% of the total Sr in the streams with an average of only 8% ($n = 21$). These data clearly indicate that the majority of the Sr in these streams is derived from chemical weathering, as suggested by Jones and Faure (1978).

In addition, ten stream sediment samples from Taylor Valley have been analyzed for their chemical composition and the data normalized to average continental crust are shown in Figure 6. (The absolute concentrations are shown in Appendix 1.) These sediments are enriched in Sr and Ca relative to continental crust, indicating a potential source of these elements to the stream waters. Ca:Sr ratios for the stream sediments range from 143 to 243 with lower ratios (i.e., higher relative Sr concentrations) in the southeast Fryxell Basin. The Taylor Valley sediment ratios are similar to the average continental crustal ratio of 204 (Wedepohl, 1995) but lower than dust ratios of 250 obtained from nearby Taylor Dome ice/snow in the East Antarctic Ice Sheet (Hinkley et al., 1997).

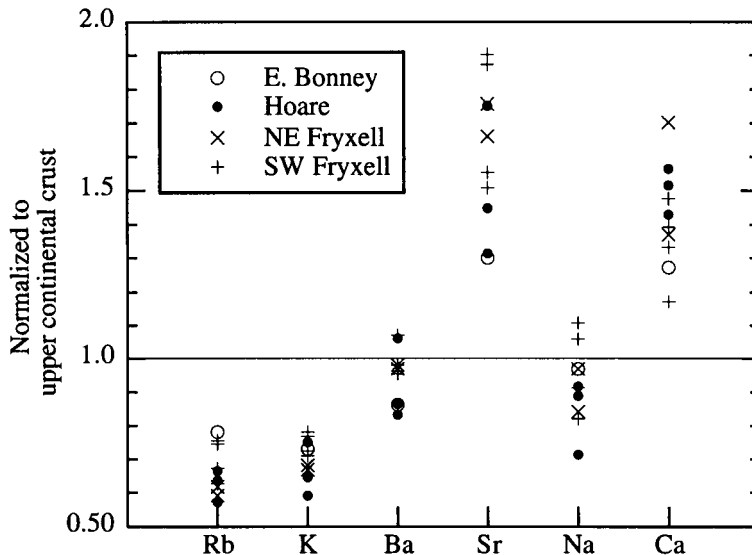


Figure 6. Taylor Valley sediments normalized to the upper crustal composition.

WEATHERING OF CARBONATES

Carbonate minerals (primarily CaCO_3) exist throughout the soils of Taylor Valley (Keys and Williams, 1981). The vast majority of this CaCO_3 is thought to have been produced *in situ* via weathering input of Ca^{2+} and HCO_3^- , and subsequently precipitated through freeze-drying and/or evaporation. Thus, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the CaCO_3 reflects that of the local geologic materials. The only other source of Sr to this CaCO_3 is through marine aerosol deposition on the glaciers and its subsequent transport via melt which, in turn, can be precipitated through evaporative processes. Unfortunately, no data exist for $^{87}\text{Sr}/^{86}\text{Sr}$ in authigenically-produced carbonate deposits within Taylor Valley. Claridge and Campbell (1977) have shown that in Taylor Valley, the soil carbonates are closely associated with the basement complex rocks. They speculate that the source of the Ca^{2+} is from the parent material. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) from soils in the Brown Hills ($79^\circ 45' \text{ E}$) yields very radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, suggesting that the source is also from the igneous basement complex (Faure and Felder, 1981). Soil salts leached from Wright Valley (to the north of Taylor Valley) have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7144–0.7148 (Figure 3). As mentioned previously, Blood Falls discharge is known to contain aragonite (Black et al., 1965). This might explain the high Sr:Rb ratios observed in the streams flowing from the Blood Falls area (Table II), as aragonite can have very high Sr^{2+} concentrations (Rimstidt et al., 1998). However, as mentioned above, the source of Sr^{2+} in Blood Falls must also be from another, more radiogenic source, because seawater (from which the aragonite is thought to have originally precipitated) has never reached a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio as high as Blood Falls (i.e., 0.71146) during Phanerozoic time (Burke et al., 1982).

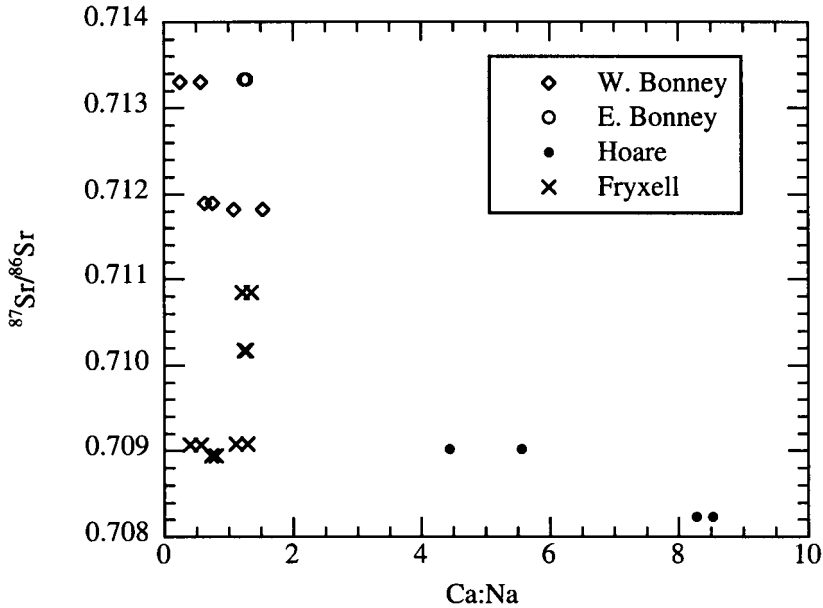


Figure 7. Sr isotopic composition of Taylor Valley streams vs Ca:Na.

Many studies have been recently conducted in order to understand the systematics of Sr isotopic variations during chemical weathering. Palmer and Edmond (1989) using a large data set for major river systems throughout the world demonstrated that rivers draining old, silicate dominated terranes have low total Sr concentrations with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios >0.710 , whereas those draining carbonates/evaporites have higher Sr concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios <0.709 . The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Taylor Valley streams is plotted versus Ca:Na in Figure 7. This trend is typical of that which is described by Palmer and Edmond (1989). The higher Ca:Na ratios and lower $^{87}\text{Sr}/^{86}\text{Sr}$ signatures undoubtedly represent streams dominated by CaCO_3 dissolution (in this case derived from marine aerosol originally), whereas the more radiogenic Sr isotopic ratios and lower Ca:Na ratios are from streams dominated by silicate mineral weathering.

SILICATE WEATHERING

As shown above, a major Sr source to the streams and lakes of TV must come from the weathering of geologic material within the stream channels. Jones and Faure (1967) demonstrated that the ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ found in surface waters of Wright Valley (Table III) were within the range of the isotopic composition of the geologic materials within the valley (Figure 3). They concluded that the Sr in the waters was derived solely from these materials.

Of all the silicic rocks in the region, only the McMurdo/Ross Island Volcanics have a $^{87}\text{Sr}/^{86}\text{Sr}$ whole rock value of less than 0.7106 (Figure 3). Even the feldspar

Table III. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of waters from Wright Valley, Antarctica.

Onyx River*	0.7144–0.7148
Lake Vanda*	0.7149 ± 0.0001
Don Juan Pond†	0.7185
Don Juan Pond inflow†	0.7154–0.7173

*Jones and Faure (1967).

†Friedman et al. (1995).

ratios for plutonic rocks are ~ 0.710 (Figure 3). The Ferrar Dolerites and associated dikes also yield a relatively high ratio (>0.710). As mentioned above, soils to the north of Taylor Valley, in Wright Valley, and tills to the south, in the Brown Hills, also have higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than modern-day seawater (Figure 3). McMurdo Volcanics, on the other hand, have ratios in the range of 0.70330–0.704439 (Figure 3).

The geology of Taylor Valley is well known and the volcanic rocks of the McMurdo series have been reconnaissance mapped by numerous investigators, and most recently summarized by Wright and Kyle (1990). The McMurdo Volcanic Group outcrops in the Lake Bonney and Hoare watersheds but at elevations above the stream channels. (Wright and Kyle, 1990). However, abundant ($>25\%$) McMurdo Group lithic fragments have been found 4 km east of Lake Fryxell at depths of less than 10 m (Porter and Beget, 1981). This volcanic rock debris was moved into the Fryxell watershed as the West Antarctic Ice Sheet advanced during the LGM as part of the Ross Sea drift. In addition to this material, clasts of anorthoclase phonolite (an extrusive rock composed of alkali feldspar and nepheline) derived from Mt. Erebus, and considered part of the McMurdo Volcanic series, are commonly observed in the moraines in the MCM (Porter and Beget, 1981), including the Lake Fryxell watershed. (Mt Erebus is an active volcano located on Ross Island, east of Taylor Valley (Figure 1).)

Friedman et al. (1995) deduced, through mixing calculations, that the isotopic signature from rock weathering in Wright Valley was 0.7197. These authors concluded that a mixture of present-day aerosol input of ~ 0.7090 and the rock weathering contribution of 0.7197 would yield the observed ratios in the Onyx River and Lake Vanda (0.714–0.715). Because the Onyx River is the longest river on the continent, one might expect a higher contribution of weathered Sr than in the Taylor Valley streams, which are much shorter in length. This argument is supported by the extremely low Sr:Rb ratio observed by us in the Onyx River (Table II). McMurdo Volcanic Group outcrops are more abundant in the Onyx River drainage than in central and eastern Taylor Valley (Wright and Kyle, 1990), yet the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the Onyx River is higher (Table III). This suggests, but does not prove, that the weathering input of Sr in the MCM is dominated by the higher Sr isotopic ratios from felsic rocks.

ANCIENT SEAWATER

Because the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of seawater has varied through geologic time, absolute ages of marine salts, such as gypsum and carbonate rocks, can be obtained from Sr isotopic measurements. During the Cenozoic, the $^{87}\text{Sr}/^{86}\text{Sr}$ of seawater has become more radiogenic, having increased from ~ 0.70825 to its present-day value of ~ 0.7092 (Hodell et al., 1991). A $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.708875 measured in shell fragments in the Jason Glaciomarine Deposits (JGD) of central Wright Valley suggests that a fjord occupied this valley 9 ± 1.5 million years ago (Prentice et al., 1993). The fossil diatoms in these sediments also suggest a middle-to-late Miocene age (Prentice et al., 1993). These authors proposed an age of 5.5 ± 0.4 million years for the Prospect Mesa gravels, also interpreted to have been deposited in fjord conditions in Wright Valley ($^{87}\text{Sr}/^{86}\text{Sr} = 0.708975$). Cores drilled at the mouth of Taylor Valley contain deposits of late Miocene and/or early Pliocene age at ~ 172 m depth (Porter and Beget, 1981). Sand grains from these intervals suggest fluvial/aeolian transport to the marine environment rather than the glacially dominated transport of recent times. It is curious that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the bottom of Lake Fryxell is 0.70886, similar to the value obtained by Prentice et al. (1993) from the JGD. The equivalent Sr isotopic age would be ~ 10 million years (Hodell et al., 1991). It is unlikely that ancient seawater could have been retained in the valley given climatic fluctuation over this time period. Flushing by glacial melt water would have surely removed any remnants of marine waters or their salt residues.

SOURCES OF SR TO THE TAYLOR VALLEY LAKES

Lake Bonney

Blood Falls and the streams draining the Taylor Glacier region can contribute as much as 95% of the total Cl^- to the west lobe of Lake Bonney, especially in low-flow years. It is clear that the surface water of the west lobe of Lake Bonney is dominated by this Sr source, as the Sr isotopic ratios of Blood Falls, Santa Fe Creek, and Lyons Creek are very similar to the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the surface water of the lake. On the other hand, the surface waters of the east lobe of Lake Bonney have a higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratio representing input from the surface water of the west lobe (Spiegel and Priscu, 1998) and input from the more radiogenic streams, such as Priscu Stream (Table I).

The bottom water ratios of both lobes of Lake Bonney are similar to each other (0.71216 to 0.71234), but higher than the surface waters (Figure 2). The source of this Sr is unknown, but it is clear that it is not derived from Blood Falls or from ancient seawater, as previously speculated (Angino and Armitage, 1963). A yet to be discovered radiogenic weathering component must have been a major contributor. This more radiogenic Sr was introduced to the lake during the Last Glacial Maximum through the early Holocene period (Hall et al., 2000). These data strongly suggest that climatic variations have greatly affected the flux and source of Sr to these lakes through time.

Lake Hoare

Andersen Creek is the only inlet of substantial length to Lake Hoare. The other streams entering this lake do not show evidence of any significant silicate weathering component (Lyons et al., 1997). Andersen Creek does have a strong silicate weathering component as demonstrated by its $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, whereas the shorter streams entering the lake from the west have either a definite marine signature, such as Wharton Creek (Table I), or ratios even less than modern seawater. These streams (McKay, Wharton, and House Creeks) also have very high Ca:Na ratios, indicating abundant CaCO_3 dissolution. The low ratios of the $^{87}\text{Sr}/^{86}\text{Sr}$ in these streams may reflect input of ancient marine or carbonate Sr source, because the weathering of Cenozoic volcanics to the west would have yielded much higher H_4SiO_4 concentrations (Lyons et al., 1998a). In fact, the H_4SiO_4 concentrations in these streams are the lowest measured in the MCM (Lyons et al., 1998a).

The Lake Hoare $^{87}\text{Sr}/^{86}\text{Sr}$ profile indicates little difference from top to bottom. This supports the idea that Lake Hoare is relatively young (maybe as little as ~ 1000 yrs) compared to the other lakes in Taylor Valley, and that its sources of Sr have not changed over this time period (Lyons et al., 1998b). It is clear that Lake Hoare Sr is a mixture of the more radiogenic weathering input from the watershed, as demonstrated in Andersen Creek, and the less radiogenic component from the glaciers and shorter streams to the west. However, the major contribution must have come from weathering because the lake water is more radiogenic than either modern or Tertiary seawater.

Lake Fryxell

Of all the lakes in Taylor Valley, Lake Fryxell has the most perplexing $^{87}\text{Sr}/^{86}\text{Sr}$ signature. During the 1994–95 field season, over 65% of the water entering Lake Fryxell came from streams emanating from the Canada Glacier (Figure 1). These are represented in our data set by Canada Stream and Green Creek, which are the most radiogenic of all the streams measured in the Fryxell basin (Table I). Approximately 18% of the water came from the Commonwealth Glacier as represented by Lost Seal Creek, and the rest of the water entering the lake came from the glaciers in the southern portion of the basin (i.e., Harnish Creek, Delta Creek, and Von Guerard Stream, Figure 1, Table I). The Sr isotopic ratio of Harnish Creek is closest to the modern surface water from Lake Fryxell, however Harnish Creek accounts for less than 1% of the total flow. Assuming that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for all the Lake Fryxell Basin streams for which we do not have data is similar to nearby streams with the same glacier source, we can normalize the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to flow and calculate that the $^{87}\text{Sr}/^{86}\text{Sr}$ signature of Lake Fryxell surface water should be ~ 0.7096 . This calculation indicates that the Sr isotopic ratio of current surface water is less radiogenic than expected from the streams flowing into the lake. The stream flow in 1994–1995 was relatively low compared to the past flows of the late 1980s and early 1990s (McKnight et al., 1999). It may be that in higher flow years, there is more input from the less radiogenic Sr sources.

The least radiogenic Sr ratio observed in the MCM, 0.70886, is in the bottom of Lake Fryxell. Currently, there are three possible sources of this non-radiogenic Sr to the lake: 1) the selective weathering of Cenozoic volcanic rocks that occur in the moraines and glacial drift in the region, 2) weathering of the Asgard Marble, a unit of the basement complex, or 3) dissolution of ~ten-million-year old seasalt containing Sr. Based on the mineralogy of the moraines/till, especially in the eastern portion of the Fryxell Basin, we suggest that weathering of volcanic rocks has contributed a significant amount of Sr to Lake Fryxell. Reconstructions of past ice sheet movements indicate flow of the West Antarctic Ice Sheet from Ross Island in the east into Taylor Valley during the LGM (Hall et al., 2000). As mentioned above, this Ross Sea drift, which contains numerous phonolite erratics, also referred to as kenyite, can be observed as far into the valley as the Canada Glacier (Hall et al., 2000). This rare phonolite may contribute greatly, relative to its overall abundance, to the Sr isotopic budget of Lake Fryxell. In addition, the Asgard Marble occurs in the eastern portion of Taylor Valley. Although it does not crop out in the Lake Fryxell watershed, pieces of it are contained in the glacial drift believed to have been pushed inland from the Marble Point area (located northeast of the Fryxell watershed) during the Last Glacial Maximum (LGM). It has an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of ~ 0.7088 (Figure 3).

It is unlikely that the source of this lower $^{87}\text{Sr}/^{86}\text{Sr}$ in the Taylor Valley is from ancient seawater. Taylor Valley opens to McMurdo Sound and the Ross Sea without a significant barrier so that, if Wright Valley were inundated by seawater, Taylor Valley would have been inundated as well. Wilch et al. (1993) have estimated a total of 350–360 m uplift of Taylor Valley since the late Miocene. At the end of the LGM, outflow from Glacial Lake Washburn could have surely washed any salt accumulated out into the McMurdo Sound area. The Sr isotopic ratio of seawater is currently at its highest since the beginning of glaciations on the continent of Antarctica. The observed ratios that are higher than modern seawater (i.e., 0.70916) must have been derived from silicate mineral weathering.

$^{87}\text{Sr}/^{86}\text{Sr}$ Differences between the Epilimnion and Hypolimnion

Lake Hoare is thought to be a relatively young lake having only been in existence for the last ~ 1000 yrs (Lyons et al., 1998b). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in both the shallow and the deeper portions of the lake are similar and, as mentioned above, are within the range of the ratios of the streams entering the lake. Because the solutes in the hypolimnia of Lakes Bonney and Fryxell represent salt input into the lakes from much older time periods (Matsubaya et al., 1979; Lyons et al., 1998b), the differences in their $^{87}\text{Sr}/^{86}\text{Sr}$ signatures must represent real differences in the sources of Sr into these lakes in the past. The current, more radiogenic input to Lake Fryxell and the less radiogenic input to Lake Bonney must reflect a major change in the material being weathered within their basins. This change in $^{87}\text{Sr}/^{86}\text{Sr}$ in the past few decades may represent a response to higher stream flows and warmer conditions from the 1970s into the early 1990s (McKnight et al., 1999).

Conclusions

This paper presents a very complex picture of the Sr isotopic systematics of the Taylor Valley. This complexity is due in part to the diversity of rock types in the tills within the valley floor where the streams flow. Although the three lakes under investigation are within 15 km of each other, they have very different Sr signatures and hence Sr sources. The data we have presented help to provide a more detailed picture, not only of present-day sources of solutes to the streams and lakes, but also show how these sources have changed through time. The lowest measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the MCM waters are in the bottom waters of Lake Fryxell. The only three possible sources of this Sr are from the Cenozoic volcanic debris in the watershed, the local marble basement rocks, or Miocene seawater. We favor the former two possibilities. Lake Bonney, on the other hand, has much higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than present-day seawater, indicating that past and present input of Sr from the weathering of felsic rocks has occurred. Lake Hoare water is slightly enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ relative to present-day seawater, also indicating a radiogenic, weathering-derived component of Sr also entering the lake. These results suggest that chemical weathering can indeed occur in this polar environment as previously suggested (Jones and Faure, 1978). These data, when combined with results of previous work, suggest that increased water flow in the dry valley streams brought about by increased glacier melt due to warming in the region over the past 1,000 years, may have significant effects on the overall chemistry of the lakes in Taylor Valley.

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Appendix

Table A1. Taylor Valley stream channel sediment analyzed by XRF spectrometer. Concentrations are mM.

	Rb	K	Ba	Sr	Na	Ca	Mg
<i>E. Bonney</i>							
Priscu 12	1.006	535	4.19	4.69	1081	934	1295
<i>Hoare</i>							
Anderson 1	0.819	550	5.16	6.31	1023	1050	1171
Anderson 2	0.737	433	4.05	5.23	991	1115	1556
McKay 3	0.854	473	4.20	4.74	797	1150	1327
<i>NE Fryxell</i>							
Lost Seal 11	0.761	490	4.71	6.33	939	1006	1422
Canada 4	0.796	499	4.76	5.99	1081	1250	1615
<i>SW Fryxell</i>							
Delta 6	0.959	571	5.20	6.86	1181	979	541
Delta 7	0.971	531	4.76	5.60	1236	861	935
Aiken 8	0.866	520	4.67	5.44	1020	1024	1226
Aiken 9	0.807	563	4.64	6.76	916	1084	1461
Upper Crust (from Wedepohl, 1995)	1.287	733	4.86	3.61	1117	735	556

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