

# **Estimating Relative Surface Ages and Wetting Histories in Ice-Free Antarctic Regions Using Geochemical Analysis of soils**

Senior Thesis

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By

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Approved by

A handwritten signature in black ink that reads "W.B. Lyons". The letters are cursive and fluid, with the first name "W.B." and the last name "Lyons" written in a single continuous stroke.

W.B. Lyons, Project Advisor

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## Abstract

The ice-free regions of Antarctica are polar deserts where atmospheric aerosols are deposited and can accumulate over time in the surface soils. The McMurdo Dry Valleys (MDV) are the largest ice-free area on the continent and contain soils ranging in age for a few 1000's of years to as old as 14 million years. Soils in the Transantarctic Mountains to the south of MDV have similar ages. These ages relate to the waxing and waning of both the West and the East Antarctic Ice Sheets as the climate has changed. For this reason, types and concentrations of water soluble salts found in these soils can be used as a relative surface age dating parameter. I have measured the elemental composition of soils from several, ice-free locations in Antarctica. They range from coastal sites a few 10s of meters above sea level, to sites 800 kilometers inland and elevations of 2500m. Soils samples were leached with deionized water and filtered through 0.4 $\mu$ m filters. The leachate was then analyzed using ion chromatography to determine concentrations of the anions Cl<sup>-</sup>, F<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, and PO<sub>4</sub><sup>3-</sup>. The leachate was also analyzed by an inductively coupled plasma optical emission spectrometer to measure the concentrations of Li and B.

Locations further inland and at higher elevations tend to have higher concentrations of NO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, and F<sup>-</sup>. Most coastal sites at high elevations generally had higher Cl<sup>-</sup> values. Chloride, NO<sub>3</sub><sup>-</sup>, and B are clearly atmospherically derived, suggesting that if deposition fluxes are known, their concentrations may be good indicators of relative time since last wetting of the soil, including periods of glacial coverage. Analyte concentrations were compared against elevation and distance inland using ANOVA tests. Li concentrations vary the least with elevation and distance, suggesting it is not sourced from the atmosphere, but is produced *in situ* via chemical weathering. These data were compared to previous work on the surface exposure age of these surfaces and discussed in terms of glacier movement during the Pleistocene.

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## Introduction

Much debate has existed about the stability of the Antarctic Ice Sheets, especially the East Antarctic Ice Sheet (EAIS). Some believe that the glaciers have been stable for the last 14-15 million years, others believe that they are much less stable. The history of the ice sheets is of great importance for the future. This debate of ice sheet stability will only become more important in the coming years as climate change and the warming of polar regions continues. Knowing the degree of stability will allow researchers to estimate at what temperature the ice sheet will no longer be stable, and predict how much melt will be added to the ocean.

Because the majority of continental Antarctica is a polar desert, the ice-free areas can accumulate “salt” deposited through atmospheric processes over time. Thus, the amount of total salt and its chemical and isotopic composition may serve as a good relative indicator of the age of the surface of the landscape. Determination of the surface ages of ice free zones provides information on the last time that region was covered in ice, and can be helpful to determine the timing and movement history of glaciers in that region. The method used to estimate relative surface age in this work was to determine the time since last glacier retreat over soils in the Beardmore Glacier and McMurdo Dry Valleys (MDV) region. Atmospheric salts will accumulate *in situ* unless they are wetted. This accumulation of salt indicates dryness and allows confidence that the last time of wetting for these soils coincides with melt from the last glacier to cover them. I will use the terms “exposure age” or “soil age” to represent this concept in the text.

The soluble salt concentrations of the MDV have been investigated since the 1960's, and much is known about the general distribution of various salts and the ions associated with them (Keys and Williams, 1981; Bockheim and McLeod, 2015, Jackson et al., 2016). Although there have been many attempts to quantize the distribution and source of these salts, only recently has there been attempts to use their distribution to solve “process” oriented problems (Toner et al., 2013; Lyons et al., 2016). As noted above, this technique of relative age dating can only be utilized if no water exists to solubilize the salts. If yearly accumulation rates are known, this technique can be used to estimate wetting age of the ice-free soils (Lyons et al., 2016). Each type of salt or elemental composition has a unique geographical distribution. Chloride concentrations are high in coastal regions due to being close to the ocean, whereas  $\text{NO}_3^-$  concentrations are higher inland (Keys and Williams, 1981).

Previous research has clearly demonstrated that although  $\text{Cl}^-$  has a more coastal, oceanic source, its major source, along with  $\text{SO}_4^{2-}$  and  $\text{NO}_3^-$  is from long-traveled tropospheric and stratospheric aerosols (Bao et al. 2008, Michalski et al. 2005, Lyons et al. 2016). The distribution of these anions,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$ , are all well documented in the MDV soils but little to no work has been previously done on B and Li. Both Li and B have been observed in high concentrations in the saline and hypersaline lakes of the MDV (Lyons and Welch, 1997; Lyons et al., 2005). Isotope data may suggest the sources of these two elements are primarily from chemical weathering (Witherow et al. 2010; Leslie et al. 2014), yet B:Cl profiles in these waters suggest a marine origin (Lyons et al. 2005). Hence it is unclear at this time what the major source(s) of Li and B to the terrestrial regions of Antarctica are. This study predicts that concentrations of water soluble salts will increase with increasing elevation and distance inland, as dryness increases as well.

# Study Locations

## McMurdo Dry Valleys

The soils studied come from two regions of Antarctica, the McMurdo Dry Valleys and the Beardmore Glacier region of the southern Transantarctic Mountains. The McMurdo Dry Valleys located at 78°S Latitude were used because they are the largest ice-free region in Antarctica, and is in a location where the East Antarctic Ice Sheet and the West Antarctic Sheets have waxed and waned and thus they provide a unique location to document climate change.

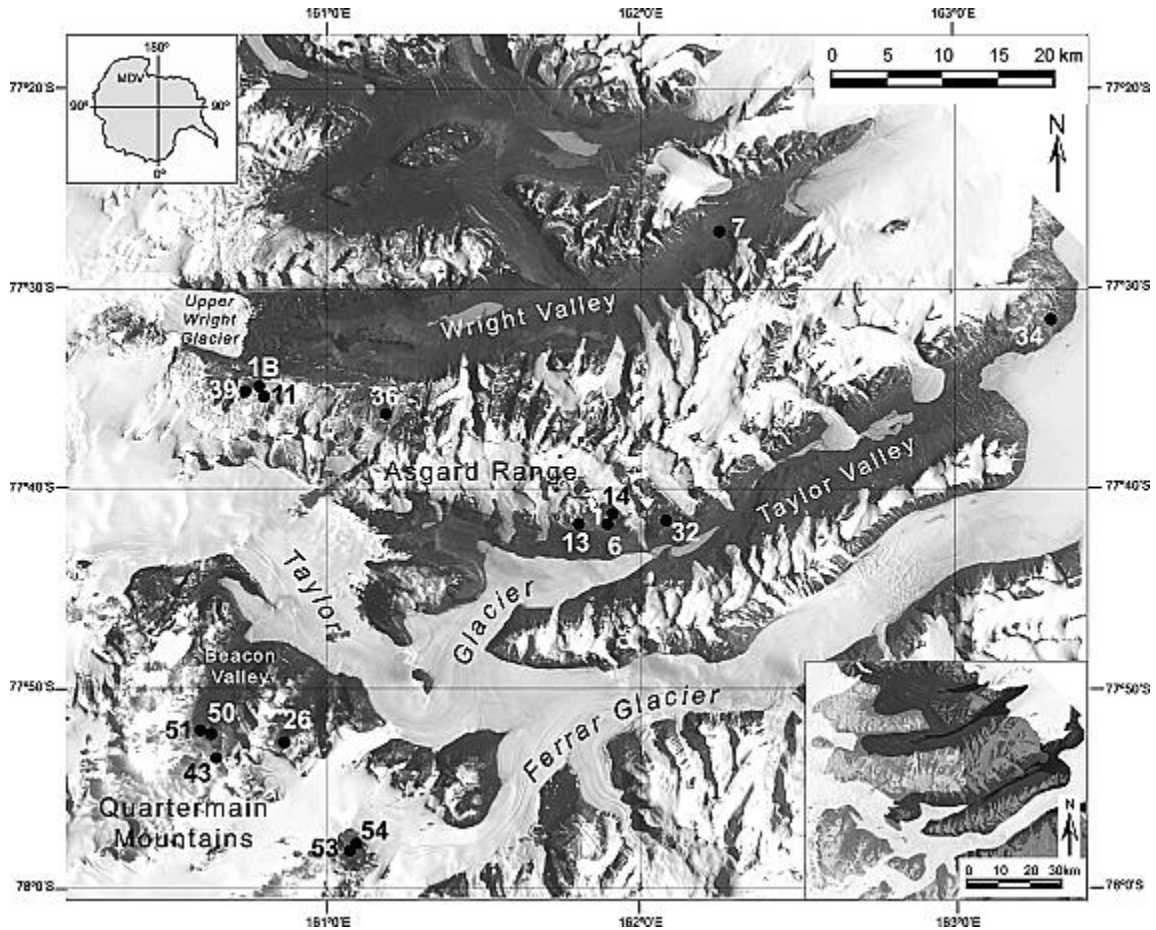


Figure 1: Map of Taylor, Wright, and Beacon Valleys in the McMurdo Dry Valleys (Bao et al. 2008)

In addition, since 1993, the MDV have been the main focus of The U.S. National Science Foundation's supported McMurdo Dry Valleys Long-Term Ecological Research (MCM-LTER) site. Because of this ongoing research, abundant soil samples have been collected over this time as a primary focus of their monitoring program. Numerous descriptions and details of the MDV soils, their physical, biogeochemical and ecological properties have been published over the past 25 years, and will not be repeated here. The Beardmore Glacier region was used because it is an inland location deep within the Transantarctic Mountains and thus represented a different setting where changes in climate and its impact on glacier movement may be subtler.

The Dry Valleys region is a region of extreme cold and dryness, and represents a polar desert. The region can be split into three separate micro-climates based primarily on elevation (Marchant and Denton, 1996). Zone one represents the coastal region, where mean annual temperature ranges from -17 degrees C to -27 degrees C, and the average soils have around 12.7 weight percent moisture. Zone two represents an intermediate climate. It has a mean annual temperature from -21 degrees C to -27 degrees C in the west, and -27 degrees C to -35 degrees C in the east. The average soil has around 3.5 weight percent moisture. Zone three represents the highest, coldest, and driest region in the Dry Valleys. The average yearly temperatures are below -27 degrees C. Glaciers in zone three currently do not produce any melt. The average soil has about 1.0 weight percent moisture. The primary winds in the region come from the inland polar plateau and are extremely low in humidity (Marchant and Denton, 1996).

Most of the samples used in this work were collected by K. Foley and K. Harris in 2003 as part of Foley's M.S. research advised by professor W.B. Lyons, School of Earth Sciences, The Ohio State University. Others were collected by MCM-LTER team members in 2003. The locations of the samples were analyzed along with their distance inland, elevation and zone classification based on the Marchant and Denton work. These values are provided in Table 1.

## Transantarctic Mountains

The Beardmore Glacier is a major outlet glacier for the EAIS. Its elevation increases from the Ross Ice Shelf to over 8000 meters above sea level.

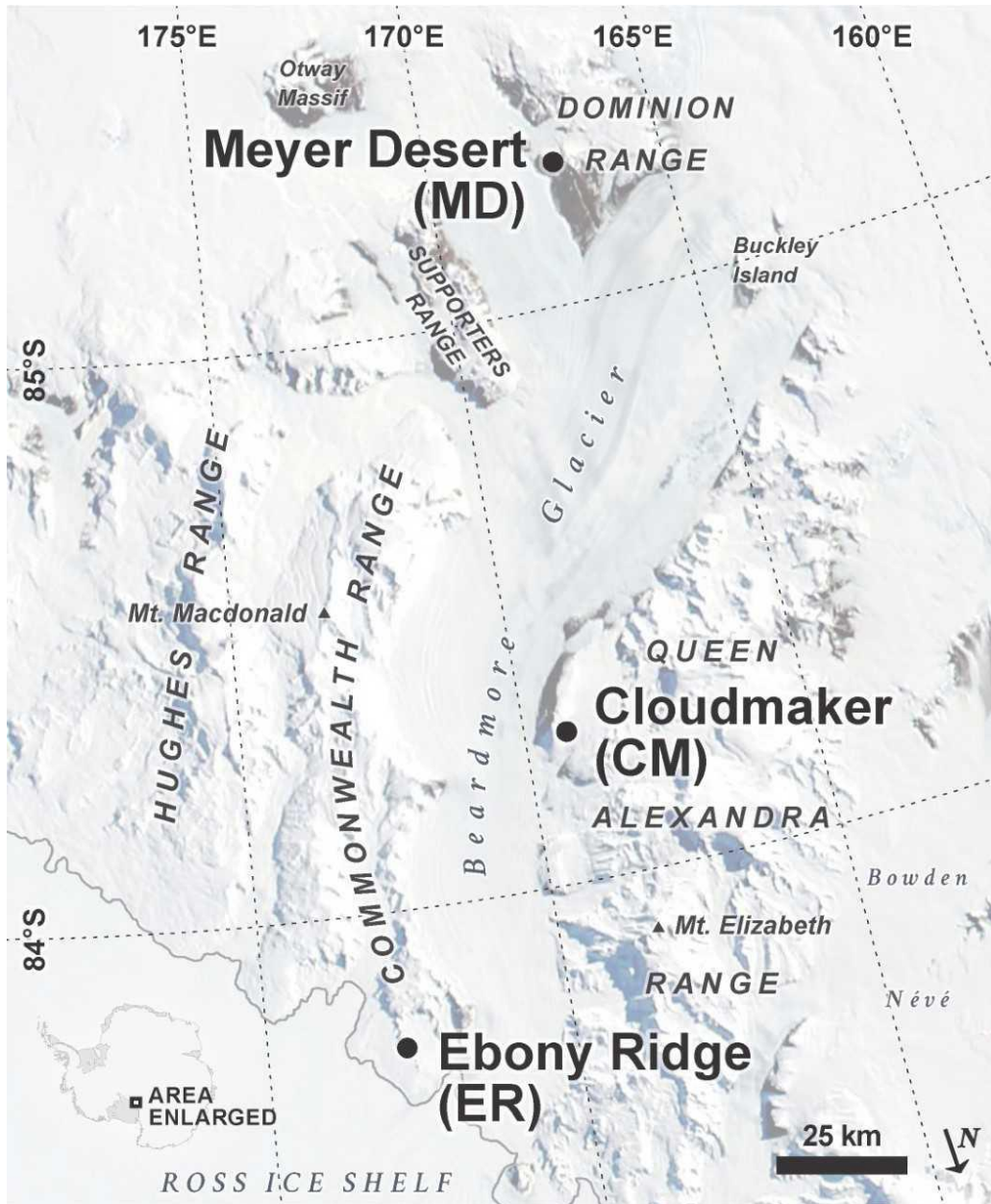


Figure 2: Map of Beardmore Glacier Region (Lyons et al., 2016)

The Transantarctic soil samples analyzed come from the Meyer Desert, Cloudmaker, and Mt. Kyffin regions. These are locations that currently raise above the Beardmore Glacier and are described in detail in Lyons et al. (2016). Locations of the Beardmore Glacier samples with their elevation and estimated distance inland are shown in Table 2.

# Methods

## Sample Collection

As noted above, samples from the McMurdo Dry Valleys region were collected by members of the MCM-LTER team. A few of the samples were collected in 2003, by other MCM-LTER members. Samples from the Beardmore Glacier region were collected by the Lyons et al. (2016) study. Soil samples were collected from the top 10cm of surface soil with clean plastic scoops. These samples were then placed into clean plastic bag, sealed and double bagged until further use. Upon reception, the soils were stored at room temperature in a secure USDA approved location either at the Byrd Polar and Climate Research Center, or the School of Earth Sciences until analyzed. The locations of the samples are shown in Table 1.

## Preparation and Analysis

Soil samples which had previously been disaggregated were carefully weighed and then leached using deionized water with a 1:5 soil to DI water ratio, 5 grams of soil, 25 grams of water. The leaches were then left to sit for an hour to let particles separate from suspension before filtration. The samples and process blanks were then filtered through a 0.4 $\mu$ m cellulose acetate filter using a motorized vacuum pump to expedite the process. These filtered leachates were then stored in a laboratory refrigerator at  $\sim$ 4 degrees C until analysis. The 1:5 ratio of soil to water was used in order to be able to compare to previous work of MCM-LTER soil scientists, even though more recent work suggests that the least soluble salts in the soil, such as CaCO<sub>3</sub> and CaSO<sub>4</sub>\*2H<sub>2</sub>O are not completely dissolved by the procedure (Toner et al., 2013).

The filtered leachates were placed into tubes and analyzed by a Dionex Ion-Chromatograph (IC). Samples that were too concentrated were diluted at a 1:10 leachate to deionized water ratio, although some with higher anion concentrations were diluted at a 1:50 ratio to fit within our testable range. These samples were then analyzed using ion chromatography for the anions F<sup>-</sup>, Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and PO<sub>4</sub><sup>3-</sup> using the technique outlined in Welch et al. (2010). PO<sub>4</sub><sup>3-</sup> concentrations were consistently found to be below our detectable limit and were not reported.

B and Li concentrations were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The leachates were too saline to use on the instrument without dilution, because sodium would accumulate inside the instrument if undiluted. For this reason, the original leachate was placed into precleaned plastic test tubes and diluted at a 1:5 ratio before analysis. The accuracy the IC measurements and the precision of all the measurements are presented in tables 3 and 4.

The data were compiled into a spreadsheet with the corresponding elevation and geographic coordinates of each sample (Foley 2005). Geographic coordinates were determined using Google Earth and a straight line to the ocean was drawn using its ruler tool to estimate distance inland for samples with no distance inland previously given by either Foley (2005) or Lyons et al. (2016).

Table 1: Sample names ordered by their climatological zone as a function of elevation and distance inland described by Marchant and Denton (1996).

Zone 1	Elevation (m)	Distance Inland (km)
South Lake Hoare 1	31	17
South Lake Hoare 2	101	17
South Lake Hoare 3	101	17
South Fryxell, Taylor Valley 1	53	10
Fryxell Pit 1	30	12
Fryxell Pit 2	30	12
Fryxell Pit 3	30	12
Fryxell Pit 4	30	12
Hoare Pit 1	110	23
Hoare Pit 2	110	23
Hoare Pit 3	110	23
Bonney Pit 2	107	40
Bonney Pit 3	107	40
Bonney Pit 4	107	40
West Lobe Lake Bonney	110	40
Zone 2		
Pearse Valley 1	420	51
Lake Vida, Victoria Valley 1	370	37
Pearse Valley 2	420	51
Pearse Valley 3	420	51
Lower Victoria 1	420	40
Lower Victoria 3	420	40
Bull Pass 1	690	45
Bull Pass 3	690	45
Zone 3		
Lower Arena Valley	1100	93
Lower Arena Valley 2	1100	93
Beacon Pit 1	1348	84
Beacon Pit 2	1348	84
Beacon Pit 3	1348	84
Beacon Pit 4	1348	84
East Dais, Wright Valley 2	850	75
West Dais, Wright Valley 3	940	64

Table 2: Beardmore Glacier Region samples with their corresponding elevations and distances inland.

Transantarctics	Elevation	Distance Inland
MDBJA1	8379	810
MDBJA2	7783	810
MDBJA3	7694	810
MDBJA4	7586	810
Cloudmaker CMUN1	5369	700
Cloudmaker CMUN8	6478	700
Mt Kyffin KYUN2	488	630
Mt Kyffin KYUN7	547	630

Table 3 USGS Intercalibration Results October 2015

SRS	Analyte	units	Method	analyzed	our value	MPV	%difference
M-216	Chloride	mg/L	IC	20150903a	21.1	19.7	7.11
M-216	Fluoride	mg/L	IC	20150903a	0.255	0.242	5.37
M-216	Sulfate	mg/L	IC	20150903a	8.08	8.40	-3.81
N-128	Nitrate as N	mg/L	IC	20150921a	2.81	3.04	-7.62
On-going results 2015-16							
			F	Cl	Br	SO4	
USGS M-216 MPV			0.242	19.7	0.283	8.4	

Table 4: Percent variation was found by dividing the sample with the largest departure from the mean by the average of three replicate samples for F<sup>-</sup>, Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup>. Li and B percent variation was found using the same technique, but using nine replicate samples.

F <sup>-</sup>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	Li	B
±12%	±1%	±2%	±8%	±3%	±4%

## Results

### McMurdo Dry Valleys

Water soluble ion concentrations in the Dry Valleys did show a relation with distance and elevation to varying degrees.

Water soluble concentrations of  $\text{NO}_3^-$  ranged from undetectable to 3.3 mg/g dry weight soil.  $\text{Cl}^-$  concentrations ranged from 2.0E-04 mg/g to 3.7 mg/g.  $\text{SO}_4^{2-}$  concentrations ranged from below 4.9E-05 mg/g, to 19 mg/g. Water soluble  $\text{F}^-$  concentrations ranged from 9.2E-06 to 1.8E-01 mg/g.  $\text{PO}_4^{3-}$  concentrations fell below testable range for most samples and were not plotted.

Concentrations were lower for most compounds between 800 and 1000 meters elevation and between 50 to 80km inland. These data points represent samples from Wright valley.

Table 5: Ion Concentration Ranges in Dry Valleys Samples

$\text{NO}_3^-$	Four samples below 9.7E-06 to 3.3 mg/g
$\text{Cl}^-$	2.0E-04 to 3.7 mg/g
$\text{SO}_4^{2-}$	Six samples below 4.9E-05 to 1.89E+010 mg/g
$\text{F}^-$	9.2E-06 to 1.8E-01 mg/g
Li	2.4E-06 to 3.3E-05 mg/g
B	5.9E-05 to 4.1E-04mg/g

Water soluble soil ion concentrations are presented in mg of ion per dry weight gram of soil vs elevation and distance inland for each sample (Figures 3 and 4). Transantarctic Mountain samples are plotted separately. All the data are tabulated in Appendix A.

In the MDV  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{F}^-$  concentrations typically increased with increasing elevation, while Li and B concentrations varied little (Figure 3). Concentrations were much lower for  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{F}^-$  between 800 to 1000m elevation. These data represent samples from Wright Valley. This discrepancy could be explained if Wright Valley has a younger lower surface exposure age with less time to accumulate salts.



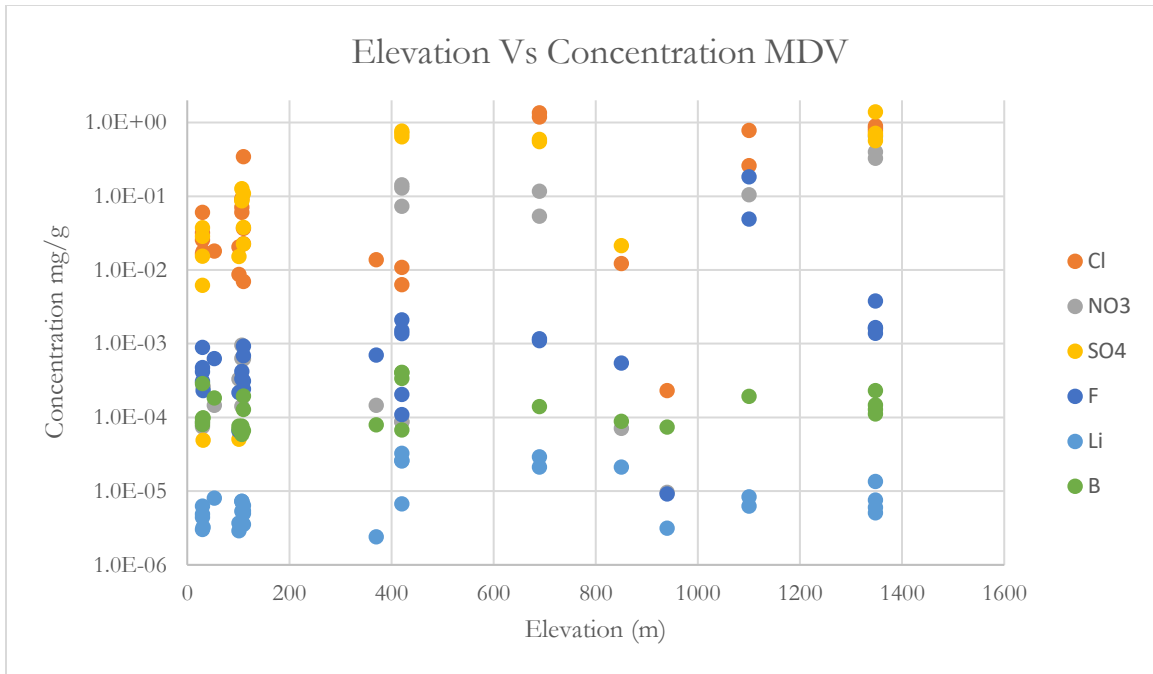


Figure 3: Comparing concentrations of water soluble salts vs elevation in the McMurdo Dry Valleys. Concentrations plotted on a logarithmic scale, elevations on a linear scale in meters.

Fluoride, and  $\text{SO}_4^{2-}$  were the only ions that showed a clear and marked relation between concentration and distance inland. Samples in the 60-80km range with low concentrations for  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{F}^-$  correspond to samples from Wright Valley.

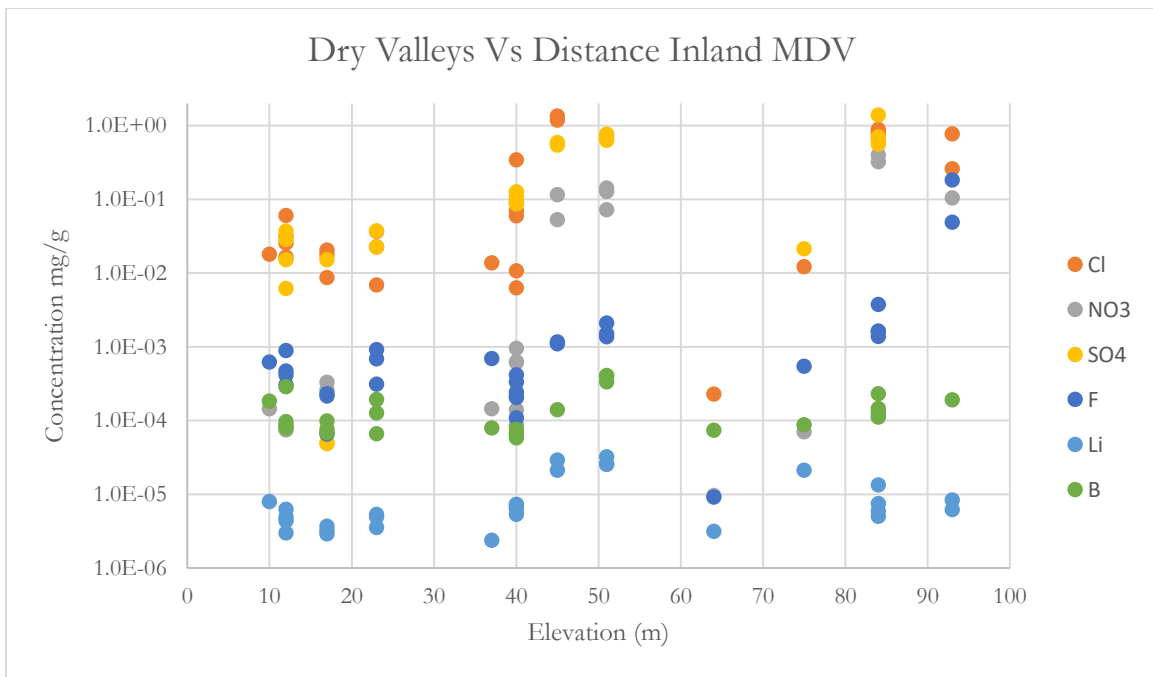


Figure 4: Comparing concentrations of water soluble salts vs distance inland in the McMurdo Dry Valleys. Concentrations plotted on a logarithmic scale, distances on a linear scale in km.

Significance probability values associated with F statistics are located in table 6. As determined by a two-way ANOVA test, significance of the relation between elevation and concentration was good for  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{F}^-$ , but low for B and Li. Significance of the relation between distance inland and concentration was only good for  $\text{F}^-$  and  $\text{SO}_4^{2-}$ . Significance for the relation of elevation and distance inland combined to concentration was good for  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{F}^-$ , and Li. Lithium concentrations were much more consistent however, with only one order of magnitude difference between the highest and lowest measured concentrations (Appendix A).  $\text{SO}_4^{2-}$ , and B had low significance for relation between concentrations and elevation and distance inland combined (Table 6).

Table 6: Significance between Concentration, Elevation, Distance Inland, and Elevation + Distance Inland.

Significance codes: 0 '\*\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

Two Way ANOVA Significance Results	$\text{Cl}^-$	$\text{F}^-$	$\text{NO}_3^-$	$\text{SO}_4^{2-}$	Li	B
Elevation	0.0538 .	0.0495 *	0.00112 **	0.0457 *	0.203	0.558
Distance Inland	0.3124	0.0278 *	0.30111	0.0579 .	0.20406	0.324
Elevation and Distance Inland	0.0758 .	0.0466 *	0.03865 *	0.1018	0.00209 **	0.533

Aridity in the dry valleys is a function of elevation and distance inland in conjunction. To relate aridity better to water-soluble ion concentrations, ion concentrations were plotted as bubble size against distance inland and elevation on the X and Y axes (Figures 5-10).

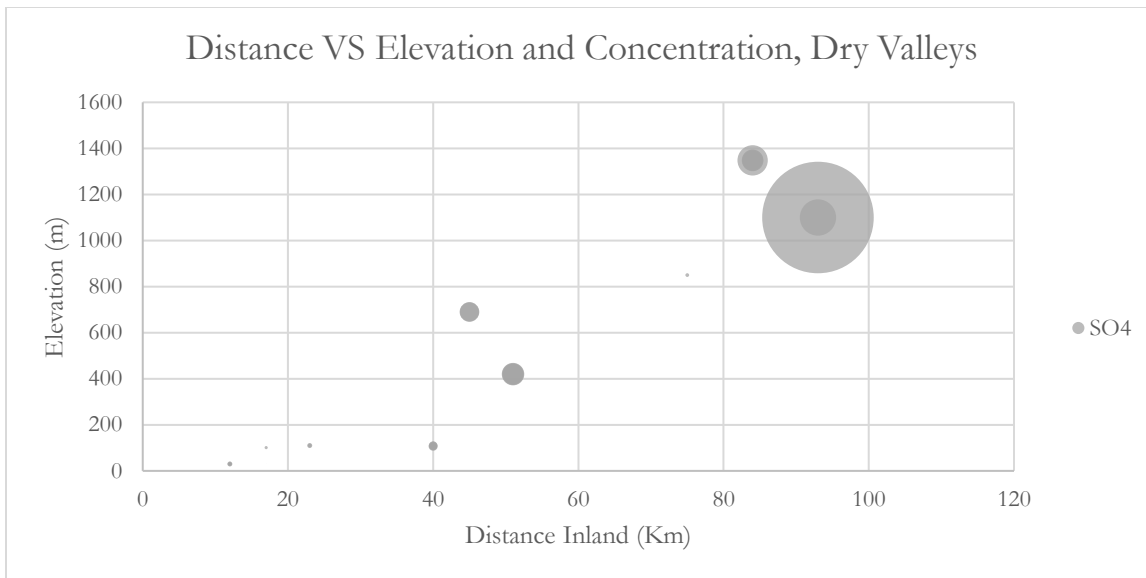


Figure 5: Plotting elevation, distance inland, and concentrations of  $\text{SO}_4^{2-}$  in the McMurdo Dry Valleys. X axis relates to distance inland, Y axis to elevation. The size of bubble relates to concentrations at that location. The relation between  $\text{SO}_4^{2-}$  concentrations and elevation was significant. The relation between  $\text{SO}_4^{2-}$  and distance inland was significant. The relation between elevation and distance inland combined was not significant with concentrations in a two-way ANOVA test (Table 6).

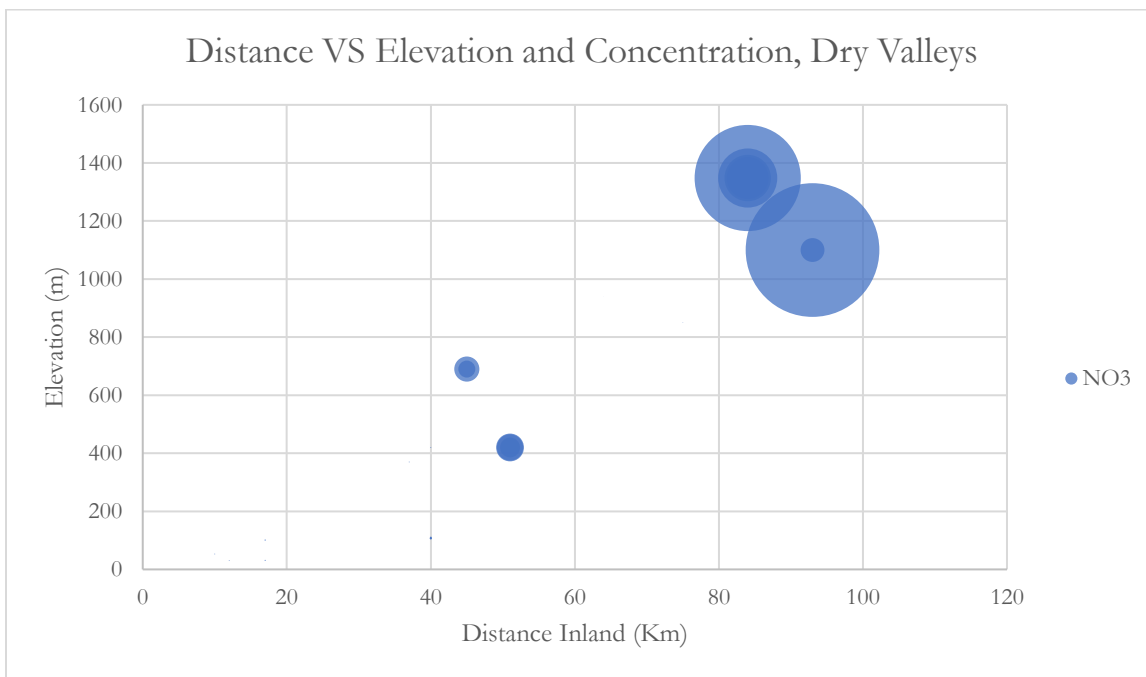


Figure 6: Plotting elevation, distance inland, and concentrations of  $\text{NO}_3^-$  in the McMurdo Dry Valleys. X axis relates to distance inland, Y axis to elevation. The size of bubble relates to concentrations at that location. The relation between  $\text{NO}_3^-$  concentrations and elevation was significant. The relation between  $\text{NO}_3^-$  and distance inland was not significant. The relation between elevation and distance inland combined was significant (Table 6).  $\text{NO}_3^-$  had the largest variation in concentrations, with some samples with concentrations so low that they are difficult to visualize.

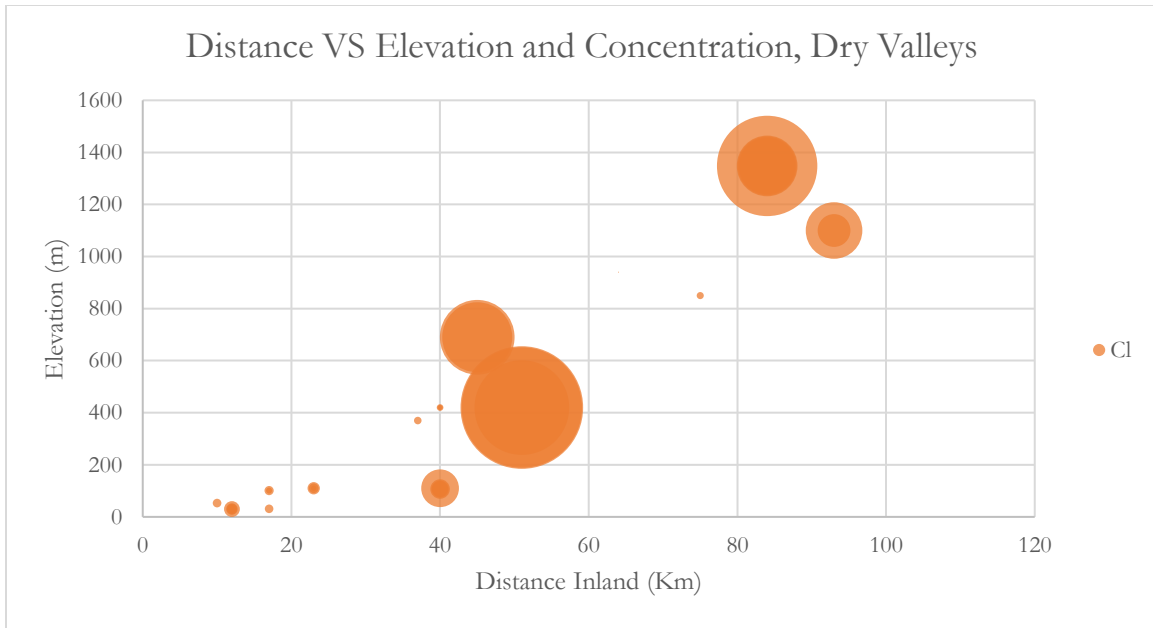


Figure 7: Plotting elevation, distance inland, and concentrations of Cl<sup>-</sup> in the McMurdo Dry Valleys. X axis relates to distance inland, Y axis to elevation. The size of bubble relates to concentrations at that location. The relation between Cl<sup>-</sup> concentrations and elevation was significant. The relation between Cl<sup>-</sup> and distance inland was not significant. The relation between elevation and distance inland combined was significant with concentrations (Table 6).

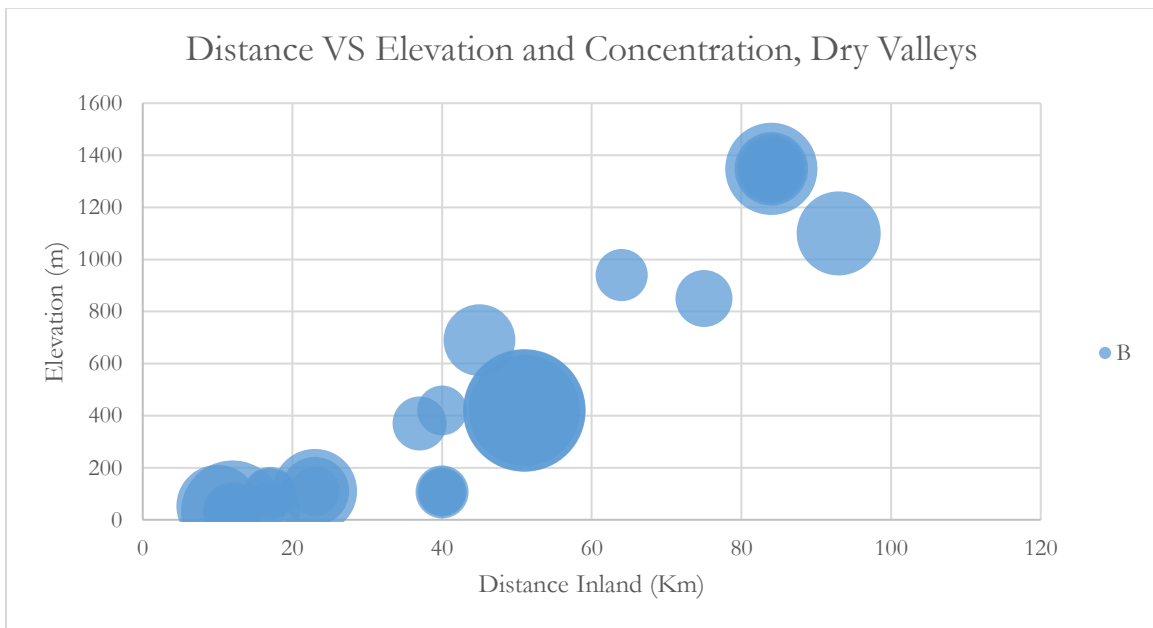


Figure 8: Plotting elevation, distance inland, and concentrations of B in the McMurdo Dry Valleys. X axis relates to distance inland, Y axis to elevation. The size of bubble relates to concentrations at that location. The relation between B concentrations and elevation was not significant. The relation between B and distance inland was not significant. The relation between elevation and distance inland combined was not significant with concentrations (Table 6).

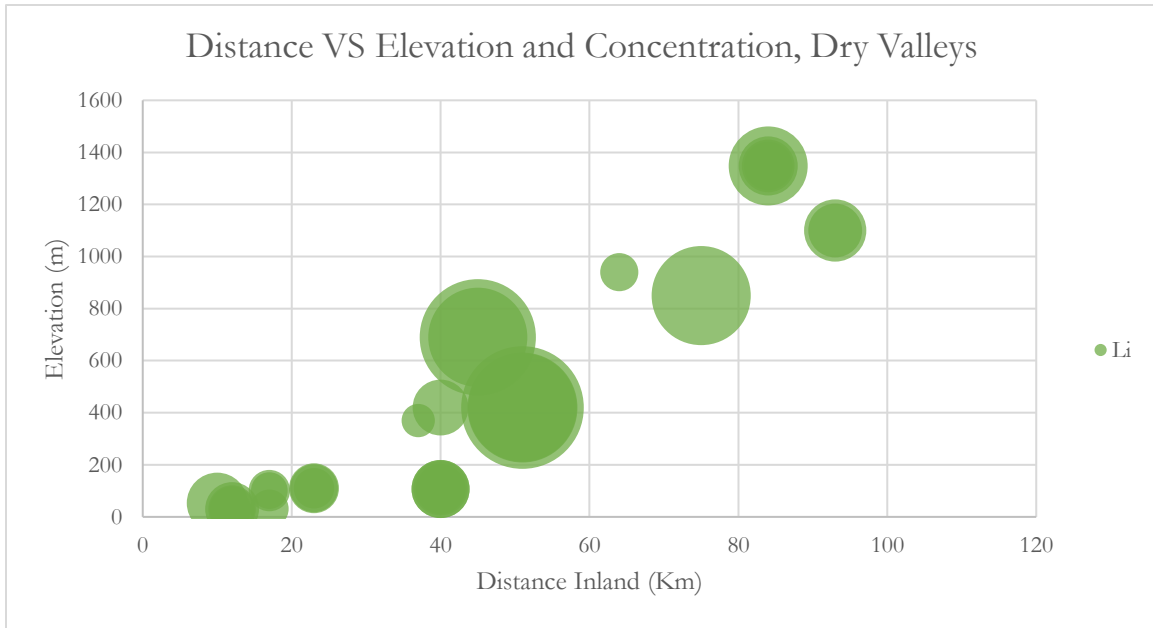


Figure 9: Plotting elevation, distance inland, and concentrations of Li in the McMurdo Dry Valleys. X axis relates to distance inland, Y axis to elevation. The size of bubble relates to concentrations at that location. The relation between Li concentrations and elevation was not significant. The relation between Li and distance inland was not significant. The relation between elevation and distance inland combined was significant with concentrations (Table 6). The range of concentrations was very low.

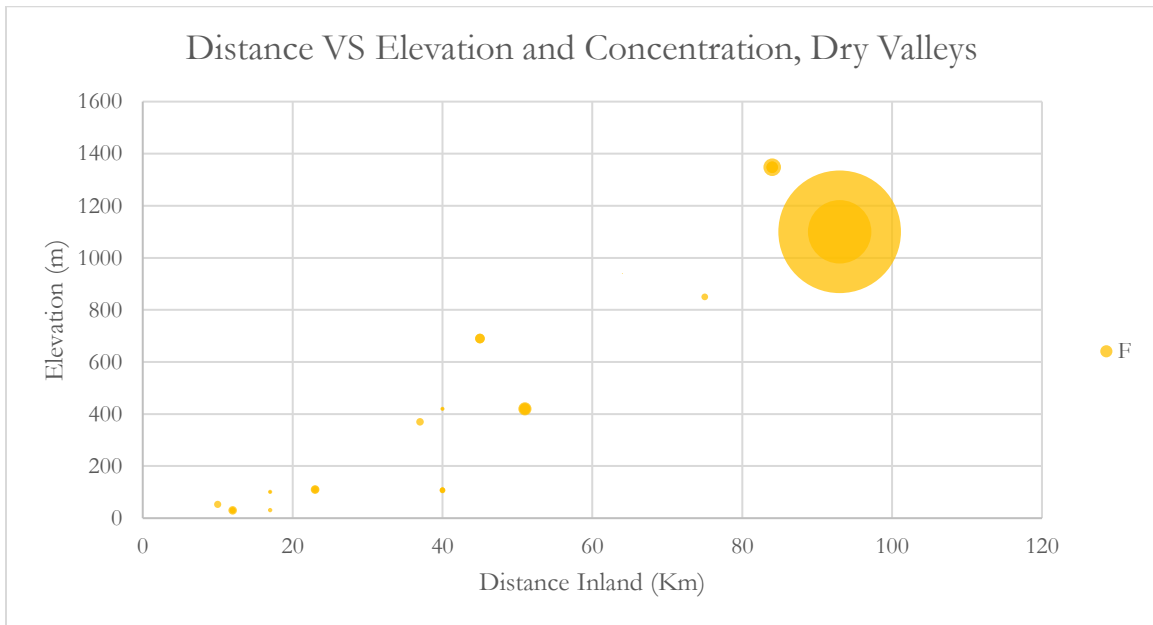


Figure 10: Plotting elevation, distance inland, and concentrations of F<sup>-</sup> in the McMurdo Dry Valleys. X axis relates to distance inland, Y axis to elevation. The size of bubble relates to concentrations at that location. The relation between F<sup>-</sup> concentrations and elevation was significant. The relation between F<sup>-</sup> and distance inland was significant. The relation between elevation and distance inland combined was significant with concentrations (Table 6).

Relative surface ages from Marchant and Denton’s model were found to relate to water soluble salt concentrations for F<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup> (Figure 11).

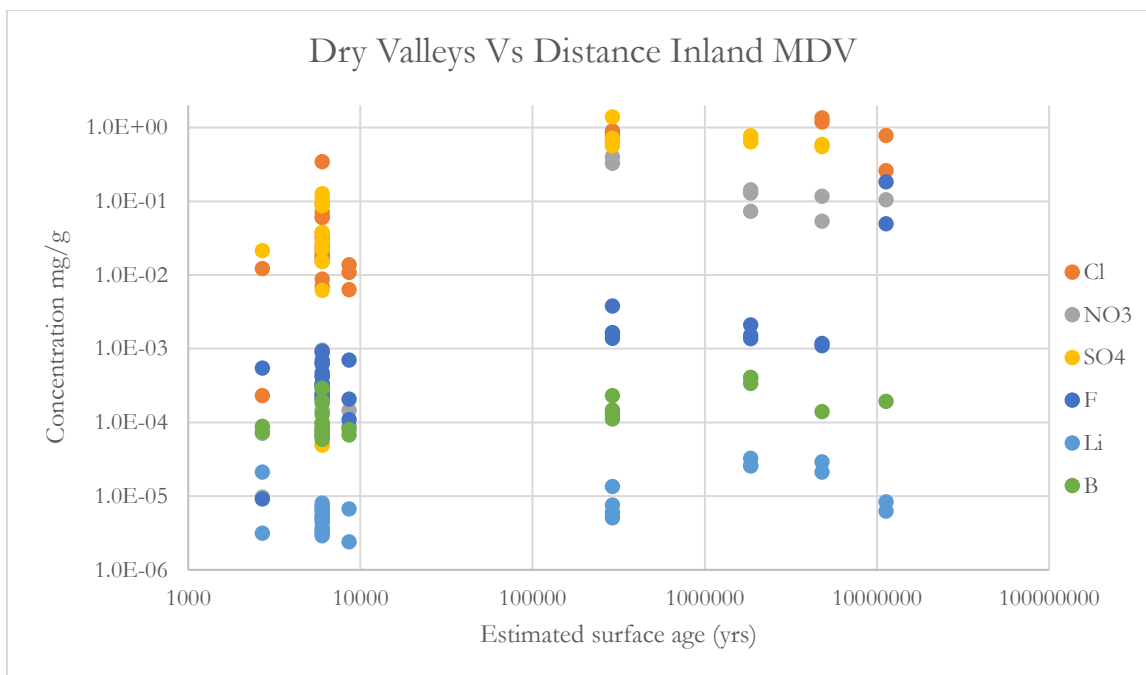


Figure 11: Concentration plotted against estimated surface age in Taylor Valley of the McMurdo Dry Valleys. X axis: logarithmic scale of estimated age. Y axis: logarithmic scale of concentration in mg per gram dry weight of soil.

Figure 11 shows that water soluble ion concentrations are related to estimated surface age. Instances where concentrations are lower than in younger soils may be due to other relations such as aridity as a function of elevation and distance inland. More arid regions have higher salt accumulation rates.

The relations between age and F<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup> concentrations had high significance in an ANOVA test, while the relationship between age and Cl<sup>-</sup>, Li, and B concentrations did not (Table 7).

Table 7: Significance between Concentration and Estimated Soil Age, MDV.

Significance codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

ANOVA test	F <sup>-</sup>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	Li	B
Ages Significance	2.48e-07 ***	0.257	0.00874 **	6.87e-05 ***	0.174	0.137

## Transantarctic Mountains

$\text{NO}_3^-$ , and  $\text{Cl}^-$  show the most variation, from  $1.0\text{E}-05$  to  $8.2\text{ mg/g}$ , in the case of  $\text{NO}_3^-$  while B and Li concentrations remained more consistent, ranging roughly one order of magnitude.  $\text{NO}_3^-$  and  $\text{SO}_4^{2-}$  each had one sample with concentrations below detectable limit. The water soluble ion concentrations of soils from the Transantarctic Mountains region showed a modest relation with respect to elevation for nitrate, chloride, fluoride, sulfate, and possibly boron, but little to no relation with lithium.

Table 8: Ion Concentrations ranges from Transantarctic Mountains samples

$\text{NO}_3^-$	$1.0\text{E}-05$ to $8.2\text{ mg/g}$
$\text{Cl}^-$	$1.2\text{E}-02$ to $9.0\text{E}-01\text{ mg/g}$
$\text{SO}_4^{2-}$	$1.0\text{E}-03$ to $5.3\text{ mg/g}$
F <sup>-</sup>	$2.0\text{E}-04$ to $1.6\text{E}-02\text{ mg/g}$
Li	$5.2\text{E}-06$ to $2.5\text{E}-05\text{ mg/g}$
B	$4.9\text{E}-05$ to $8.4\text{E}-04\text{mg/g}$

Concentrations of  $\text{NO}_3^-$ , F<sup>-</sup>,  $\text{SO}_4^{2-}$ , and possibly  $\text{Cl}^-$ , and B appear to increase with increasing elevation in the Transantarctic Mountains region, while Li does not (Figure 12). However, none of the analytes had a significant relation, largely due to having a smaller sample size than the MDV.

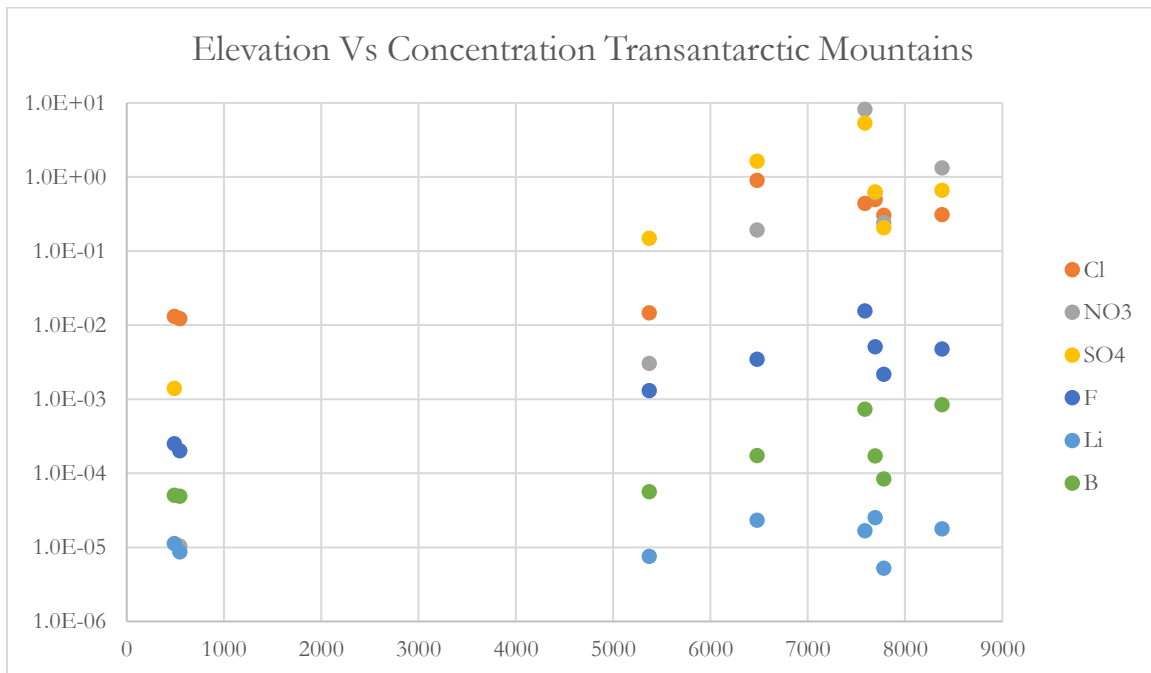


Figure 12: Ion concentrations plotted with respect to concentration and elevation in the Beardmore Glacier region. Concentrations plotted on a logarithmic scale.

Soluble ion concentrations do appear to increase with distance inland, although only 3 different distances were used, lowering significance. Low significance was found for each of the analytes. Concentrations of  $F^-$ ,  $NO_3^-$ ,  $Cl^-$ , and  $SO_4^{2-}$  increased with distance inland (Figure 13).  $SO_4^{2-}$  demonstrated the strongest trend. The variation in the water soluble B concentrations possibly show a similar, although weaker relation with distance inland. Lithium concentrations remained relatively constant.

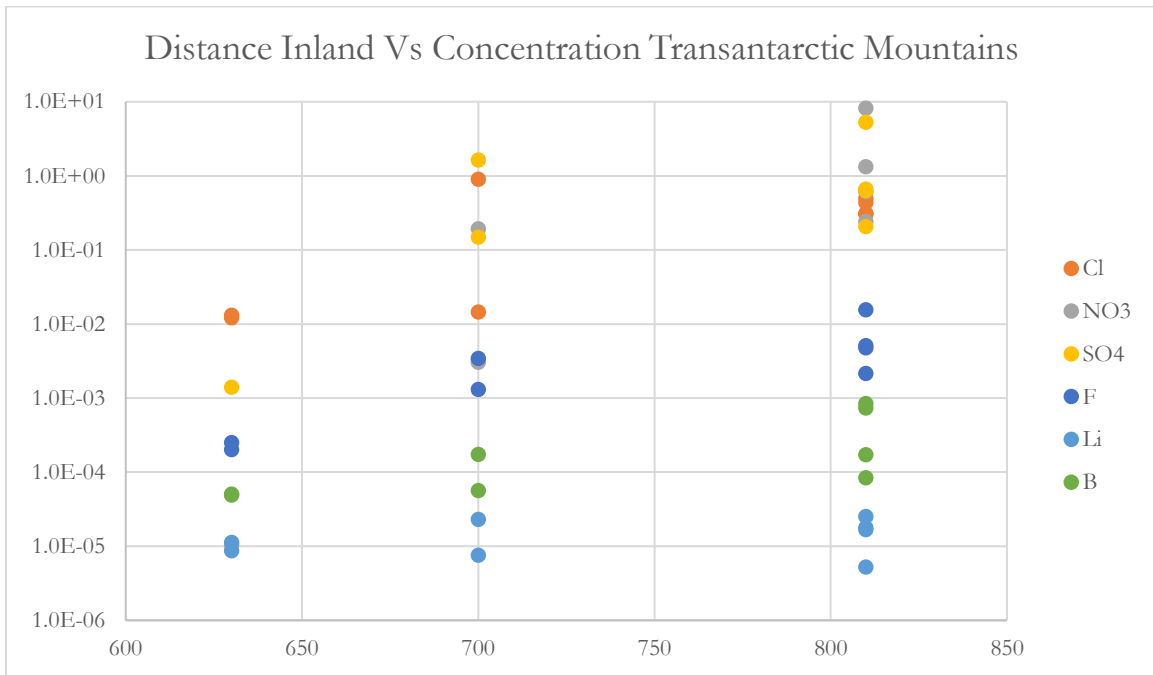


Figure 13: Ions plotted with respect to concentration and distance inland in the Beardmore Glacier region. Concentrations plotted on a logarithmic scale.



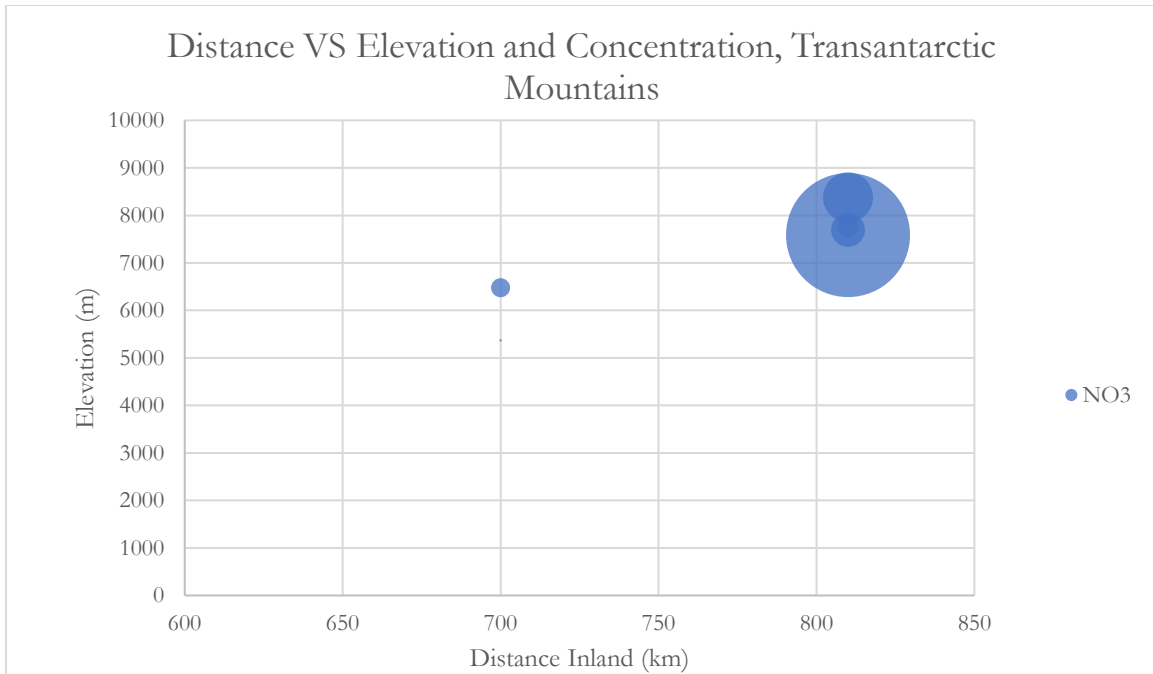


Figure 14: Plotting elevation, distance inland, and concentrations of NO<sub>3</sub>- in the Beardmore Glacier region. X axis relates to distance inland, Y axis to elevation. Size of bubble relates to concentrations at that location.

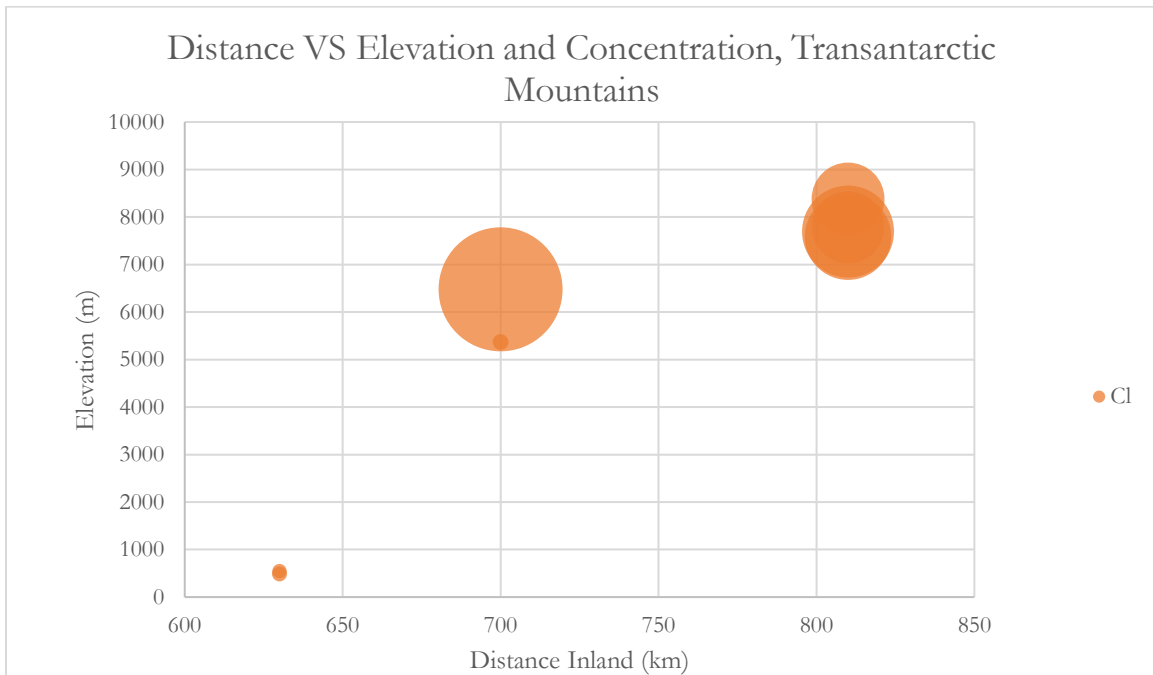


Figure 15: Plotting elevation, distance inland, and concentrations of Cl in the Beardmore Glacier region. X axis relates to distance inland, Y axis to elevation. Size of bubble relates to concentrations at that location.

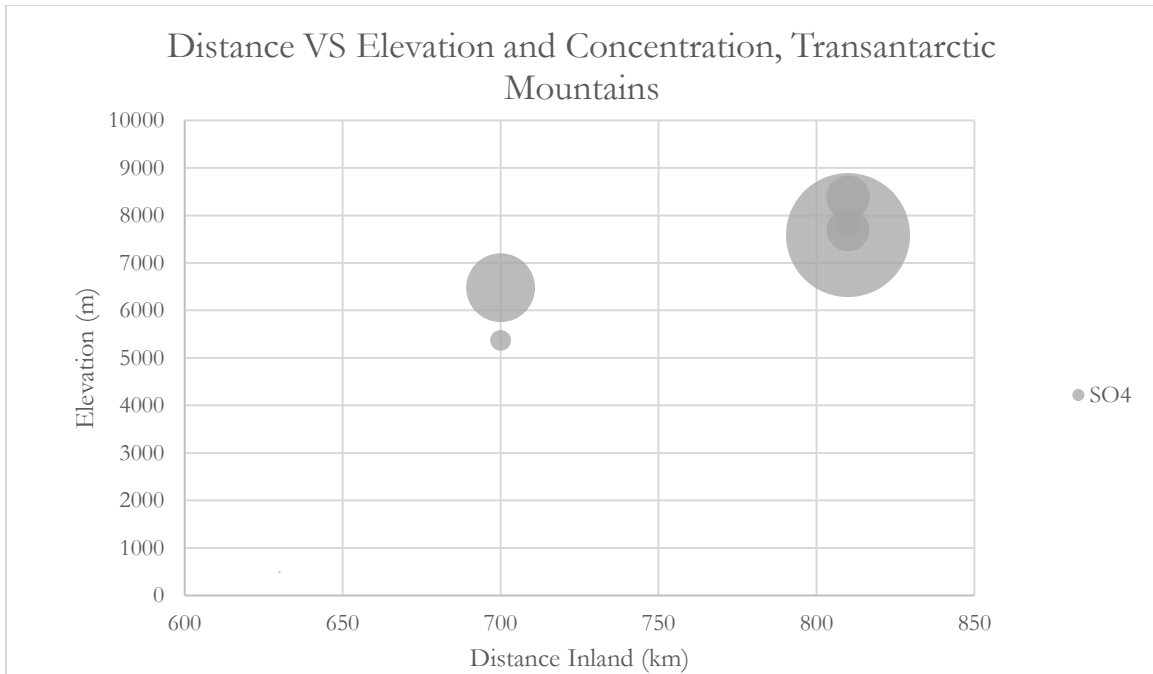


Figure 16: Plotting elevation, distance inland, and concentrations of SO<sub>4</sub><sup>2-</sup> in the Beardmore Glacier region. X axis relates to distance inland, Y axis to elevation. Size of bubble relates to concentrations at that location.

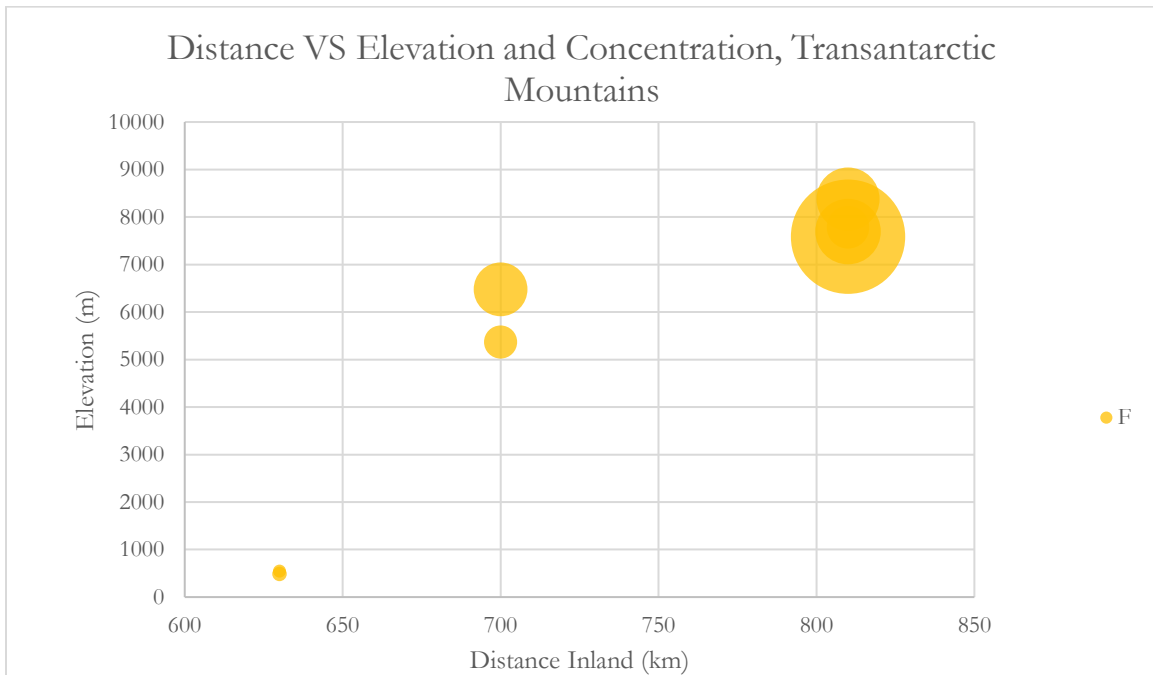


Figure 17: Plotting elevation, distance inland, and concentrations of F in the Beardmore Glacier region. X axis relates to distance inland, Y axis to elevation. Size of bubble relates to concentrations at that location.

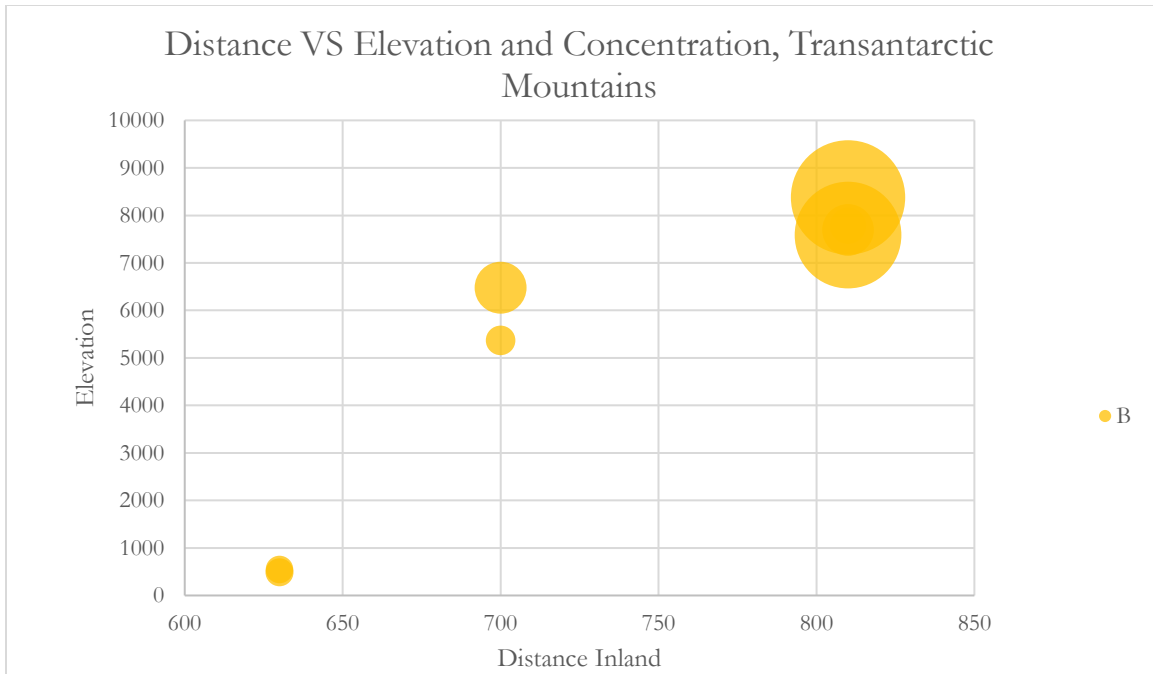


Figure 18: Plotting elevation, distance inland, and concentrations of B in the Beardmore Glacier region. X axis relates to distance inland, Y axis to elevation. Size of bubble relates to concentrations at that location.

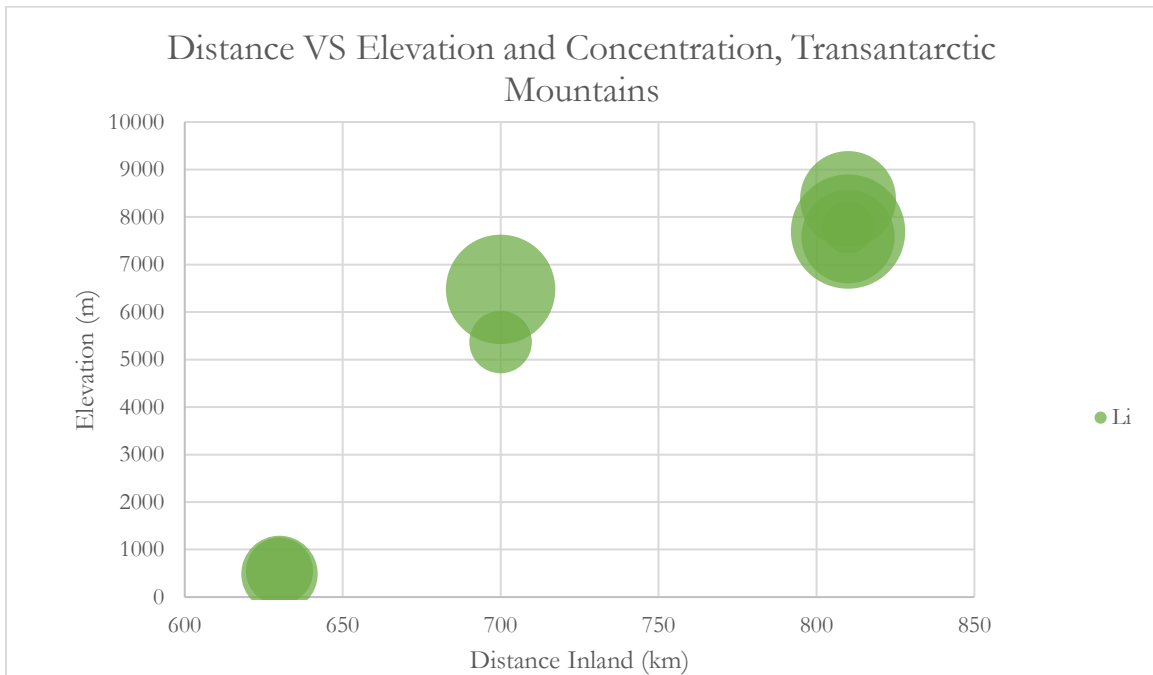


Figure 19: Plotting elevation, distance inland, and concentrations of Li in the Beardmore Glacier region. X axis relates to distance inland, Y axis to elevation. Size of bubble relates to concentrations at that location.

## Discussion

Concentrations of water soluble ions were predicted to increase with increasing elevation and distance from the ocean, as well as increasing surface exposure age. These relationships were found to varying degrees with each analyte tested.

Chloride had the highest concentrations of all the soluble ions. The source of Cl<sup>-</sup> in these soils is derived from marine aerosols blowing inland to both regions. NO<sub>3</sub><sup>-</sup> concentrations are deposited from long-traveled aerosols and show the largest variations in concentration in both the Dry Valleys and the Transantarctic Mountains. SO<sub>4</sub><sup>2-</sup> is also sourced from the atmosphere, and like Cl<sup>-</sup>, is at relatively high concentrations, increasing slightly with increasing elevation, inland distance and surface soil age. Fluoride is mostly sourced from the atmosphere, although some may come from chemical weathering of the soils. It shows moderate concentrations and moderate increases for each of the three parameters.

Unlike NO<sub>3</sub><sup>-</sup>, B concentrations show little to no relationship with elevation, distance inland nor surface exposure age in the MDV. This may be due in part to the variation of B speciation with pH, with the borate ion more likely stable in the soil than boric acid. Lithium concentrations showed significance with aridity, but not surface soil age. Overall there was little notable change of Li with location, with the highest measured concentration being only one order of magnitude higher than the lowest measured concentration. Lithium is also believed to be a product of *in situ* weathering (Witherow et al. 2010).

Overall, concentrations of the water soluble ions Cl<sup>-</sup>, F<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and Li in surface soils increase with elevation and distance inland in both the Transantarctic Mountains and McMurdo Dry Valleys regions. Some relationship of SO<sub>4</sub><sup>2-</sup> with elevation and distance inland was found but the relationship was less strong than for the other ions. These observations suggest that in soils at higher elevations and further inland, ions have higher accumulation rates due to increased aridity. In addition, SO<sub>4</sub><sup>2-</sup>, F<sup>-</sup>, and NO<sub>3</sub><sup>-</sup> concentrations were related to estimated surface soil ages in the MDV, suggesting measured concentrations are a function of both aridity and surface exposure age.

The Transantarctic Mountain samples show less variation in salt concentrations when plotted against elevation than the Dry Valleys samples. Similarly, concentrations increase with distance inland. However, because the Transantarctic Mountains were sampled at only three different distances, there is much lower statistical significance. Overall, samples from the Transantarctic Mountains region appear to demonstrate similar characteristics to the MDV, apart from boron concentrations, which appear to be more related to aridity in the Transantarctic Mountains than in the MDV.

## Conclusions

Higher concentrations of highly water soluble salts are found in areas of increasing elevation and distance inland. These concentrations also relate to surface wetting ages, that is, the last time the surface soils were wetted. Concentrations of  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{F}^-$  show a statistically significant relation to all three of these geographic variables.  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{F}^-$  may be relatively good indicators of age, while Li and B are not.

## **Recommendations for Future Work**

Future work should be done by analyzing more samples along the valley walls. These samples would help demonstrate the viability of relating soil salt concentrations to surface age. One might expect to observe increasing soluble salt concentrations along the elevational gradient. Samples could also be collected at the same elevation, but at different distances inland and vice versa, allowing a more robust geochemical view of this technique.

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## Appendix

Zone 1	Latitude S	Longitude E	Elevation	Distance	F mg/g	Cl mg/g	NO3 mg/g	SO4 mg/g	Li mg/g	B mg/g	Est Soil Age
+South Lake Hoare 1	77°38'02"	162°54'17"	31	17	2.32E-04	1.78E-02	2.61E-04	4.90E-05	3.23E-06	9.88E-05	6000
+South Lake Hoare 2	77°39'27"	162°54'19"	101	17	6.59E-05	8.74E-03		1.53E-02	2.91E-06	6.86E-05	6000
+South Lake Hoare 3	77°39'27"	162°54'19"	101	17	2.17E-04	2.06E-02	3.32E-04	5.05E-05	3.70E-06	7.65E-05	6000
+South Fryxell, Taylor Valley 1	77°36'60"	163°14'05"	53	10	6.27E-04	1.81E-02	1.46E-04		8.01E-06	1.84E-04	6000
*Fryxell Pit 1	77°36'35"	163°16'53"	30	12	4.73E-04	2.56E-02	7.48E-05	6.19E-03	4.40E-06	9.70E-05	6000
*Fryxell Pit 2	77°36'35"	163°16'53"	30	12	3.08E-04	1.66E-02		2.86E-02	4.89E-06	8.00E-05	6000
*Fryxell Pit 3	77°36'35"	163°16'53"	30	12	4.17E-04	6.06E-02		1.54E-02	6.27E-06	8.68E-05	6000
*Fryxell Pit 4	77°36'35"	163°16'53"	30	12	8.94E-04	3.18E-02	8.60E-05	3.74E-02	3.01E-06	2.89E-04	6000
*Hoare Pit 1	77°38'06"	162°53'45"	110	23	3.13E-04	6.95E-03			3.55E-06	6.64E-05	6000
*Hoare Pit 2	77°38'06"	162°53'45"	110	23	6.90E-04	2.28E-02		2.26E-02	4.96E-06	1.28E-04	6000
*Hoare Pit 3	77°38'06"	162°53'45"	110	23	9.26E-04	3.69E-02		3.78E-02	5.38E-06	1.94E-04	6000
*Bonney Pit 2	77°43'34"	162°19'52"	107	40	3.36E-04	7.09E-02	6.33E-04	8.97E-02	7.29E-06	6.54E-05	6000
*Bonney Pit 3	77°43'34"	162°19'52"	107	40	4.21E-04	6.03E-02	9.56E-04	8.69E-02	7.28E-06	7.65E-05	6000
*Bonney Pit 4	77°43'34"	162°19'52"	107	40	2.12E-04	9.27E-02	1.42E-04	1.27E-01	5.35E-06	5.87E-05	6000
*West Lobe Lake Bonney	77°44'30"	162°19'42"	110	40	2.44E-04	3.45E-01	6.21E-04	1.09E-01	6.37E-06	7.878E-05	6000
Zone 2											
*Pearse Valley 1	77°43'12"	161°31'40"	420	51	1.37E-03	3.52E+00	1.29E-01	7.11E-01	2.55E-05	3.36E-04	1850000
*Lake Vida, Victoria Valley 1	77°23'21"	162°02'36"	370	37	6.98E-04	1.38E-02	1.46E-04		2.40E-06	7.97E-05	8600
*Pearse Valley 2	77°43'12"	161°31'40"	420	51	2.11E-03	3.65E+00	1.43E-01	7.69E-01	3.25E-05	4.10E-04	1850000
*Pearse Valley 3	77°43'12"	161°31'40"	420	51	1.52E-03	2.17E+00	7.30E-02	6.37E-01	2.61E-05	4.03E-04	1850000
*Lower Victoria 1	77°21'49"	161°19'07"	420	40	2.06E-04	6.33E-03	8.65E-05				8600
*Lower Victoria 3	77°21'49"	161°19'07"	420	40	1.10E-04	1.08E-02	8.80E-05		6.74E-06	6.73E-05	8600
*Bull Pass 1	77°28'32"	160°48'44"	690	45	1.10E-03	1.35E+00	1.17E-01	5.49E-01	2.92E-05		4800000
*Bull Pass 3	77°28'32"	160°48'44"	690	45	1.17E-03	1.19E+00	5.36E-02	5.90E-01	2.12E-05	1.40E-04	4800000
Zone 3											
+Lower Arena Valley	77°48'60"	160°01'60"	1100	93	1.84E-01	7.78E-01	3.31E+00	1.89E+01	8.38E-06		11300000
+Lower Arena Valley 2	77°48'60"	160°01'60"	1100	93	4.93E-02	2.61E-01	1.05E-01	2.01E+00	6.26E-06	1.92E-04	11300000
*Beacon Pit 1	77°51'08"	160°33'16"	1348	84	1.61E-03	7.77E-01	4.00E-01	5.66E-01	6.01E-06	1.29E-04	291500
*Beacon Pit 2	77°51'08"	160°33'16"	1348	84	3.78E-03	2.45E+00	2.09E+00	1.40E+00	1.35E-05	2.31E-04	291500
*Beacon Pit 3	77°51'08"	160°33'16"	1348	84	1.65E-03	8.40E-01	3.26E-01	7.12E-01	5.08E-06	1.11E-04	291500
*Beacon Pit 4	77°51'08"	160°33'16"	1348	84	1.39E-03	8.94E-01	6.46E-01	6.73E-01	7.55E-06	1.47E-04	291500
*East Dais, Wright Valley 2	77°33'02"	160°43'09"	850	75	5.48E-04	1.22E-02	7.10E-05	2.15E-02	2.12E-05	8.83E-05	2700
*West Dais, Wright Valley 3	77°32'60"	161°09'42"	940	64	9.18E-06	2.30E-04	9.67E-06		3.15E-06	7.40E-05	2700
Transantarctics											
MDBJA1	85° 14.995	167° 18.914	8379	810	4.75E-03	3.11E-01	1.33E+00	6.61E-01	1.78E-05	8.44E-04	
MDBJA2	85° 14.994	167° 20.088	7783	810	2.16E-03	3.05E-01	2.43E-01	2.06E-01	5.22E-06	8.36E-05	
MDBJA3	85° 14.982	167° 20.208	7694	810	5.12E-03	4.95E-01	6.11E-01	6.29E-01	2.53E-05	1.72E-04	
MDBJA4	85° 14.985	167° 17.622	7586	810	1.56E-02	4.38E-01	8.19E+00	5.31E+00	1.68E-05	7.35E-04	
Cloudmaker CMUN1	84° 15.905	169° 15.713	5369	700	1.31E-03	1.46E-02	3.04E-03	1.48E-01	7.56E-06	5.65E-05	
Cloudmaker CMUN8	84° 15.878	169° 19.352	6478	700	3.45E-03	9.01E-01	1.93E-01	1.64E+00	2.31E-05	1.74E-04	

\*Collected in 2003 by separate members of MCM-LTER Team

+Collected by Foley (2005)