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THE GEOCHEMISTRY OF SOLUBLE SALTS
IN THE WRIGHT AND TAYLOR VALLEYS,
SOUTH VICTORIA LAND, ANTARCTICA

A thesis
submitted in partial fulfilment
of the requirements for the
Degree of Master of Science
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ABSTRACT

Samples of salt deposits, snow, meltwater and soils were collected in the Wright and Taylor Valleys, South Victoria Land, during the summer field season of 1973-74. The primary aim of the work carried out was to demonstrate the application of chemical techniques to geological problems in the Dry Valleys of Antarctica.

Salt samples identified by X-ray diffraction patterns were halite, thenardite and mirabilite. Snow, ice and groundwater samples were analysed for Na^+ , Ca^{2+} , Mg^{2+} , K^+ , Cl^- and SO_4^{2-} . The results show that atmospheric transport from the sea is probably the most important source of supply of salts to the Dry Valley system, with saline groundwater flows as important means of transport of salts to the Dry Valley lakes.

Variations of soil moisture movement caused by different climatic conditions have been used to describe the differentiation of salts arriving in the Dry Valleys. The salts mostly dissolve in regions of high relative humidities, especially near the snowline, and when they soak into the soil are controlled by temperature and vapour pressure gradients through the soil layer.

In regions of perennially low relative humidity and low

relief, it might be expected that salt movement through the soil is negligible. Thus it could be possible to "date" surfaces by measuring the accumulation of salts. A "salt map" of an alpine glacier moraine near Lake Vanda, Wright Valley, was prepared by plotting results of chloride analyses of soil core samples onto a vertical air photograph. Four separate moraine sheets are distinguished, their accumulation ages ranging from 5×10^3 to 5×10^5 years B.P. These suggest that the Wright Valley has not been occupied by either a through-valley glacier or a body of water for approximately $10^5 - 10^6$ years.

Salt accumulations in the soils of Taylor Valley show an abrupt change coinciding with a linear feature visible on the north wall at an altitude of 210m above Lake Bonney, suggesting that it is a former lake level with a minimum accumulation age of 6×10^3 years B.P. The higher feature occurring at 400m does not show any change in salt content, and is probably a lateral moraine left by a previous advance of the Taylor Glacier.

The use of chemical techniques in studying Dry Valley problems holds great promise, although certain limitations are encountered in work on Dry Valley soils, mainly because of the lack of independently datable material.

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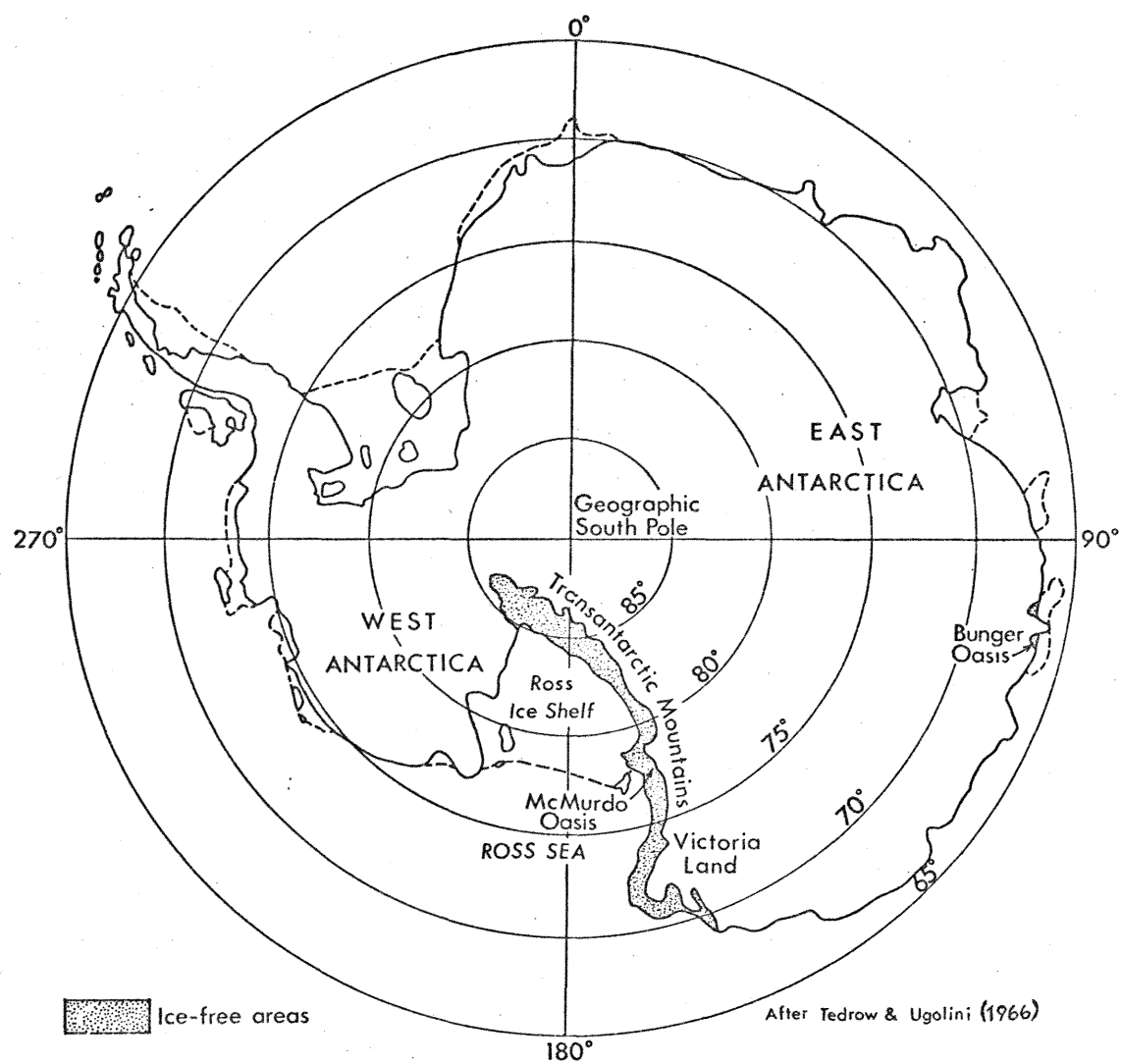
Chapter 1

INTRODUCTION1.1 Purpose of study

This thesis describes a study that began in the 1973 academic year with chemical analyses of Antarctic salt samples collected by previous investigators. Further samples of salt, soil and water were collected in the McMurdo Dry Valleys during the 1973-74 summer season, as part of the field programme of the Antarctic Research Unit, University of Waikato. These were analysed in the field and back in the laboratory, and the results were used to obtain information about salt geochemistry in the frigid and arid environment of the ice-free valleys of southern Victoria Land, (Fig. 1).

Two main groups of findings are presented : one dealing with the occurrence and movement of salts in Dry Valley soils, as well as the chemical compositions of ice, water and soil extracts; the other providing a basis for calculating the approximate ages of glacial moraines. Little success has so far been achieved in determining reliable dates for glacial and climatic events by classical radiometric and stratigraphic methods because of the complexity of late Cenozoic history and the almost complete absence of organic material (McKelvey and Webb, 1959; Péwé, 1960). It is thought that the salt concentrations in Dry Valley soils, (as well as weathering), is proportional to the age of the soil, and so arose the idea of "salt mapping", an attempt to distinguish

Figure 1: ANTARCTICA



between moraines of different ages by comparing the values of salt concentration in the moraine soils.

In such a region of complex and unusual physical conditions, an application of chemical expertise and technique to the many problems presented may well produce answers that the more conventional methods cannot.

1.2 Locality and physiography

The Wright and Taylor Valleys are two adjacent ice-free areas in the McMurdo Dry Valley region of southern Victoria Land, Antarctica, which lies along the western coast of the Ross Sea, in the McMurdo Sound region of the Transantarctic Mountains, (Fig. 2). The Dry Valley system lies between 77° and 77° 45'S latitude, and 160° and 164°E longitude, trends east-west, and has a total area of approximately 4000 km².

The Wright Valley is about 30 km long and extends up to the terminus of the Upper Wright Glacier at an altitude of about 900 metres. Further to the east, two parallel forks run from the Labyrinth, a dissected dolerite sill, and join past the flat-topped Dais to form the valley proper. The most notable feature of the valley is Lake Vanda, which is 7 km long, approximately 70 metres deep and perennially covered by some 3 metres of ice (Nelson and Wilson, 1972). Relict lake beaches and strandlines are cut into the moraines and talus slopes surrounding the lake, as shown in Figure 3, an aerial view looking west up the valley.

On both sides of the Wright Valley are mountain ranges and alpine valley glaciers, most of which feed ephemeral streams during the summer months. Steep talus and bedrock slopes stretch between the valley floors and the high rock cliffs, and in places show benches cut by previous glacial action. Lake Vanda has an eastern inflow, the Onyx River, but no outflow.

Figure 2: McMurdo Sound.

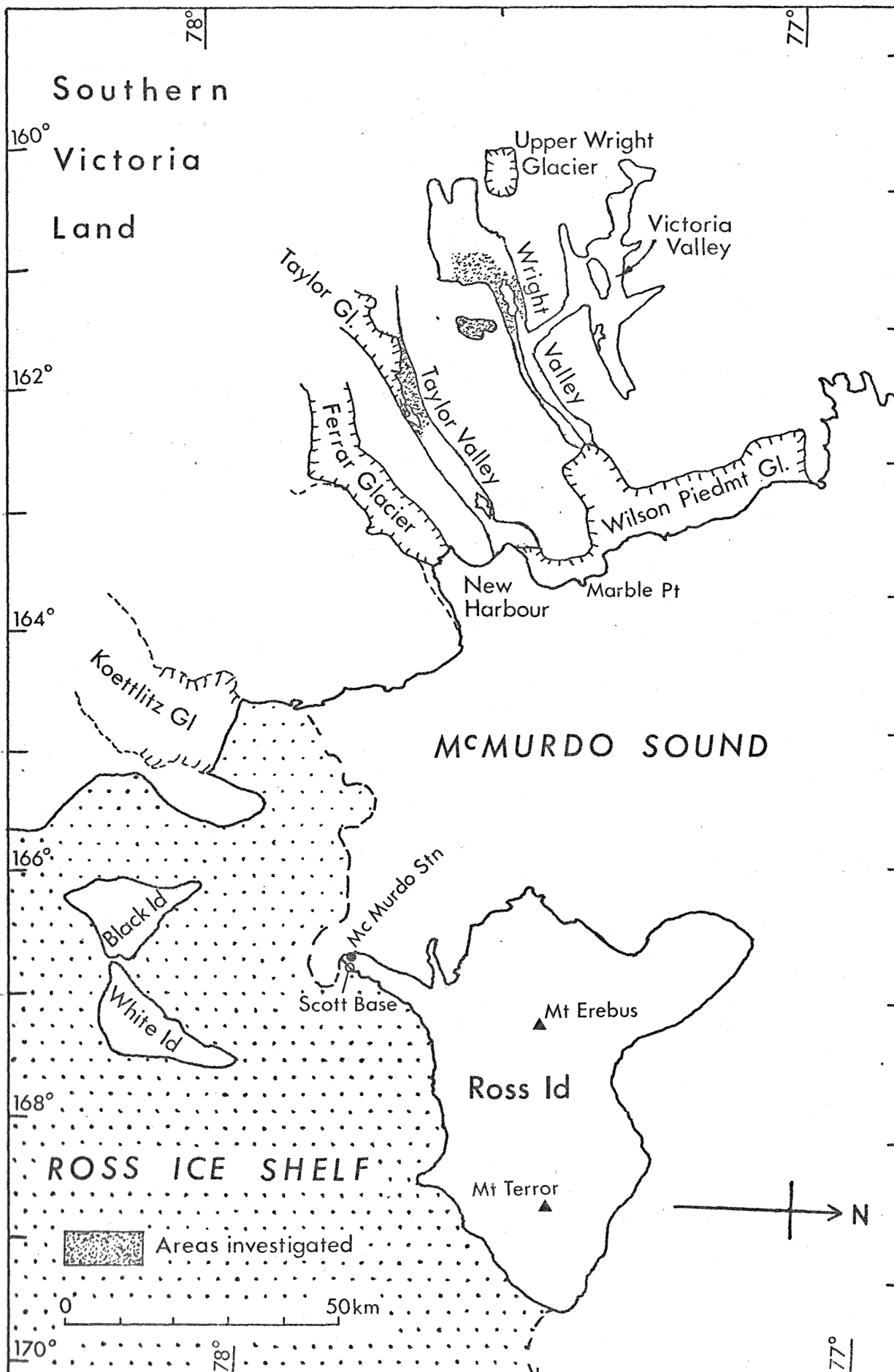


Figure 3 : Oblique aerial photograph of Upper
Wright Valley, showing Lake Vanda,
the Dais and the Upper Wright Glacier
(U.S. Navy photograph)



West of White Sulphur Springs

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Several small frozen lakes and saline playas are present around Lake Vanda, particularly in the moraines of the South Fork, (the southern extension of Wright Valley behind the Dais, extending past Don Juan Pond; not a recognised geographical name).

The Taylor Valley lies to the south of the Wright Valley. Its western section has a narrow floor occupied by several frozen lakes and at its extremity it is completely filled by the Taylor Glacier, an extension of the Polar Plateau ice. The valley walls are steep, rising up to the Kukri Hills in the south and to the Asgard Range in the north (Fig. 4). The largest lake in the valley, Lake Bonney, is divided into two lobes by a bedrock constriction and is fed by meltwater from the Taylor Glacier and several alpine glaciers, and groundwater. The lake is 5 km long and 0.5 km wide.

Wright Valley soil and salt samples were collected from the southern and western banks of Lake Vanda, in the area between Don Juan Pond and the slopes of Mt. Odin, Asgard Range. Salt samples were collected from the high regions of the Asgard and Olympus Ranges flanking the Wright Valley, and snow samples were gathered occasionally during helicopter trips.

In the Taylor Valley sampling was mostly restricted to the north shores of Lake Bonney, especially above the western lobe. Detailed attention was given to the valley walls on both sides of the Rhone Glacier.

Figure 4 : Oblique aerial photograph of Taylor
Valley, looking east from Taylor Glacier
and Lake Bonney to McMurdo Sound



1.3 Climate

Both the Wright and Taylor Valleys occur in an area which is almost entirely free of ice throughout the year. Continuous weather observations were made at Vanda Station, Wright Valley, and were extended through the 1969 and 1970 winters. The results of the two years of observations were published by Thompson, Craig and Bromley (1971), and Thompson, Bromley and Craig (1971). The following climate information is taken from these two papers.

Table 1

Meteorological Data, Vanda Station

	<u>1969</u>	<u>1970</u>
Total days of snow	59	11
Extreme max. temp. (°C)	+8.5	+10.4
Extreme min. temp. (°C)	-56.9	-55.2
Mean temp. (°C) (averaged from mean monthly temps.)	-21.8	-18.2
Mean windspeed (m/sec.)	4.2	5.3
Max. relative humidity (%)	83	63
Min. relative humidity (%)	38	28
Max. 8 cm ground temp. (°C)	+2.9	+4.5
Min. 8 cm ground temp. (°C)	-39.0	-36.7
Estimated total snowfall (cm)	8.2	0.7

The Dry Valley climate is characterised by low precipitation, low humidities and relatively low mean cloud cover. The Taylor Valley apparently receives fewer summer

snowfalls than the neighbouring areas (McCraw, 1967). The air temperatures are 7°C warmer in midsummer than those of adjacent snow-covered areas and $5-7^{\circ}\text{C}$ colder in midwinter. The mean annual temperature for 1969 and 1970 was -20.0°C .

A regular sequence of winds blows up and down the valley during the summer season. Easterly winds of 8-10 m/sec. blow during the warmer part of the day, and westerlies of similar strength blow during the cooler hours. During the summer months, the easterlies are more frequent, but the westerly winds are more common during the winter. These winds are warmer, being heated adiabatically as they descend into the valleys from the higher western and southern land. Relative humidities are much lower during westerly winds (Bull, 1966), and values of less than 10% have been recorded.

1.4 Literature Discussion : The Geochemistry of a Rainless Desert

The climatic characteristics of the McMurdo Dry Valleys, as mentioned in the previous section are those of an extreme-cold desert environment, having very low relative humidity, low temperatures and dessicating winds (Tedrow and Ugolini, 1966). A distinguishing feature of the ice-free valleys is their very low annual precipitation, which consists only of a few centimetres of snow (as water equivalent); the Dry Valley system can thus be classified as a rainless desert.

Previous work on the geochemistry of such environments is limited, and excluding chemical examination of the various saline lakes in the valleys, has consisted mainly of observations of the occurrence of salt deposits in the soils.

Glazovskaia (1958, 1970) did much of the early work on the geochemistry of cold arid regions, and investigated the mobility of sodium and calcium sulphates and chlorides in soils of the Bunger Oasis, East Antarctica.

Gibson (1962), Johannesson and Gibson (1962) and Nichols (1963) noted the occurrence of many salts as efflorescences in the Dry Valley soils, particularly during geological investigations in the area. Detailed analyses of some of the salts were done.

Jones and Faure (1969) analysed the isotopic compositions of strontium in soluble salts of Wright and Taylor Valley

soils, finding that many have been formed in situ within the past 2-4 million years. The field of ion movement in frozen soil has been well-covered. Cary and Mayland (1972) gave a theoretical account of salt and water movement through frozen soil. Ugolini and Anderson (1973) performed detailed experiments on ionic migration through frozen Dry Valley soils, placing emphasis on the significance of their results in relation to chemical weathering.

Keys (1972) analysed many salt deposit samples and found them to be mainly of marine origin, with minor contributions from chemical weathering of bedrock. He discussed distribution processes of the salts and showed that salt weathering is primarily a physical process. Driessen and Schoorl (1973) studied the mineralogy and morphology of efflorescent salts in soils of arid and semi-arid regions.

Hendy (1973) described the preliminary investigations into the work covered in this thesis, including a reconnaissance of the soil salts of the Victoria Valleys, and analyses of the abundance and occurrence of salt in the Wright Valley soils.

Chapter 2

FIELD AND LABORATORY PROCEDURE2.1 Methods of sample collection

Soil samples were collected by driving down to permafrost level a steel coring tube with a cross-sectional area of 1.8 cm^2 . Not uncommonly, buried boulders and rocks in the soil obstructed easy core penetration and several attempts had to be made to obtain suitable samples. These were placed in numbered polythene bags and sealed until later analysis.

In the Wright Valley, a random series of samples were collected to obtain an idea of salt properties. Soils were collected along profiles up valley sides or were cored in a regular pattern to get the maximum coverage of the geomorphic features in various areas, such as in the South Fork moraines. In the Taylor Valley sampling sites were chosen to obtain a representative coverage of the north bank of Lake Bonney, east and west of the Rhone Glacier.

Samples were normally analysed for their salt content on the day of collection and sampling locations transferred to maps or aerial photographs. Figure 5 shows a sketch map of the distribution of sample collection in the valleys.

Salt deposits and snow and ice samples were frequently collected, using polythene bags. Water samples from melt streams or lake edges were taken in bottles, polythene bags or plastic jars.

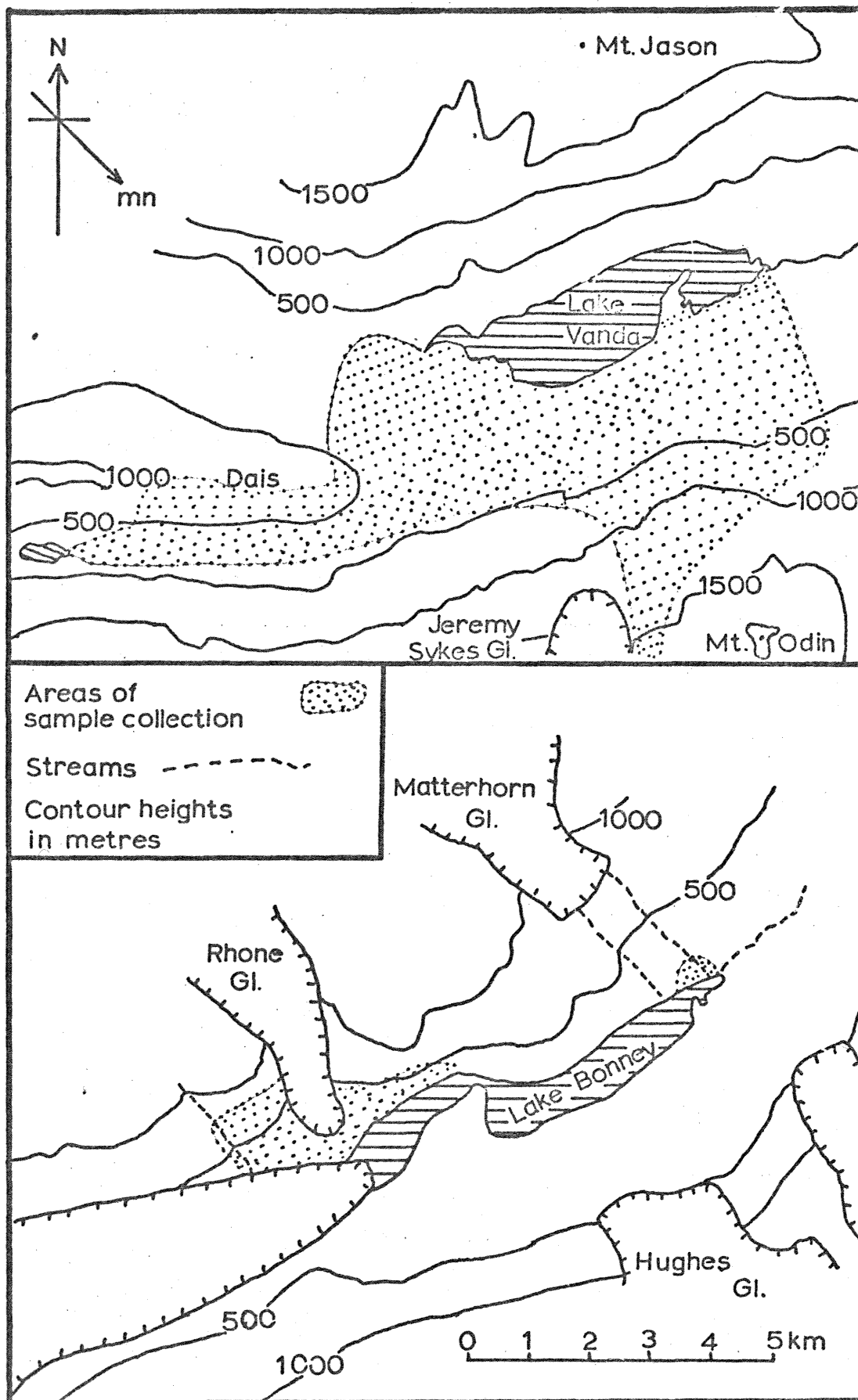


Figure 5 : Sketch Map of Sample Collection Areas

2.2 Field and Laboratory Analyses

(a) Field analyses : a large number of analyses for chloride ion concentration, with a few sulphate ion determinations, were carried out in the field. This was done to help select future sampling sites and to obtain first impressions of the salt compositions of the valley soils.

The analytical techniques used in the field were simplified versions of those used later in the laboratory. Chloride ion was determined by the Mohr titration, described in APHA (1971), using previously standardised silver nitrate solution as titrant with potassium chromate as indicator. A 10 cm graduated pipette was used as a burette, the sample being held in an enamel evaporating basin.

Sulphate ion was determined by the modified Chesnin and Yien method (Hesse, 1971), where a barium sulphate precipitate is formed and measured turbidimetrically by a generator-powered spectrophotometer.

Soil salts were extracted in 100 cm³ water per sample. Occasionally, the anions were determined in solution made up in the actual sample bags, but usually the soil samples were transferred to polyethylene bottles and the water added. The water for analyses was obtained by melting pure high-standing lake ice or by deionising glacial melt-water with an ion-exchange resin, e.g. Biodemineralite.

(b) Laboratory analyses : samples not analysed in the field or at base camps were brought back to New Zealand for further examination. These were put into several categories :

1. Chloride and sulphate analyses of remaining soil samples.
2. Determinations of concentrations of Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- and SO_4^{2-} ions in snow, ice, melt-water and late and ground-water samples.
3. Total ion analyses of a number of salt efflorescences.
4. X-ray diffraction and x-ray fluorescence analyses of salt samples to determine their mineralogy.
5. Ion analyses carried out on a series of soil samples exhibiting differential salt movement.

Table 2

Analytical laboratory techniques

<u>Ion</u>	<u>Method</u>
Cl^-	1. Mohr titration, (AgNO_3 solution with K_2CrO_4 as indicator) 2. Titration with HgNO_3 solution with mixed diphenylcarbazone indicator
SO_4^{2-}	Turbidimetric analysis of BaSO_4 precipitate (modified Chesnin & Yien method)
Na^+	Flame emission spectroscopy.
Ca^{2+}	Flame emission and atomic absorption spectroscopy.
K^+	Flame emission spectroscopy.
Mg^{2+}	Atomic absorption spectroscopy.

Table 2 above summarises the techniques of laboratory analysis used. Three SO_4^{2-} determinations for snow and ice samples were checked, using an acid-reduction method, by soil research staff of Ruakura Agricultural Research Station. Some glacier and snowfield samples contained very small amounts of sulphate ion, requiring modifications to the turbidimetric method :

1. A precipitate "conditioning agent" was omitted.
2. 4 cm silica cells were used instead of 2 cm cells.
3. A more accurate and reliable spectrophotometer was used, the single-beam Hilger - Watts "Uvispek".

2.3 Presentation of results

The results of the analyses carried out are presented in tables and diagrams in the thesis, accompanying the relevant sections. Results comprising large amounts of repetitive data are contained in the Appendix at the back of the thesis.

Chapter 3

SALT GEOCHEMISTRY IN AN ARID ANTARCTIC ENVIRONMENT3.1 Occurrence of salts in Dry Valley soils(a) Previous Work

The presence of salts in and upon the soils of the McMurdo Dry Valleys is well-documented in the literature and several chemical analyses of their compositions are available. The following list summarises the work published on Dry Valley salts.

1. Jensen (1916) : found soluble chlorides and sulphates in the Taylor Valley.
2. Gibson (1962) : found : (i) gypsum and sodium iodate in depressions near Lake Vashka
(ii) gypsum and thenardite in the Balham Valley
(iii) a mixture of gypsum, epsomite and sodium nitrate in Beacon Group sandstones.
3. Johanneson and Gibson (1962) : found calcium sulphate, and carbonate, with sodium sulphate, nitrate and chloride as single salts and salt mixtures in salt pans and efflorescences and in moraines.

4. Nichols (1963) : found sodium chloride, calcium carbonate and magnesium chloride dissolved in saline ponds and evaporated as thin veneers. Observed surface efflorescences composed of 50% sodium chloride and 50% sodium sulphate. Halite, thenardite, epsomite, gypsum and calcite occur as salt layers in lower Wright Valley moraines.
5. Claridge (1964) : analysed Taylor Valley soils for calcium carbonate and soluble salt content. Found thenardite in summit soils, but abundant gypsum and calcite in other valley soil samples.
6. Keys (1972) : analysed lower Taylor Valley samples, finding calcite, halite, thenardite and gypsum in soil profiles and forming surface efflorescences.

(b) Observations : during the 1973-74 field season, salts were frequently observed in the Dry Valleys, particularly in the Wright Valley. They occur as :

1. Nodules in soil profiles.
2. Surface veneers apparently derived from evaporation of water or snow.
3. Patches beneath rocks and boulders.
4. Fragments of laminated calcite, containing some gypsum, found at low altitudes around Lake Bonney, Taylor Valley.

On the floor of the Wright Valley, south of Lake Vanda, hard halite pans were found just below the soil surface. In some places south of Lake Vanda these were 10 cm thick and resembled deposits about Don Juan Pond.

Salts forming surface veneers are common in both the Wright and Taylor Valleys. They are predominantly found as thin powdery films of halite and thenardite on pebbles, rock fragments and soil particles on the edges of saline lakes. Similar deposits were observed around damp patches of soil throughout the Lake Vanda region and around Lake Bonney. Where glacial meltwater has evaporated from rocks, a very thin film of halite remains.

Salt accumulations beneath rocks and boulders fall into two categories :

1. Those occurring in soils of glacial moraines, especially in the entrance to the South Fork, Wright Valley.
2. Those found at moderately high altitudes on mountain slopes and in intermontane passes.

The moraine salts were usually halite while the salts found higher up were thenardite or mirabilite. Moraine halite deposits (Fig. 6) contain rock detritus and quartz and feldspar fragments and were often found under rocks with hollow basis. Here the salts have undoubtedly played some part in weathering of rock surfaces.

Table 3 shows the mineral compositions of a variety of salt samples analysed by X-ray diffraction spectroscopy.

Figure 6 : Halite deposit in South Fork moraines,
Wright Valley



Table 3 : Mineral compositions of salts analysed by
X-ray diffraction spectroscopy

<u>Sample No.</u>	<u>Locality</u>	<u>Salts</u>
TG1	Ice of Taylor Glacier snout, Taylor Valley	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, possible NaNO_3 and $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
M1A	Beneath rocks in moraines 276m above L. Vanda, Wright Valley	NaCl
M1B	As for M1A, 185m above L. Vanda.	NaCl , possible CaCO_3
M3A	Sparse crystals beneath rocks, 194m above L. Vanda	Na_2SO_4
M17A	Salt efflorescence in moraines 98m above L. Vanda	NaCl
OT4	Salt veneer on soils of slopes of Mt. Odin, Wright Valley	Na_2SO_4 , $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
A18	Salt efflorescence on North Wall of Taylor Valley, 386m above L. Bonney	NaCl
W2	Polar Plateau, above Taylor Valley	Na_2SO_4 , $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$
W3	Ridge between camp and east valley, Asgard Range	Na_2SO_4 , $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$
W4	Campsite, Black Valley, Asgard Range	Na_2SO_4 , $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$
W7	Salts under rocks at top of Olympus Range	Na_2SO_4
W9	Top of Asgard Range, near Asgard Hut	Na_2SO_4

A very fine silty sediment frequently outcrops in the Wright and Taylor Valleys and has been identified as "bedded polymicton" by Murrell (1973). It is generally khaki-yellow in colour and has a very low density and is thought to be lake-deposited sediments and rock-flour. In the Wright Valley the sediment has been deposited in a depression at the western tip of Lake Vanda, into which lake water must flow should the lake level rise. The polymicton also outcrops in the South Fork moraines southwest of Lake Vanda, where it is characteristically draped in fine concentric layers over large buried boulders (Fig. 7).

The sediment is far more abundant in the Taylor Valley and was often observed about the Rhone Glacier, adjacent to the Taylor Glacier snout. Fine-grained sediments were often interbedded with coarse till and formed most of the outwash plain below the Rhone Glacier. Gullies cut by melt streams showed that the polymicton bed extended to a maximum depth of 10 metres.

The sediment was almost always very bitter to taste and in such localities high values of soil salt concentration are found. The Wright Valley deposit described above gave a value of 242 mg Cl /cm², (which is plotted on Fig. 12).

X-ray diffraction patterns for the sediment showed only quartz as a definite constituent, with diffuse peaks possibly corresponding to halite and phillipsite. Jones et al. (1973) described two deposits of a very similar sediment about Lake

Figure 7 : Polymicton beds, South Fork moraines,
Wright Valley



Vanda and concluded that they were probably water-laid volcanic ash deposits containing chlorophaeite, a mineraloid derived from the alteration of volcanic ash. Linkletter (1974) described two lake basins in the Taylor Valley which contained fine-grained, low-density and highly coloured sediments : the predominant mineral present was phillipsite. Murrell (1973) claims that the bedded polymicton was deposited from a floating glacier or ice-tongue.

3.2 The supply of salts to the Dry Valley system

There has been considerable debate over the origin of the salts in the McMurdo Dry Valleys. Various sources have been suggested, including the following :

1. Atmospheric transport of marine salts.
2. Trapping of large bodies of seawater, followed by evaporation and/or freezing.
3. Chemical weathering of soil and rock.
4. Hydrothermal activity.

It seems likely that Lake Bonney and its salts are derived from a large body of trapped seawater (Wilson and Hendy, 1972; Hendy, in press) but it is probable that for most of the Dry Valley system the most important process of salt transport is atmospheric transfer from the sea.

Chemical weathering is claimed by many authors to be the most important source of the Dry Valley salts. Jones and Faure (1969) measured $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of salts about the Meserve Glacier, Wright Valley and concluded that most of them had formed in situ. However Kelly and Zumberge (1961) found from quantitative investigations on the weathering of quartz diorites at Marble Point that physical weathering was the predominant process producing rock disaggregation. The chemical weathering process cannot be shown to produce the huge quantities of chloride and sulphate salts that are present in the Dry Valleys.

No evidence was found to indicate that hydrothermal activity is a significant source of Dry Valley salts, although

there are reported signs of previous volcanic activity (McKelvey and Webb, 1959; Hamilton and Hayes, 1960).

The atmospheric transport of marine salts has been studied extensively in recent years; a common finding is that the concentration of elements in Antarctic precipitation is subject to geographical variation. Brocas and Delwiche (1963) found from many samples in Queen Maud Land that average chloride concentrations decrease from about 2.3 ppm at the coast to 0.5 ppm in the interior of the continent. Murozumi and Shimizu (1972) analysed 6 samples from West Enderby Land, East Antarctica, which represented one year's precipitation. These contained very low concentrations of chemical constituents having compositions similar to marine salt. Matveev (1970) found that precipitation in the ice-free area near Mirny, East Antarctica, was characterised by a dominance of bicarbonate, sodium and calcium ions. He concluded that the main source of the ionic constituents of central Antarctic and coastal precipitation was sea salt.

Wilson and House (1965) measured the annual infall of elements in South Polar snow and obtained the following results :

<u>Element</u>	<u>Infall, gm/cm²/yr</u>
Na	1 x 10 ⁻⁷
K	5 x 10 ⁻⁸
Cl	2 x 10 ⁻⁷

Ocean-derived salts may be introduced into the atmosphere as minute aerosols (Junge, 1963). Very strong winds occur in the Dry Valleys and the McMurdo Sound coast is only 50 km from the head of the Wright Valley. There are probably at least two processes producing airborne salt particles that are later removed from the atmosphere by precipitation.

Wellman and Wilson (1963) found extensive deposits of hydrated sodium sulphate, together with calcium carbonate and sodium chloride, on the surface of the sea-ice in McMurdo Sound. The salts are thought to form by a process of freezing and concentration of seawater during percolation through cold compacted snow. An estimated one million tons of salt are deposited per annum. This could be important source of marine salts, particularly during the winter months when the Sound is frozen.

The other source of marine salts is sea-spray. When drops of seawater freeze in the atmosphere, solid calcium carbonate and sodium sulphate form (Thompson and Nelson, 1956). The ice can evaporate, leaving salt particles behind.

Table 4 shows the ionic compositions of snow and ice samples from glaciers in and near the Wright and Taylor Valleys. They indicate the quantities of salts available to the Dry Valley soil/water system. The transfer of salts from precipitation to the soil layer is aided considerably by the climate conditions peculiar to the Dry Valleys. The major process of snow removal is direct sublimation, brought about

Table 4 : Ionic Concentrations (ppm) of Snow and Ice Samples

<u>Sample</u>	<u>Na⁺</u>	<u>Ca²⁺</u>	<u>K⁺</u>	<u>Mg²⁺</u>	<u>SO₄²⁻</u>	<u>Cl⁻</u>	<u>SO₄²⁻ / Cl⁻</u>
Scott Base snow	3.45	0.59	0.16	0.79	1.46	7.00	0.2
Lower Wright Glacier snow	0.23	0.12	0.10	0.02	0.48	0.84	0.6
Snow on Lake Vanda	0.53	0.30	0.09	0.40	2.80	0.89	3.1
Upper Wright Glacier snow	0.46	0.17	0.09	0.07	0.66	0.54	1.2
Rhone Glacier meltwater	2.08	1.61	0.41	0.55	1.48	2.23	0.7
Taylor Glacier snout ice	0.18	0.29	0.10	0.02	0.40	0.84	0.6
Upper Taylor Glacier ice	0.08	0.01	0.06	0.03	0.26	0.20	1.3
Canada Glacier névé	0.50	0.19	0.10	0.30	0.30	1.56	0.2
Catspaw Glacier névé	1.40	0.42	0.06	0.19	0.94	2.42	0.4
Fresh snow, Canada Glacier	4.00	0.50	0.47	0.46	10.4	1.12	9.3
Terminal stream, Canada Glacier	5.25	10.0	1.57	1.46	5.5	6.14	0.9
Jeremy Sykes Glacier snow	2.16	0.65	0.63	0.27	0.5	3.07	0.2

by the action of dry winds, low relative humidities and solar radiation. Once the snow has evaporated, the salts remain as a light powder on the soil surface. An increase in relative humidity can dissolve some of the salts, particularly sodium chloride and calcium chloride. The saline solutions formed soak into the soil, where new distribution processes operate.

3.3 Movement and separation of salts in Dry Valley soils

(a) Previous Work

Studies on the behaviour of the salts in Dry Valley soils have been limited. Keys (1972) explained the distribution of salts in the McMurdo Oasis as the effect of a relative humidity separation mechanism operating along valley sides and possibly in the soil layer itself. Ugolini and Anderson (1973) performed radiotracer studies on the vertical movement of sodium and chloride ions from a point source in Wright Valley moraine soils.

Publications on salt movement in frozen and unfrozen soil are more common. Smith (1972) used calcium chloride in leaching experiments to investigate the rate of chloride ion movement. Todd and Kemper (1972) set up concentration gradients in soil columns and derived salt dispersion coefficients for the region near an evaporating surface. Cary and Mayland (1972) studied salt and water movement in unsaturated frozen soil and showed that liquid phase movement occurs in water films adsorbed onto soil particles.

(b) Observations

Appreciable volumes of groundwater were observed flowing through the soil profile above the permafrost layer in two localities :

1. Down the northern bank of East Lobe, Lake Bonney. The flow produced a dark colour on the surface of the soil (Fig. 8) and was estimated to be flowing at about 100 ml/min.

Figure 8 : Saline groundwater flow into East Lobe
of Lake Bonney, Taylor Valley



2. Down a small valley in moraines of the South Fork, Wright Valley, nearly 2 km east of Don Juan Pond. The estimated flow, which was in the direction of the playa, was between 1 and 2 l/min.

Both flows were very saline. Their ionic compositions are included in Table 5 together with those of surface water flows in the Wright and Taylor Valleys.

The major ions transported by the single Wright Valley sample analysed were, in decreasing order of concentration, chloride, calcium, sodium and magnesium. For the two flows sampled on the shores of Lake Bonney, the major ions were chloride, sodium, magnesium and calcium.

(c) Discussion

Certain characteristics of the water-soil system of the Wright and Taylor Valleys that require explanation. These are :

1. The occurrence of sodium sulphate salts at moderate-to-high altitudes, of sodium chloride at low altitudes and the large amounts of calcium chloride on the floor of Wright Valley.
2. The high concentrations of sodium, calcium, magnesium and chloride ions in groundwater flows near the valley floors, and the relative magnitudes of these ions compared to those contained in snow and ice at greater altitudes.

It is interesting to note the similarities in the relationships between very saline groundwater flows and the

Table 5 : Ionic Compositions of Surface and Subsurface Water Flows (mg/l)

<u>Sample No.</u>	<u>Location</u>	<u>Na⁺</u>	<u>Ca²⁺</u>	<u>Mg²⁺</u>	<u>K⁺</u>	<u>SO₄²⁻</u>	<u>Cl⁻</u>	<u>SO₄²⁻/Cl⁻</u>
BE 1	Subsurface flow on north bank of East Lobe, Lake Bonney, Taylor Vy.	8,560	2,510	4,750	510	4,125	25,490	0.08
BE 2	" " "	8,560	2,920	4,850	630	263	26,775	0.01
W 10	Surface stream 100 m from Taylor Glacier snout, on south bank	2.8	7.3	0.9	1.6	6.8	3.6	1.88
W 11	Main surface stream on south bank of West Lobe, Lake Bonney	4.6	15.8	1.4	2.3	5.8	5.0	1.15
-	Terminal stream, Canada Glacier, Taylor Valley	5.3	10.0	1.5	1.6	5.5	6.1	0.9
D 19	Terminal stream, Jeremy Sykes Glacier, Wright Vy.	44.5	17.0	7.1	8.1	39.5	162	0.24
D 39	Surface stream flowing into Don Juan Pond from west	83.0	75.0	16.2	25.0	2.5	150	0.02
D 41	Subsurface flow towards Don Juan Pond from east :South Fork, Wright Vy.	9,900	18,100	6,890	635	10.8	61,400	0.002
-	Onyx River, upstream of entry into Lake Vanda, Wright Vy.	6.3	4.7	2.0	1.0	3.0	14.7	0.2
M 25A	Stream flowing from Asgard Range into South Fork moraines, Wright Vy.	140	60	36.8	8.6	171	222	0.77

lakes into which they descend. For the flow moving towards Don Juan Pond and for the playa itself,

$$[\text{Ca}^{2+}] > [\text{Na}^+] > [\text{Mg}^{2+}]$$

This relationship also holds for Lake Vanda waters down to a depth of 49 metres (Angino and Armitage, 1963). The bottom waters of Lake Bonney and the groundwater flow at the eastern end of the lake share the relationship.

$$[\text{Na}^+] > [\text{Mg}^{2+}] > [\text{Ca}^{2+}]$$

These inequalities indicate that dense saline groundwater flows are possible sources of salt ions in Lake Bonney and Don Juan Pond.

Keys (1972) explained the distribution of salt with altitude as the result of a process of relative humidity gradient separation, acting up and down the Dry Valley walls. At the same time, a seasonal relative humidity separation process could occur in the soil profile. Different salts have certain characteristic relative humidity values, above which they will dissolve in atmospheric moisture. Salts deposited in regions of high relative humidity will remain there if their relative humidity indices are higher than that of their surroundings. If not, they will form solutions and trickle away down-hill until they reach an area of sufficiently low relative humidity to allow them to precipitate out. It is doubtful if a series of comparatively constant relative humidity values could be maintained up Wright and Taylor Valley walls. At Vanda Station, Wright Valley, mean monthly humidities taken over a period of two years varied from 28% to 83% (Thompson *et al.* 1971a). The variability of the moisture content,

duration and direction of the Dry Valley winds would only permit very rough average values at any point. Nevertheless, the high relative humidities at high altitudes, particularly near the snow-line, probably prevent salts such as sodium chloride and calcium chloride remaining in solid form after snow has evaporated from the soil surface.

Both of these salts can dissolve in the water available from atmospheric water vapour, provided that the critical relative humidity value for each salt at that particular temperature is exceeded. Once a liquid solution of the salts has formed, it will percolate into the soil.

Salts having particularly high critical relative humidity values will remain as solids in the localities where they were initially precipitated after snow evaporation or to which they were blown after being deposited elsewhere. This explains the large amounts of sodium sulphate present at moderate altitudes in the forms of mirabilite and thenardite ($\text{Na}^+\text{SO}_4 \cdot 10\text{H}_2\text{O}$ and Na^+SO_4 respectively). Calcite has been reported as occurring on mountain peaks in the Dry Valley area (Keys, 1972).

Freezing of Dry Valley Soils

The Dry Valley soils are frozen except during the few summer months when up to 50 cm of soil layer thaws. This layer, subject to seasonal (and sometimes diurnal) freeze-thaw process, is called the "active layer" and can contain temporarily frozen soil at times. McCraw (1967) proposed the term "frozen ground

table" for the upper surface of temporarily frozen ground, which sinks during a thaw and coincides with the permafrost table at maximum thaw. Figure 9 is an idealised diagram of a Dry Valley soil profile at approximately mid-thaw.

Figure 10 shows the 1969 monthly mean ground and air temperatures measured by Thompson et al. (1971b) at Vanda Station. The depth of permafrost freezing was estimated to be approximately 40 cm. The top 20 cm of soil undergoes extremes of temperature and only reaches temperatures above 0°C in December and January.

Between February and October the 8 cm and 20 cm ground temperatures are lower than those of the 46 cm depth and below. The temperature difference between the 8 cm and 46 cm levels is approximately equal to that between the soil surface and the permafrost table, varying from 0.4°C to 7.1°C. So, in Dry Valley soils there is always a temperature gradient whose direction reverses twice a year. This reversal does not coincide with the thawing of the upper soil layers, which only occurs in November or December of each year. The movement of salt and moisture through Dry Valley soils occurs in three different settings :

1. frozen soil, temperature increasing upwards
2. frozen soil, temperature increasing downwards
3. unfrozen or partly unfrozen soil, temperature increasing upwards.

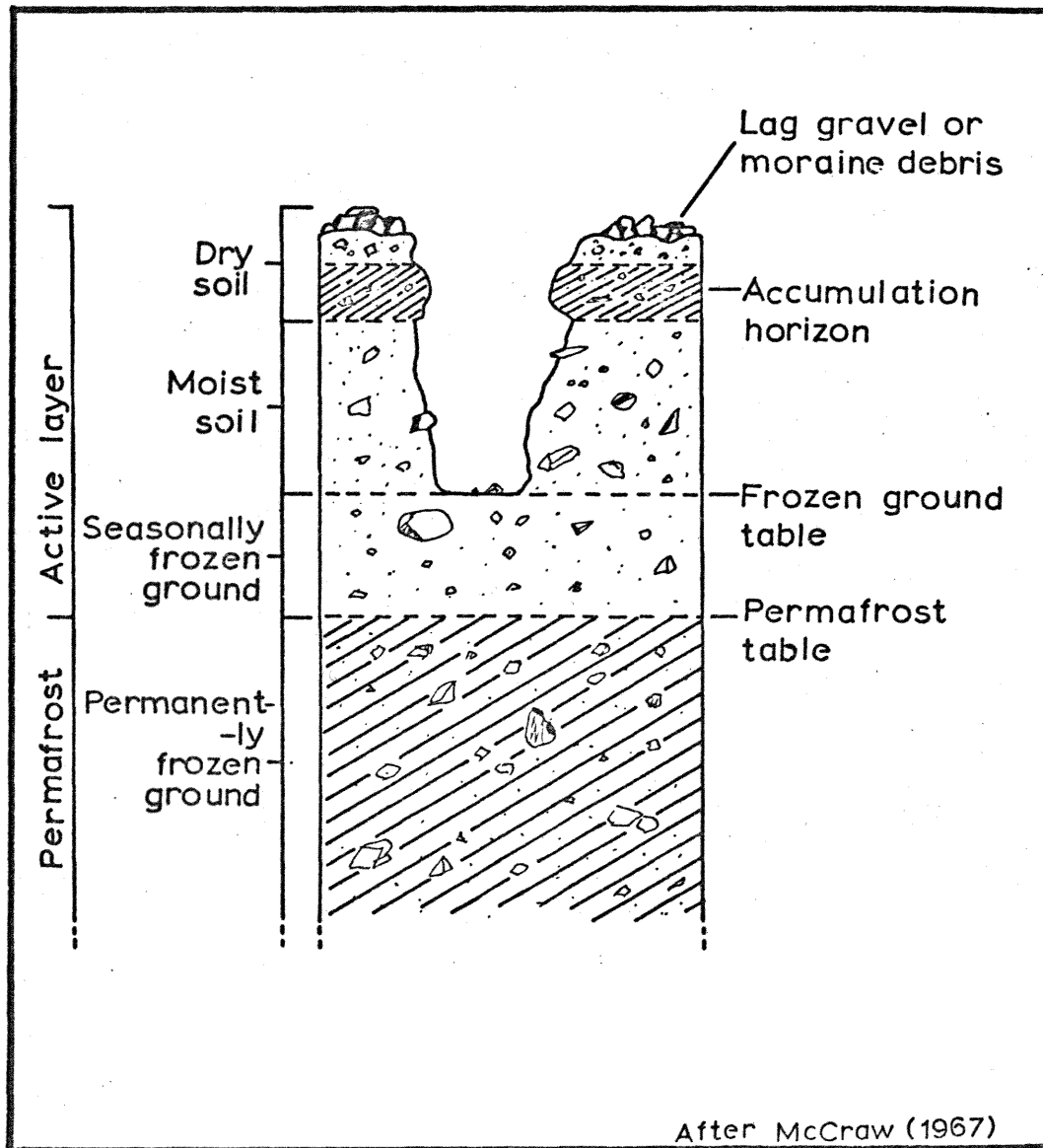


Figure 9 : Profile of Dry Valley soil

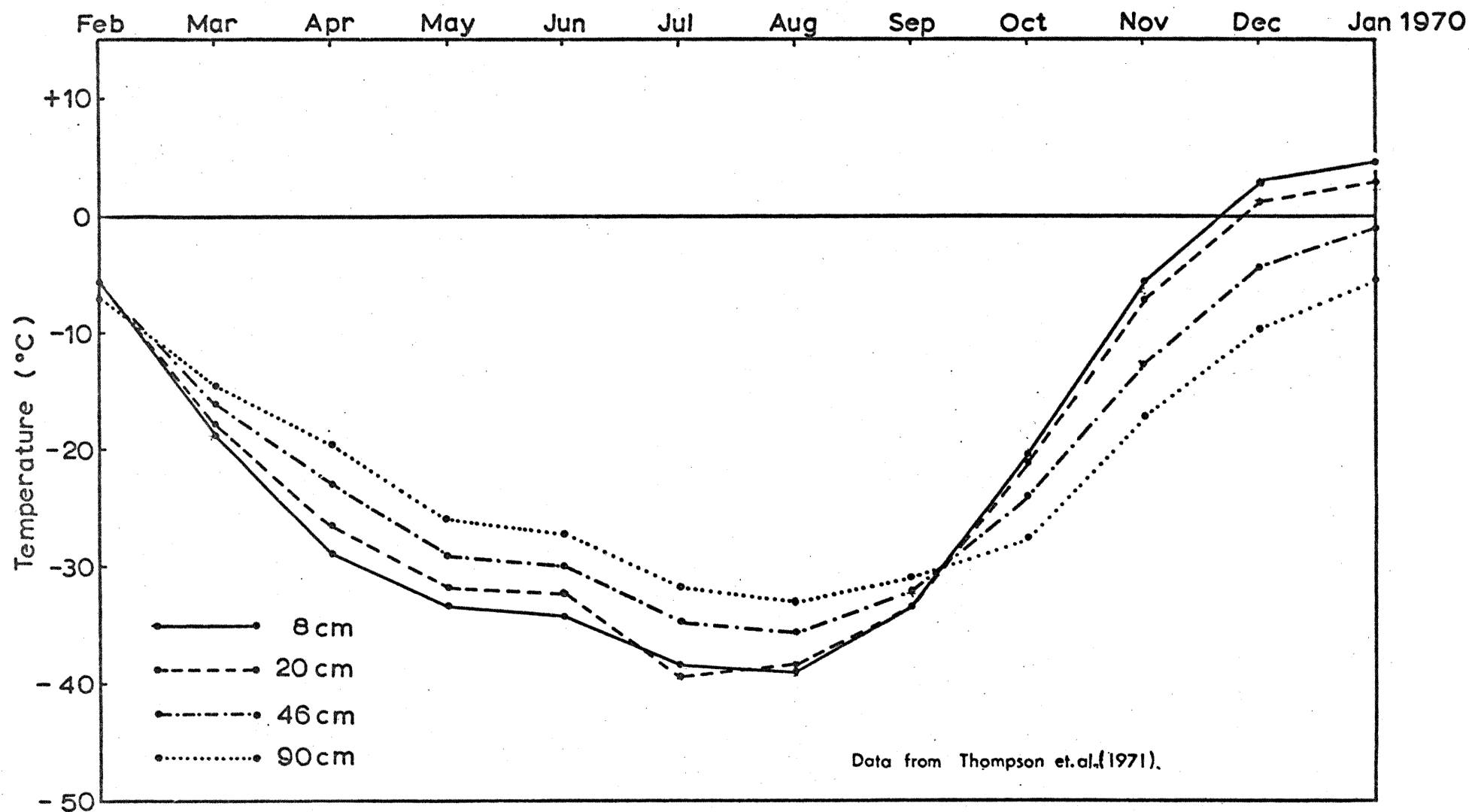


Figure 10 : 1969 mean monthly ground temperatures at Vanda Station, Wright Valley

Movement of water and salts

It is known that water in soil moves from warmer areas to cooler areas (Ferguson et al. 1964). Cary and Mayland (1972) showed that both water and salt moved from warm to cool regions in the soil and that the movement was affected by cation exchange reactions in the soil and by salt solubilities at high concentrations. Relative humidity generally increases inversely with temperature, so that a temperature gradient operating upwards through the soil should be accompanied by a relative humidity gradient in the reverse direction, but by a spontaneous fugacity, or vapour pressure, gradient in the same direction. However, for unfrozen soils the relative humidity changes very little with temperature (Hoekstra, 1966).

Water flow can occur in the vapour phase as well as the liquid phase (Cary and Mayland, 1972). Hoekstra (1966) found that water transported by liquid films on soil particles is more important than vapour transfer at low temperatures, although moisture transfer decreased rapidly with decreasing temperature.

Cary and Taylor (1963) expressed the rate of movement of moisture under the influence of temperature gradients in terms of the chemical potential of soil water. To find the magnitude of the free-energy gradient produced by a temperature gradient, Hoekstra (1966) determined the chemical potential of water as a function of temperature.

Figure 11 shows the solubility curves of salts at low temperatures. As the temperature decreases, the concentrations of soluble salts in the remaining brine solutions will increase. As the soil solutions move toward the cold front, water freezes out and leaves the salt to further concentrate the brine. In such a situation, thermal diffusion and salt sieving do not seem to be important, although vapour and salt diffusion are sometimes significant. The results of Cary and Mayland (1972) suggest that mass flow of dissolved salts in liquid films of water is the principal transfer process.

Ion-exchange reactions could be expected to occur between ions travelling in solution and soil minerals, particularly those between solution K^+ and mineral Ca^{2+} . Comparison of snow and groundwater Ca/K ratios suggest that a large increase in calcium relative to potassium does occur between the snowfall area and the arrival of groundwater at the valley floors, especially in the Wright Valley.

Between February/March and September of each year, the cold front to which salt solutions migrate is the soil surface (See Fig. 12). Salts precipitate in and on the soil surface if evaporation of frozen ice occurs during the winter. This is likely to occur because the Dry Valley winters are usually dry with a predominance of adiabatically warmed westerly winds (Thompson et al. 1971a). The winter migration of soluble salts to the soil surface explains the occurrence of salt deposits on and near the surface, particularly under boulders (Fig. 6).

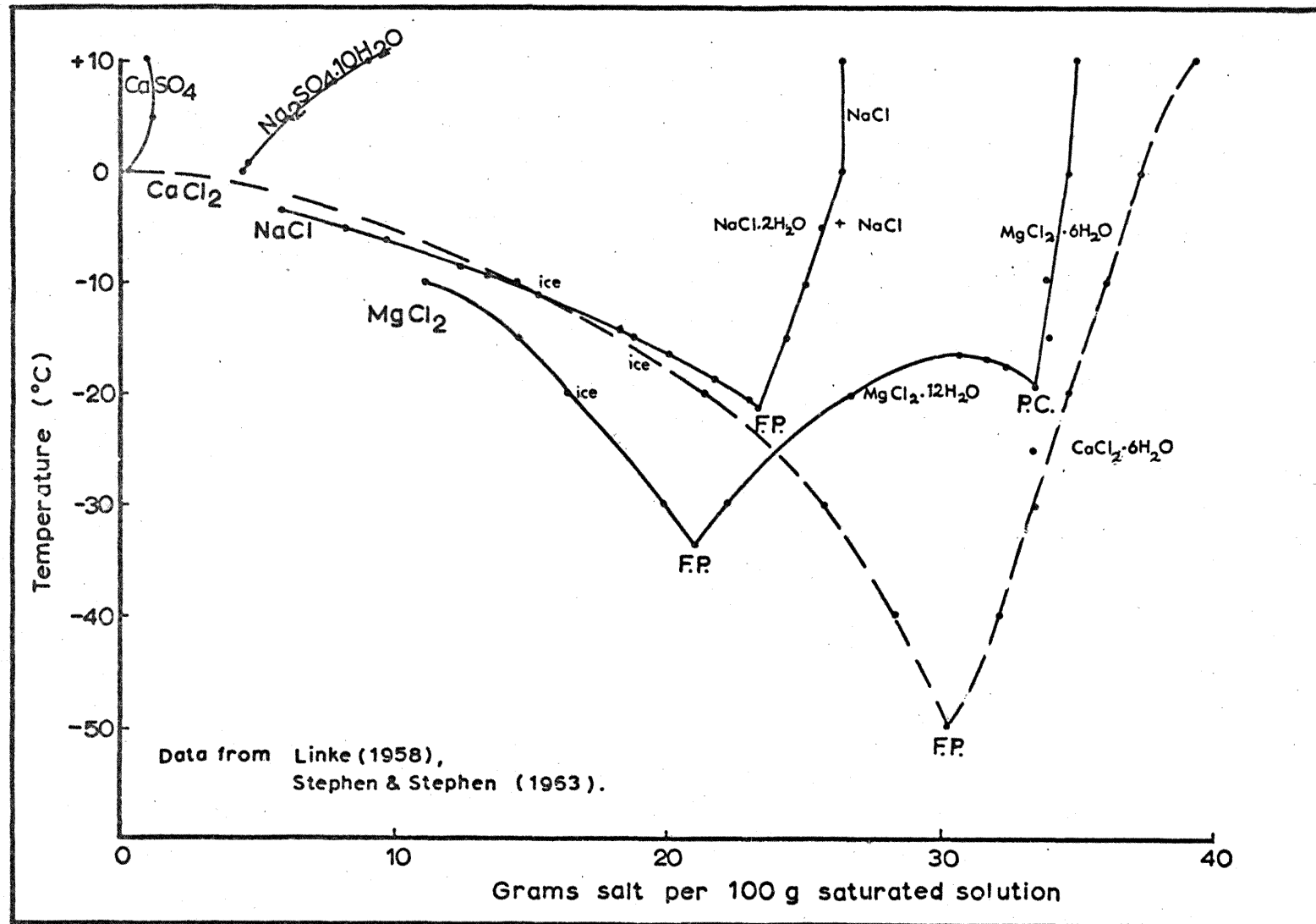


Figure 11 : Solubility curves for salts in saturated solutions at low temperatures.

In frozen soil the free energy of moisture is independent of the total water content, that is the chemical potential of ice is not affected by the presence of soil. In an unfrozen soil the chemical potential (i.e. the partial molar free energy) is a strong function of moisture content and decreases in proportion to moisture decrease. If a temperature gradient is exerted through a soil layer, with the temperature of the cold front above freezing, an equilibrium moisture content distribution will result. No such equilibrium moisture distribution is attained in frozen soil because the chemical potential is not influenced by the total amount of water. The frozen soil therefore tends to act as a "sink". Water flow in unfrozen soil is mainly due to a moisture content gradient and is of the same order of magnitude as that in frozen soil (Hoekstra, 1966).

Salt Movement in Dry Valley soils

The soluble salts carried by mass flow in liquid films may be subject to :

1. electrostatic "salt sieving" by soil mineral surfaces,
2. diffusion along salt concentration gradients,
3. thermal diffusion along temperature gradients (Cary

and Mayland, 1972). These authors found that during water and salt movement through frozen soil towards a cold front, the water and salts moved independently. This behaviour can be explained by the mechanisms described above but the most important is the influence of the change in salt/liquid water concentrations with temperature change, in equilibrium with ice.

Between September and November/December the soil is still frozen, but the cold front is then the permafrost table; the temperature gradient is reversed and salt solutions descend. By December the active layer has thawed and salt solutions still travel to the permafrost table at approximately the same rate as in unsaturated frozen ground (Hoekstra, 1966).

On arrival at the permafrost layer, a very hard and solid ice boundary, most of the saline solutions travel downhill under the influence of gravity until they reach the valley floor. The proportion of brines that soak into the permafrost is very small (Koopmans, 1965).

The very saline brines that arrive at the Dry Valley floors are therefore derived originally from snow- and wind-transported marine salts. They have undergone changes in direction of movement as temperature gradients reverse, and have been modified by solubility/temperature changes and by ion-exchange reactions. These saline flows that find their way into salt playas and sometimes into saline lakes are products of a unique geochemical system that alters its inputs by extremes of temperature and moisture content.

Chapter 4

SALT MAPPING IN THE DRY VALLEYS

4.1 Introduction

Ageing of Antarctic soils is accompanied by increases in degree of oxidation, proportion of fine material, depth to the permafrost layer and salt concentration (Ugolini and Bull, 1965; McCraw, 1967; Ugolini and Anderson, 1973).

Ugolini and Bull (1965) found a good correlation between salt content (sulphates and chlorides) and age for Wright Valley soil specimens.

Chemical weathering processes would not affect soil chloride concentrations, as chlorine rarely occurs in sedimentary and igneous rocks (Goldschmidt, 1954).

A constant supply of salts to the Dry Valley system from the atmosphere, as discussed previously, can be expected. The relative ages of geomorphic features in the Wright and Taylor Valleys might be determined by comparing the chloride content of their soils. Where a given soil chloride value is associated with a feature of an accurately known age, an approximate rate of chloride accumulation can be determined. From this rate, ages can be given for such features, particularly moraines, that have remained undisturbed since their formation. However, the application of accumulation rates to dating moraines should be restricted to the same small area. Brocas and Delwiche (1963) found that the salt content of Antarctic snow was proportional to distance from

the ocean. The accumulation rate of chlorides would vary from place to place and so the moraines dated should be in the same valley, at the very least, as the locality of known age.

Any process which alter the soil salt concentration, as for example, those discussed in Chapter 3, will change the relationship of age with salt content. A locality affected by horizontal water movement could not be considered, but the action of vertical moisture movement only would probably not change the salt content/age relationship. McCraw (1967) found that in older soil layers, soluble salts and calcite were distributed through the soil rather than concentrated near the surface. As soil samples were taken by cover down as far as possible, vertical salt movement would not change the chloride value.

A good test case for determining the validity of salt mapping as an index to ages is a moraine system such as those in and near the South Fork of the Wright Valley, south-west of Lake Vanda. Although they contain several kettle lakes, no appreciable evidence of moving groundwater was observed during the 1973-74 field season.

4.2 Salt mapping of Wright Valley moraines

Figure 12 is a vertical air photograph of moraines south-west of Lake Vanda. The numbers plotted on the photograph are the chloride concentrations in mg/cm^2 of the soil at each point, determined by the method described in Chapter 2. The boundaries drawn on the overlay on the figure approximately follow the natural edges of each moraine lobe.

The diagram shows a progressive series of four distinct moraine sheets, each containing a different range of soil chloride concentrations. The magnitudes of the salt values increase from south to north, i.e. the oldest moraines are closest to Lake Vanda while the youngest lie against the talus slopes of the Asgard Range.

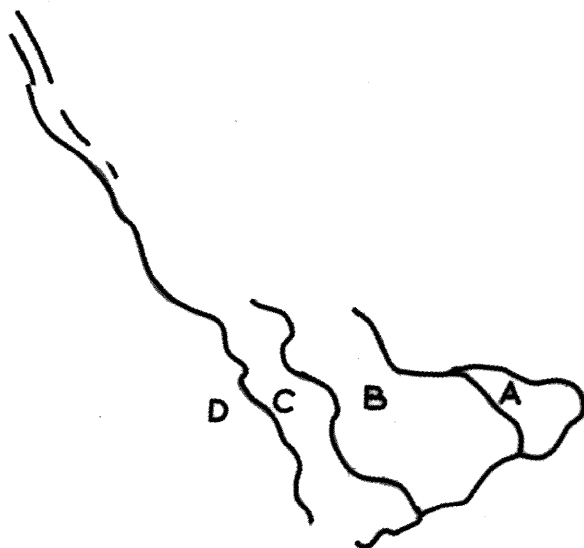
The moraines are labelled as A, B, C and D in the photograph. Below are tabulated the ranges of salt values for each.

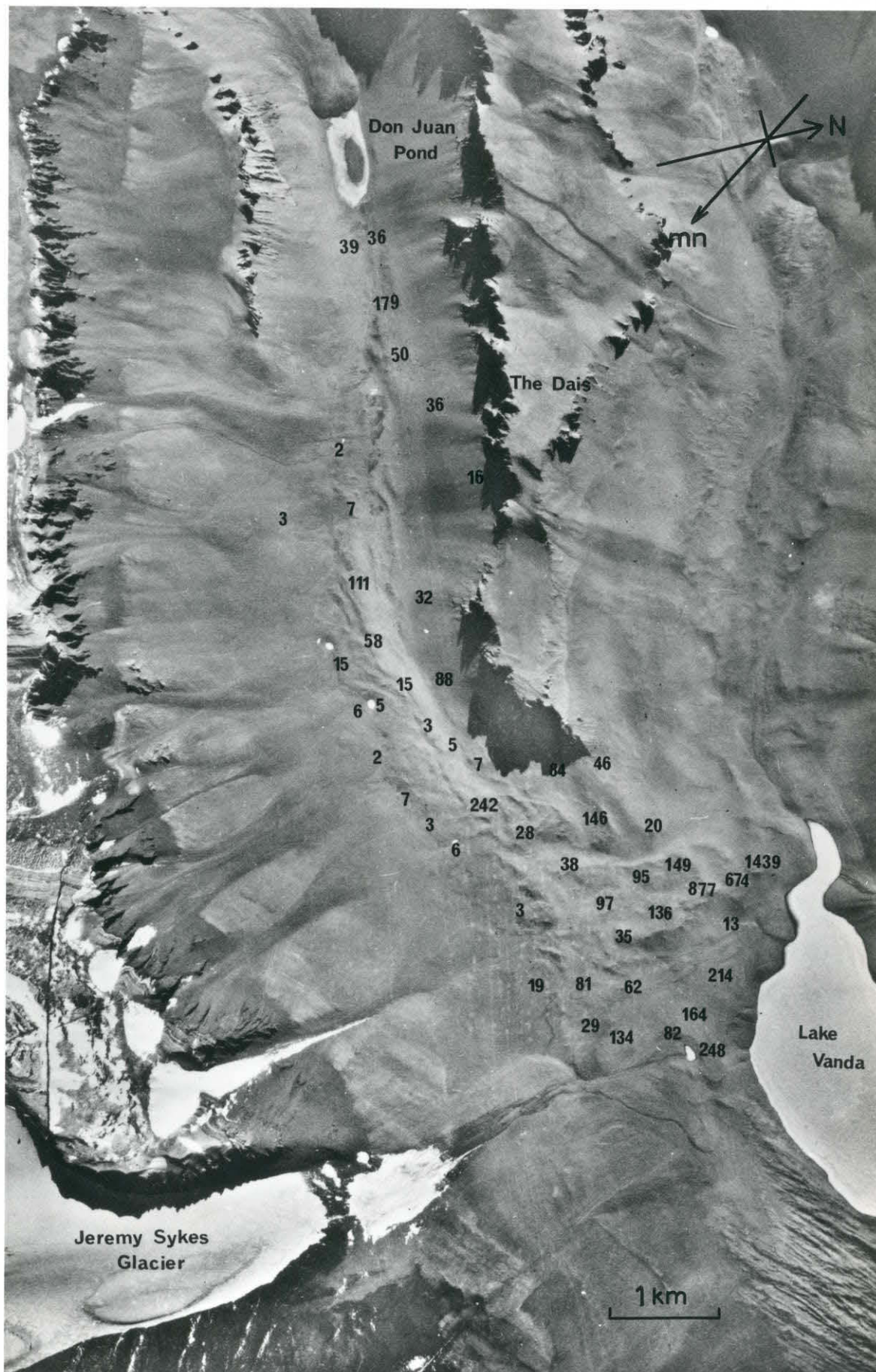
Table 6

<u>Moraine No.</u>	<u>Range ($\text{mg Cl}^-/\text{cm}^2$)</u>
A	674 - 1439
B	95 - 877
C	28 - 35*
D	2 - 19

*Value of $242 \text{ mg}/\text{cm}^2$ not included: sample of bedded polymicton

Figure 12 : Salt map of South Fork moraines,
Wright Valley. Overlay follows edges
of moraine lobes. The figures represent
soil chloride concentrations in mg/cm^2





The upper lake levels of Lake Vanda are approximately 56 m above the present lake surface (Nichols, 1963). The time that has elapsed since the lake dropped from the highest level was found by radio-carbon dating of algal remains left behind. The radio-carbon date of the algae has been given as 3000 yrs B.P. \pm 50 yrs (A.T. Wilson, pers. comm.).

Salts already present in old soils that became inundated by a high-standing lake would be largely washed out although some salts would be left behind from the lake water itself. The lake probably dropped very quickly from the upper level, reaching near dryness in as little as 500 years (C.H. Hendy, pers. comm.). One way to determine the rate of chloride accumulation is to average the chloride concentrations in the soils below the upper lake level and then relate this value to the date given above. Using the values for the north bank of Lake Vanda, as shown on Figure 13, an average chloride concentration of 48 mg/cm² is obtained. Taking the algae radio-carbon date of 3000 yrs B.P., this gives a chloride accumulation rate of 16 mg/cm²/1000 yrs. This calculation assumes that the accumulation rate is constant with time and ignores the time taken for the lake to drop to its present level. The chloride values for soils on the southern bank of Lake Vanda (the Mt. Odin traverse) are much lower than the corresponding northern results and have an average of 3 mg/cm². The accumulation rate is therefore 1 mg/cm²/1000 yrs. The chemical analyses of East Antarctic snow performed by Hanappe et al. (1968) gave an average chloride concentration of 0.3 ppm. Using a fairly realistic Wright Valley

accumulation rate of $10 \text{ gm snow/cm}^2/\text{yr}$, the chloride accumulation rate is calculated as $3 \text{ mg/cm}^2/1000 \text{ yrs}$.

More figures are obtained by using the chloride concentrations found in neves near the Wright Valley. Still using the snow accumulation rate of $10 \text{ gm/cm}^2/\text{year}$:-

1. Upper Taylor Glacier ice : 0.2 ppm Cl^- , accumulation of Cl^-
 $= 2 \text{ mg/cm}^2/1000 \text{ yrs}$
2. Snow on Lake Vanda : 0.9 ppm Cl^- , accumulation of Cl^-
 $= 9 \text{ mg/cm}^2/1000 \text{ yrs}$

Obviously a great deal of variation in the rate of chloride ion accumulation in Dry Valley soils will be encountered, depending mainly on the locality of the sampled snow and the annual snow accumulation rate. Another important problem is that of the mobility of the chloride ion. It is probably not valid to use chloride accumulation rates determined from soils on steep slopes or valley walls. The effect of chloride movement down towards the valley floors would be to increase the chloride accumulation rate. Of the above-mentioned rates calculated above, (i.e. 1, 2, 3, 9 and $16 \text{ mg Cl}^-/\text{cm}^2/1000 \text{ yrs}$), only the low values should be considered. The average of these is $2 \text{ mg/cm}^2/1000 \text{ yrs}$. Using this rate, the table of ranges of moraine salt values can be converted to a table of ranges of moraine ages.

Table 7

<u>Moraine No.</u>	<u>Range (years)</u>
A	327,000 - 719,500
B	48,000 - 439,000
C	14,000 - 17,500
D	1,000 - 9,500

From the shape of the moraine lobes studies, it seems most likely that they were produced by alpine placiers from the Asgard Range, not by large scale through-valley glaciations.

The variations in absolute age for each moraine lobe, A to D, are large. The assumptions made in order to calculate them, such as the constant rate of snow accumulation, would become less valid with age increase. The relative ages of the different moraine sections are probably much more reliable than the absolute ages.

It is interesting to compare the tentative ages above with figures obtained by other workers. By determining the depth of ice core in a moraine ridge occurring within moraine B of Figure 12, Bell (1966) calculated its age of deposition to be at least 75,000 years. Wilson (1969) had calculated that Lake Vanda, as well as other saline lakes, has a "chloride age" of more than 60,000 years. Both of these ages fall within the admittedly wide age range calculated for moraine B.

4.3 Accumulation of Salts in the Lake Vanda Basin

To calculate the approximate time that has elapsed since either a large scale glacial advance moved through the Wright Valley, or the valley was inundated with water (fresh or marine), the accumulation rate of salts from the atmosphere can be related to the average concentration of salt in the soils and to the total amount of salt present in Lake Vanda. Using chloride ion in the calculation, the average input to the soil is $2 \text{ mg/cm}^2/1000 \text{ yrs}$, as determined in the previous section. Because of movement of chloride ion to and from different valley areas, the average soil concentration is probably the most representative value of soil chloride. Taken over 100 samples, the average value is $166 \text{ mg Cl}^-/\text{cm}^2$. The catchment area of the Lake Vanda basin is approximately 800 km^2 , so

$$\text{total chloride in soil} = 1.328 \times 10^9 \text{ kg}$$

The estimated amount of chloride present in Lake Vanda is 1 million tonnes, i.e. $1 \times 10^9 \text{ kg}$

$$\begin{aligned} \text{Therefore total chloride in basin} &= 2.328 \times 10^9 \text{ kg} \\ &= 2.328 \times 10^{15} \text{ mg} \end{aligned}$$

$$\begin{aligned} \text{Total chloride input from snow} &= (2 \times 800 \times 10^{10}) \text{ mg}/1000 \text{ yrs} \\ &= 1.6 \times 10^{13} \text{ mg}/1000 \text{ yrs} \end{aligned}$$

$$\begin{aligned} \text{Therefore time of accumulation} &= \frac{\text{total chloride}}{\text{total input}} \\ &= 1.46 \times 10^5 \text{ years} \end{aligned}$$

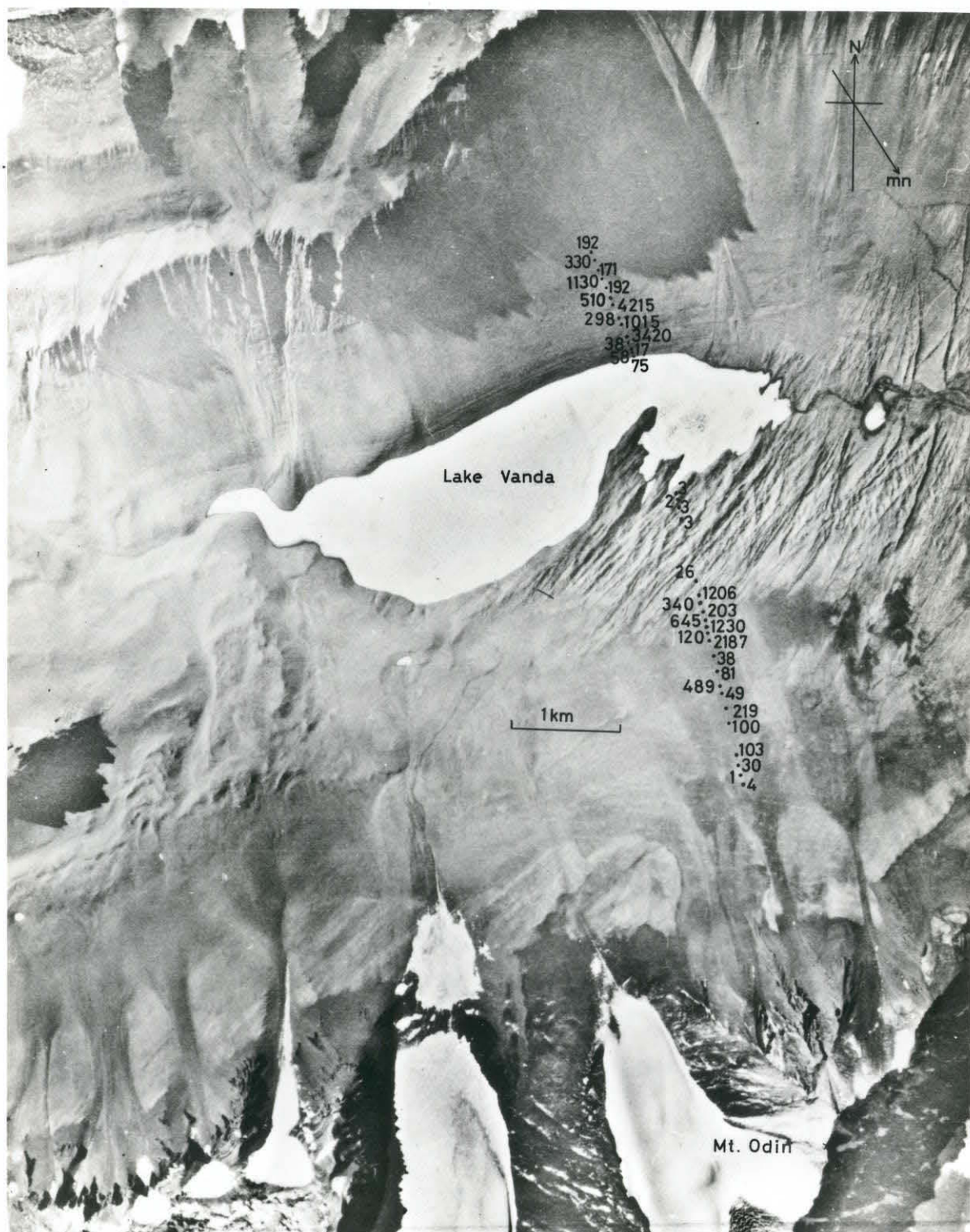
This calculation does not take into account the chloride contributed from dry salt blown in by winds from the sea.

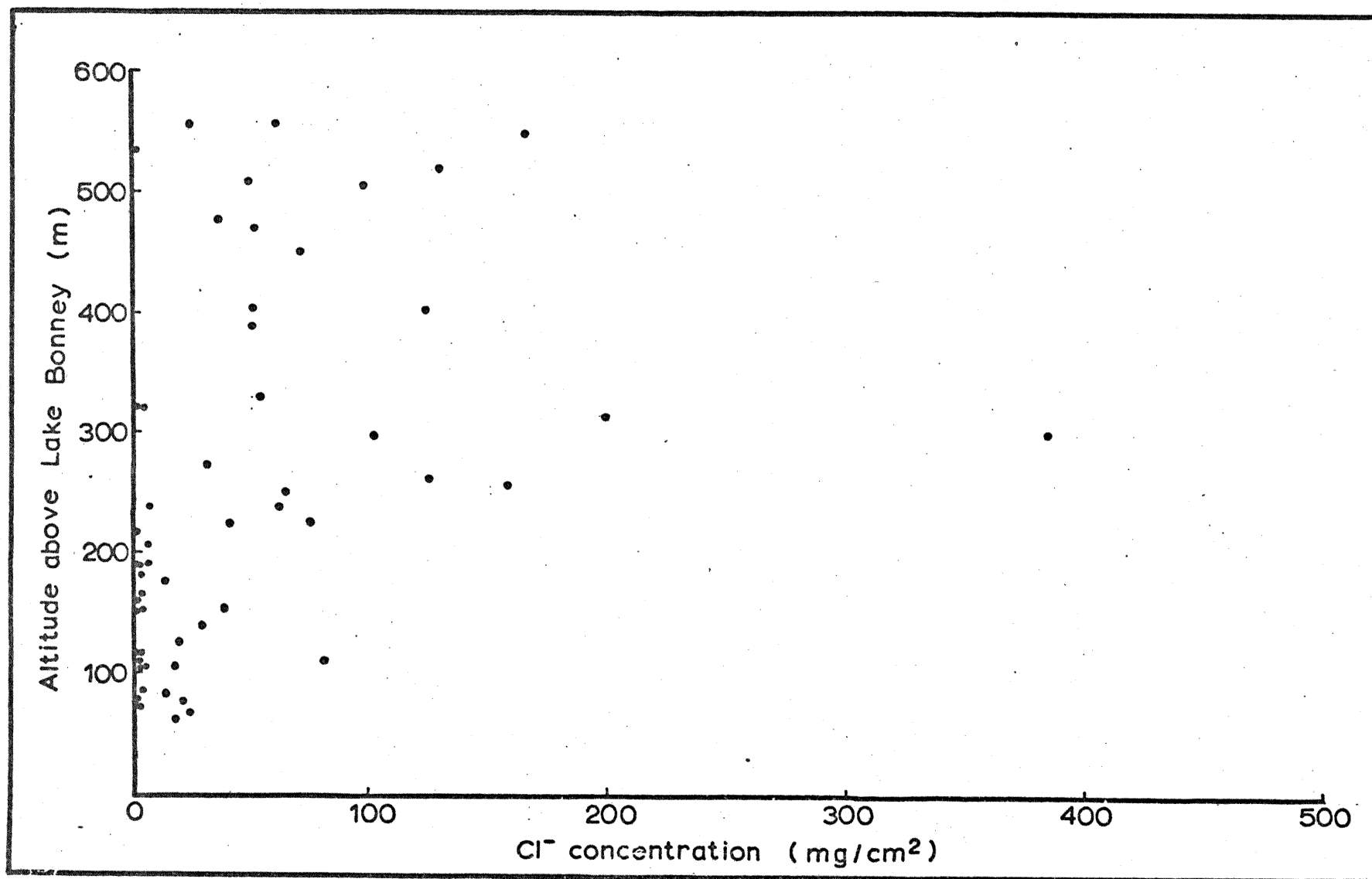
4.4 Salt concentrations in the soils of Dry Valley walls

Patterns in the distribution of soil salt concentrations are found in Dry Valley walls with respect to altitude and are associated with strandlines, (i.e. former lake levels). Figure 13 shows series of chloride ion concentrations (expressed as mg/cm^2) plotted on a vertical air photo of the Lake Vanda region. The sudden increase in chloride concentration above the uppermost strandline on the north wall is a characteristic of relict lake levels. The difference in salt values of soils above and below the high strandline is proportional to the soil age difference and resulted from washing out of the lower soil when the lake level dropped. When the Dry Valley saline lakes remain at one level for any length of time, lake moat water soaks into the bank soil and moved up by capillary action to the soil surface, so that a fine layer of evaporated salts lies on the surface, further adding to the total salt associated with an old lake beach.

Figure 14 is a plot of altitude above Lake Bonney, Taylor Valley, against soil chloride concentration. It shows that a large increase in chloride concentration occurs on the north bank at approximately 210 m above the lake. The maximum chloride value at and above this level is approximately $380 \text{ mg}/\text{cm}^2$ but the average is nearer $100 \text{ mg}/\text{cm}^2$. No suitable features for dating are associated with the 210 metre level. The only way of establishing an approximate age for this level would be to compare the salt content with the Wright Valley example, the highest lake level on the north wall. The

Figure 13 : Soil chloride concentrations (mg/cm^2)
in Wright Valley





chloride accumulation rate was calculated to be 16 mg/cm²/1000 yrs, and could tentatively be used to find an age for the Taylor Valley strandline of 6000 yrs B.P. Because of the movement of salts through the soil layer and because of the uncertainty introduced by using a Wright Valley accumulation rate to find a Taylor Valley feature's age, this date of 6000 yrs B.P. must be regarded as a rough minimum age.

A higher linear feature can be easily seen on the north wall of the upper Taylor Valley at an altitude of 400 metres above the surface of Lake Bonney. There are no conclusive trends in the altitude v. chloride graph for this line, which had a 3° slope towards the east over 6 km. It is probably a moraine ridge left behind by a through-valley glacier.

Chapter 5

CONCLUSION

The work described in this thesis has demonstrated the use of chemical techniques in the study of geological problems in the McMurdo Dry Valleys of Antarctica.

Samples of salt deposits were collected and found to be halite, thenardite and mirabilite, or various mixtures of these salts. Snow, ice and groundwater samples were taken and analysed for sodium, calcium, potassium and magnesium as well as sulphate and chloride. The results show that these samples are enriched in sulphate with respect to sea-water, indicating the importance of the sodium sulphate accumulations on McMurdo Sound sea-ice (Wellman and Wilson, 1963) as sources of salt blown into the Dry Valleys. The large amounts of chloride present in the region rules out all sources except the ocean as the place of origin of Dry Valley salts. It is concluded that salts are transported inland from the sea by winds as particles and spray and in snow.

Appreciable quantities of saline groundwater were observed flowing in the Wright and Taylor Valleys. While very concentrated, having chloride contents of up to 61,400 p.p.m., the flows share the same ionic relationships as the water bodies into which they descend. These flows are therefore probably important means of transport of salts

to Dry Valley lakes.

The occurrence of sodium sulphate at moderate altitudes is explained by its non-hygroscopic character. Near the snow-line, high relative humidities prevail and salts such as sodium chloride and calcium chloride dissolve, soak into the soil and travel downslope.

The movement of salts and water downslope through the soil layer is explained by the application of a soil moisture movement theory to the particular temperature conditions of the Dry Valleys. A set of gradients of temperature, vapour pressure and relative humidity operate in different directions at different times of the year. Salts and moisture move through thin liquid films adsorbed onto soil particles, generally from warm towards cold fronts. Only during the summer months is the permafrost layer the cold front. For the rest of the year the soil surface is the cold front, but moisture movement slows down because of the lower temperatures.

In regions of perennially low relative humidity and low relief, it might be expected that salt movement through the soil is negligible. Thus it could be possible to "date" surfaces by measuring the accumulation of salts. A "salt map" of an alpine glacier moraine near Lake Vanda, Wright Valley, was prepared by plotting results of chloride analyses of soil core samples onto a vertical air photograph. Four separate moraine sheets are distinguished, their accumulation

ages ranging from 5×10^3 to 5×10^5 years B.P. These suggest that the Wright Valley has not been occupied by either a through-valley glacier or a body of water for approximately $10^5 - 10^6$ years.

Salt accumulations in the soils of Taylor Valley show an abrupt change coinciding with a linear feature visible on the north wall at an altitude of 210m above Lake Bonney, suggesting that this is a former lake level with a minimum accumulation age of 6×10^3 years B.P. The higher feature occurring at 400m does not show any change in salt content, and is probably a lateral moraine left by a previous advance of the Taylor Glacier.

The use of chemical methods in studying Dry Valley problems is of great assistance, especially in those problems involving the saline lakes. There are difficulties introduced by the extreme mobility of certain ions, (e.g. chloride ion) in the Dry Valley soils, but even when the limitations of chemical techniques are taken into account, extremely useful results are obtained. The limitations encountered often arise because of a lack of reliable data (e.g. accurate radio-carbon dates) normally provided by conventional methods.

APPENDIX : CHLORIDE ION CONCENTRATIONS OF
DRY VALLEY SOIL SAMPLES

1. Samples collected from the north wall of Taylor Valley in an area bounded by the Rhone Glacier to the east and the Taylor Glacier to the south. The highest altitude reached was approximately 600m above Lake Bonney

<u>Sample No.</u>	<u>Cl⁻, mg/cm²</u>
A1	76
A2	25
A3	17
A4	4
A5	5
A6	39
A7	4
A8	-
A9	3
A11	1
A12	4
A13	3
A14	4
A15	101
A16	51
A17	60
A18A	24
A18B	164
A19	96
A20	128
A21A	3
A21B	60
A22	47
A23	52
A24	36
A25	51
A26	123
A27	383
A28	32
A29	124
A30	61
A31	4
A32	1
A33	30
A34	2
A35	22
B1	112
B2	106
B3	43
B4	81
B5	4
B6	1

B7	12
B8	1
B9	2
B10	157
B11	3
B12	7
B13	53
B14	198
B15	75
B16	15
B17	12
BM1	20
BM2	727
BM3	10
RG2	-
RG3	13
RG4	42
RG5	64
RG6	9
RG7	1
RG8	4
RG9	1

2. Samples collected from the north wall of Taylor Valley up to an altitude of 450m above the west Lobe of Lake Bonney and east of the Rhone Glacier

<u>Sample No.</u>	<u>Cl⁻, mg/cm²</u>
LB1	-
LB2	145
LB3	1
LB4	44
LB5	54
LB6	224
LB7	274
LB8	86
LB9	80
LB10	13
LB11	4
LB12	33
LB13	69
LB14	32
LB15	108
LB17	-
LB18	31
LB19	11
LB20	147
LB21	53
LB22	-
LB23	29
LB24	-
LB25	-

LB26	25
LB27	23
LB28	29
LB29	-
LB30	16
LB31	23
LB33	21
LB34	23
LB35	10

3. Samples collected for salt-mapping from moraines near the mouth of the South Fork of Wright Valley, south-west of Lake Vanda

<u>Sample No.</u>	<u>Cl⁻, mg/cm²</u>
D1	19
D2	3
D3	6
D5	3
D6	7
D7	2
D8	6
D9	15
D10	58
D11	15
D12	3
D13	5
D14	242
D15	11
D16	38
D17	97
D18	29
D22	4
D23	7
D24	5
D25	22
D26	31
D27	179
D28	36
D31	1590
D32	1445
D33	270
D34	39
D42	50
D43	36
D45	16
M1	35
M2	146
M3	28
M4	7
M5	88
M6	32
M7	46
M8	20
M9	95

M10	149
M11	877
M12	136
M13	81
M14	134
M15	62
M16	164
M17	214
M18	13
M19	674
M20	1439
M21	84
M22	61
M23	3
M24	2
M25	7

4. Samples taken from soils between the northern slopes of
Mt. Odin, Wright Valley and Lake Vanda

<u>Sample No.</u>	<u>Cl⁻, mg/cm²</u>
V1	1997
V2	849
V3	304
V4	79
V5	28
V6	8
V7	11
V7A	7
V8	8
V8A	5
V8B	12
OT1	21
OT2	102
OT3	40
OT5	42
OT6	197
OT7	90
OT8	287
OT9	235
OT10	903
OT11	325
OT12	233
OT13	260
OT14	180
OT15	115

5. Samples collected around Lake Canopus, immediately south
of Lake Vanda, Wright Valley

<u>Sample No.</u>	<u>Cl⁻, mg/cm²</u>
CL1	5
CL2	15
CL3	248
CL4	45
CL6	30
CL7	401

CL7A	103
CL9	70
CL10	301

CLL1	68
CLL2	29
CLL3	30
CLL4	22
CLL5	25

6. Samples taken from a small depression containing bedded polymicton approximately 500m west of Lake Vanda

<u>Sample No.</u>	<u>Cl⁻, mg/cm²</u>
PL1	9
PL2	8
PL3	102
PL4	111

7. Spot samples from around Lake Vanda, Wright Valley

<u>Sample No.</u>	<u>Cl⁻, mg/cm²</u>
VK	19
SS2	20
SS3	3

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