GLACIOCHEMICAL STUDIES AND ESTIMATED NET MASS BALANCES
FOR RENNICK GLACIER AREA, ANTARCTICA

by

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ABSTRACT
Two snow and ice cores from the Rennick Glacier area, Antarctica (study area center point lat 71°15'S, long 162°30'E) were analyzed for the chemical species: chloride, sodium, reactive silicate, sulfate and nitrate. Core E10 (6.35 m) was taken from Evans Névé, a large accumulation basin at the head of Rennick Glacier. Core M1 (4.35 m) was extracted from the accumulation zone on the central plateau of the Morozumi Range, a small mountain massif bordering Rennick Glacier. Cores E10 and M1 span the time periods from 1929 to 1981 and from 1971 to 1981, respectively, as dated using seasonal variations in chloride (E10) and sulfate (M1) concentrations. An estimated net balance of 50 kg m⁻² a⁻¹ was derived for site E10 and of 182 kg m⁻² a⁻¹ for site M1. The difference in net mass balance may be explained by elevational differences (M1 1400 m a.s.l., E10 2305 m a.s.l.). Recent (1973 to 1980) increases in sodium, silicate and sulfate at site E10 may be linked to decreases in Antarctic pack-ice extent (Kukla and Gavin 1981) for the same period.

INTRODUCTION AND BACKGROUND
The Antarctic ice sheet is considered to be one of the important driving forces behind global and atmospheric circulation (Weyant 1967). Consequently, any changes in the size of the ice masses comprising this ice sheet may have a serious influence on the Earth’s weather. North Victoria Land comprises the northernmost East Antarctic sector of the Transantarctic Mountains (Fig.1). It is bordered by the polar plateau on the south and west, the Ross Sea and Ross Ice Shelf to the east and by the Pacific Ocean to the north. Rennick Glacier, discovered during the 1959-60 traverse of north Victoria Land (Stuart and Heine 1961), is one of the more prominent physiographic features. It flows northward for approximately 400 km, attaining a maximum width of approximately 60 km and flows past several localized accumulation areas including the Morozumi Range.

The only meteorological data collected from a station located in this region are from Hallett station (Fig.1). For the period from 1957 to 1972 the mean annual temperature was -15.3°C and the mean summer temperature was -1.6°C (Duphorn 1981). Mean annual surface temperature for the upper Rennick Glacier area is estimated to be approximately -20.5°C, based on mean monthly surface temperatures (US Navy 1981). Close to Litell Rocks (680 m a.s.l., Fig.1) a constant temperature of -16.5°C at 10 to 18 m depth was recorded and is interpreted as the mean annual temperature for the site.

Snow, snow pellets, snow grains and ice crystals are the predominant forms of precipitation in north Victoria Land and rain was reported along the coast of Robertson...
Bay twice in January during the 1979-80 German Northern Victoria Land Expedition (GANOVEX) (Duphorn 1981). Annual snowfall at Hallett averages about 183 kg m\(^{-2}\) a\(^{-1}\) with the maximum monthly snowfall in March and the minimum in July. (Duphorn 1981) Glaciological methods have been used successfully for dating purposes in other sections of Antarctica (Herron 1982[a]), notably the Ross Ice Shelf, East Antarctica (Delmas and Bourtou 1980) and the Antarctic Peninsula (Aristarain and others 1982). In this study, they were employed in a study to estimate the net mass balance and sources of moisture feeding the Rennick Glacier region for purposes of glaciological reconstruction, and as a test of whether or not this technique is feasible in such an area. The only other recorded net mass balance measurement for this region is 63 kg m\(^{-2}\) a\(^{-1}\) (Stuart and Heine 1961) at Scott Base 559 (Fig. 1).

**METHODOLOGY**

In order to assess the net balance and determine sources for air masses entering the study region two coring sites were chosen. Site E10, 2305 m a.s.l., is in Evans Nève and site M1, 1400 m a.s.l., is in the Morozumi Range. The E10 site provides information concerning the accumulation basin closer to the coast than E10, and the Morozumi Range provides both a coastal comparison and a site from which to determine net mass balance and moisture sources for alpine glaciers flanking the Morozumi Range.

Methodology employed in this study is made up of five phases: (1) transport of material, (2) sampling, (3) analysis, and (4) data reduction. All acrylic plastic cutters and scrapers used in this study, and the polystyrene jars used for sample storage, were triple-washed in Milli-Q\textsuperscript{TM} water (17.9 M\(\Omega\) cm).

Cores measuring 6.35 and 4.65 m at sites E10 and M1, respectively, were recovered using a SPIRE teflon-coated auger. Sites were approached from downwind. All personnel involved with recovery wore plastic gloves and particle masks, and workers involved with packaging of the core wore plastic suits as well. Once removed from the auger barrel, cores were placed on a Saran Wrap\textsuperscript{TM}-covered work area, measured, described, scraped with plastic scrapers, and triple-bagged in particle-free bags. The cores were shipped frozen to the University of New Hampshire and stored at \(-15^\circ\)C. Sectioning of the cores was performed in a cold room \((-4^\circ\)C). A sampling interval of 0.04 m was selected wherever possible in order to provide between-seasonal resolution of ion concentrations based on an estimated snow-accumulation rate for the study area of 163 kg m\(^{-2}\) a\(^{-1}\) (Stuart and Heine 1961); however, breakage of the core during extraction did not always permit this interval. After sectioning with plastic cutters, densities were determined and the outer surfaces of the sections were removed by scraping. The sections were then put into polystyrene jars and stored in a freezer. Approximately 10 ml water equivalent was sectioned off each frozen sample and placed in a separate jar to be analyzed later by ion chromatography. The remaining samples were thawed and acidified with Ultrex\textsuperscript{TM} ultrapure nitric acid to approximately 1% by volume.

Sodium was analyzed by flame atomic absorption spectrometry using a Perkin-Elmer model 2280 instrument. Chloride, sulfate and nitrate (ACS grade) was also analyzed at the final concentration of 2% in order to control ionization. Reactive silicate was determined colorimetrically using a Technicon AutoAnalyzer II\textsuperscript{TM} (Gilbert and Loder 1977). Sample containers were kept closed to minimize room contamination. Repeated blank studies determined room contributions to be less than 0.01 \(\mu\)mol 1\(^{-1}\) for sodium and silicate.

Chloride, sulfate and nitrate were determined simultaneously on a Dionex 10 ion chromatograph using a fast-run anion separation column, an eluent consisting of 0.00001 mol H\textsubscript{2}SO\textsubscript{4} and 0.002 mol Na\textsubscript{2}CO\textsubscript{3} and a Dionex full-scale chart recorder setting. Three aliquots for each sample were injected with a gas-tight syringe (Hamilton) into a 1 ml sample loop. The ion chromatography was performed in a class 100 clean laboratory at the Mellon Institute, Pittsburgh, Pennsylvania.

Standard deviations in \(\mu\)mol 1\(^{-1}\) for the analyses were: chloride 0.63, sodium 0.09, sulfate 0.03, sulfate 0.04, and nitrate 0.01. Container blanks were normal for Milli-Q\textsuperscript{TM} water (17.9 M\(\Omega\) cm) at the time of core-sectioning. These jars were placed in the same freezer as the samples and they underwent identical handling and analytical procedures. Mean blank contamination was: chloride 1.08, sodium 0.13, sulfate 0.04, sulfate 0.06, and nitrate 0.01. The filling of chloride blank is attributed to contamination by organic solvents during storage in Pittsburgh. Aristarain and others (1982) encountered similarly high chloride blanks and assumed there was organic solvent contamination of plastic vials.

Statistical analyses included spectral and cross-spectral analysis of the time series produced from each core, factor analysis and production of a correlation coefficient matrix. All statistical manipulations and tests were performed on a DEC-10 computer.

Using time-series analysis, a mathematical transformation is made of the chemical data sets to expose characteristic variations that might normally be masked by seasonal or other oscillatory effects. This technique has been used before on other glaciochemical data (Mayewski and others 1984). A regularly spaced data set at 0.04 m core spacing (minimum sampling frequency) was constructed from the E10 and M1 analytical results and examined using a time-series program in the International Mathematical and Statistical Libraries (Release 9.1, IMSL Inc 1982) statistical package. The 0.04 m interval sampling dataset is a Nyquist sampling theorem (Kelley 1976) for what was assumed to be a good estimate of the net mass balance for the region, 163 kg m\(^{-2}\) a\(^{-1}\) (Stuart and Heine 1961).

To determine the periodicity for each chemical species downcore, spectral density (power) was computed using spectral analysis of the time series. Power is the measure of how much of the variance of a variable exists at a particular frequency (Mayewski and others 1984). Peaks in the power spectrum were used in the manual selection of maximum concentration peaks to be used as seasonal indicators.

Cross-spectral analysis was used to identify similar periodicities of different chemical species. The squared coherence in cross-spectral analysis is the proportional amount of spectral density in signal two (e.g. sodium concentrations) that could be predicted by signal one (e.g. chloride concentrations) using a linear regression that is frequency-dependent (Koopmans 1974). Thus, coherence is a measure of the extent to which one time series is similar in trend to another and is analogous to a correlation coefficient. The phase at a particular frequency is an amount that one component leads another as a Fourier representation of the time series (Koopmans 1974). Confidence intervals for power peaks and coherence were selected using tables in Koopmans (1974) and Arkin (1962).

Principal component analysis using the Statistical Package for the Social Sciences (Release 7.5, SPSS Inc 1981) was then used to evaluate how the variance in chemical concentrations for each core. Principal component analysis has been used on other glaciochemical data from Antarctica (Bourtou and Martin 1980) and is a form of factor analysis which characterizes the variance between measured variables by generating mathematical components or factors common to all of the variables (Lewis and others 1983). The communality is the measure of the total variance explained by the factors. These factors are then intuitively related to physical processes or components (Van Epsen and Adams 1983).

Correlation coefficients which measure the linear relationships between two variables have also been used previously on Antarctic glaciochemical data (Bourtou and Martin 1980) and were obtained using the SPSS factor analysis program.

For estimation of annual net mass balances, the cores are dated using seasonal concentration peaks. Because of the much lower precision in the density determination (8...
to 16%) as compared to the chemical analyses, individual sections of the core are not density-normalized, thus avoiding the introduction of additional error. Individual density values within each annual section of core are averaged and then multiplied by that core-section length to arrive at an adjusted water-equivalent net mass balance. As the time-series analysis was used only as an aid in the manual selection of concentration peaks, and in view of the low precision and relative similarity in density downcore (Figs. 2(a) and (b)), the data set for the statistical analyses was also not density-normalized for individual sections of the cores.

**RESULTS AND DISCUSSION**

Analytical results (concentration in μmol l⁻¹) are presented in Table I and possible source types of the chemical species examined in this study are discussed. Results from the statistical analyses are interpreted and the annual net mass balances estimated. Possible explanations for the observed chemical trends are then offered. To offset the large influence of the higher concentration spikes observed in some samples (Figs. 2(a) and (b)) the median concentration for each chemical species was determined (Table I).

The chemical species analyzed come from a variety of sources including marine, crustal, volcanic, anthropogenic, and cosmogenic. Source discrimination is based largely on previous Antarctic glaciochemical work. For coastal Antarctic areas such as north Victoria Land, the main source of chloride is probably from marine salt particles but some gas-derived chloride in excess of the marine ratio may be possible (Delmas and others 1982). Contributions from volcanic activity (Herron 1982[b]) or weathering of chloride salts (Dow and Neall 1974) is also possible.

Sodium, like chloride, has a marine source and minor contributions can be derived from weathered crustal materials, as observed on the Antarctic Peninsula (Aristarain and others 1982). In north Victoria Land, proximity of the core sites to the coast suggests a marine

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**TABLE I. MEDIAN CONCENTRATION OF CHEMICAL SPECIES (μmol l⁻¹) IN CORES FROM SITES E10 AND MI**

<table>
<thead>
<tr>
<th></th>
<th>E10</th>
<th>MI</th>
<th>Upper E10*</th>
<th>Lower E10**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride</td>
<td>4.15 (n=138)</td>
<td>4.60 (n=124)</td>
<td>3.78 (n=19)</td>
<td>4.20 (n=119)</td>
</tr>
<tr>
<td>Sodium</td>
<td>3.55 (n=136)</td>
<td>3.81 (n=118)</td>
<td>6.44 (n=19)</td>
<td>3.39 (n=117)</td>
</tr>
<tr>
<td>Silicate</td>
<td>0.28 (n=141)</td>
<td>0.49 (n=125)</td>
<td>1.12 (n=19)</td>
<td>0.26 (n=122)</td>
</tr>
<tr>
<td>Sulfate</td>
<td>0.71 (n=140)</td>
<td>0.76 (n=126)</td>
<td>1.32 (n=19)</td>
<td>0.67 (n=121)</td>
</tr>
<tr>
<td>Nitrate</td>
<td>0.60 (n=136)</td>
<td>0.82 (n=111)</td>
<td>0.64 (n=19)</td>
<td>0.59 (n=117)</td>
</tr>
</tbody>
</table>

* Top meter of core E10.
** Remaining length of core E10.
source for sodium, but rock exposure in the surrounding region (Fig.1), particularly at the southern end of the Morozumi Range, could provide a crustal source. Silicate is derived primarily from crustal weathering products (Mayewski and Lyons 1982) such as the extremely weathered Beacon Supergroup which comprises more than 50% of the Morozumi Range and is found in the ice-free areas around the core sites.

Sources for sulfate in Antarctica include volcanic activity, sea-salt injection and anthropogenic input (Herron 1982[b]), oxidation of marine gaseous compounds (Delmas and others 1982), and input of weathered salts (Dow and Neall 1974). Based on work at South Pole station by Delmas and others (1982), anthropogenic input of sulfate to Antarctica is considered to be minimal. Delmas and others (1982) postulate a predominantly long-range, atmospherically transported aerosol source for sulfate. Mt Erebus on Ross Island continually emits a sulfate-rich plume (Radke 1982) and storm tracks (Dort 1968) could transport aerosol here to north Victoria Land. Thus, the main source of sulfate to the coring sites is probably long-range transport supplemented by volcanic emission.

Marine, volcanic, anthropogenic and cosmogenic sources have all been suggested as potential sources for nitrate in Antarctica (Zeller and Parker 1981). These multiple sources of nitrate make it difficult to identify any principal origin, although Delmas and others (1982) consider most Antarctic nitrate to be from a distant source and to have undergone long-range, atmospheric transport.

Because multiple sources exist for several of the chemical species, correlation and factor analysis results (Table II) are used to suggest common input mechanisms for these species. In the E10 core significant correlation exists between the following species: chloride-sodium, sodium-silicate, sodium-sulfate, silicate-sulfate, and sulfate-nitrate. Factor analysis of E10 yielded two factors with factor 1 being interpreted as a crustal source because of the high factor loadings of sodium and silicate and their significant correlation with each other. High loading of chloride and sodium on factor 2 suggests a marine input mechanism. The even split of sulfate between factors 1 and 2 may be explained by some sulfate arriving with marine salts and the remainder mixing in with crustal weathering products transported to the core site. The low nitrate variance explained by the factor analysis for E10 verifies the likelihood of either multiple sources or a unique origin of nitrate unrelated to the other chemical species.

In the MI core significant correlation (99%) exists only between sodium-silicate and sulfate-nitrate. The presence of sodium and chloride in factor 1 and correlation of sodium with silicate suggests that marine input could be related to crustal input. This might be caused by intermixing of marine salts with crustal weathering products. Since the input of crustal weathering products to the core site is believed to be continuous, the association between these species might be used to suggest that marine inputs are supplied to the site throughout most of the year. Loading of most of the sulfate and nitrate and half of the chloride on factor 2 implies a common source for these species which may be in the form of long-travelled gas-derived aerosols as observed at South Pole station (Delmas and others 1982).

Table II. Results of factor analysis for cores from sites E10 and MI

| TABLE II. RESULTS OF FACTOR ANALYSIS FOR CORES FROM SITES E10 AND MI |
|--------------------------|----------------|----------------|
| Factor loading           | Factor 1 | Factor 2 | Communalty |
| Chloride                 | -0.25    | 0.65    | 0.484      |
| Sodium                   | -0.30    | 0.67    | 0.532      |
| Silicate                 | 0.84     | 0.17    | 0.742      |
| Sulfate                  | 0.53     | 0.50    | 0.537      |
| Nitrate                  | 0.10     | 0.26    | 0.076      |
| % variance               | 71.3     | 28.7    |            |

At site MI only sulfate and nitrate exhibit spectral power and only at the 0.4 m interval. A simultaneous input is suggested by the cross-spectral analysis and simultaneous input of sulfate and nitrate concentrations has been statistically demonstrated in samples from Vostok (Kyle and others 1982). Herron (1982[a]) found seasonal variations for sulfate and nitrate on Ross Ice Shelf and considered that both species had summer maxima. Thus, the sulfate and nitrate are thought to be indicative of summer input to north Victoria Land. Sulfate was selected over nitrate as a seasonal indicator for the MI core because the data set was more complete (Fig.2(b)), providing an MI record that extends from 1971 to 1980 (Fig.3) with an estimated mean annual net mass balance of 182 ± 2 kg m⁻² a⁻¹. Error is assumed to be only 0.04 m sampling interval, and since two seasonal maxima are involved for dating purposes, error for each annual determination is calculated as ±0.04 m or 30%.

At site MI only sulfate and nitrate exhibit seasonal maxima based on the estimated mean annual net mass balance of 50 ± 2 kg m⁻² a⁻¹. Because error is estimated at ±0.02 m for each seasonal concentration maximum based on the
snow stratigraphy based on identification of five annual
layers.

The lower seasonal resolution in the E10 core resulted from using a sampling scheme based on the only
three increased chemical species and the higher
concentrations (±1 standard deviation) of sodium, silicate
and sulfate, similar chloride and lower nitrate
concentrations. The chloride concentrations are similar
within the relatively large standard error (0.63 μmol l⁻¹)
and precision might have yielded an expected higher chloride value for MI due to its more coastal location.
The large sodium, silicate and sulfate inputs are visible in the upper meter of E10 (Fig.2(a)) and might
reflect a source unique to the E10 site that has become
available during the period 1971-80. Comparison of the
upper meter of E10 (1971-80) with the remainder of the
core (1929-72) shows increased sodium, silicate,
and sulfate, similar chloride and nitrate, concentrations
(± standard deviation).

Crustal weathering would be a source type common
to the two sites. Increased chemical species and the higher
concentrations might be explained by the larger
areal extent of ice-free islands and changes in atmospheric
circulation patterns. One possible driving mechanism for
these changes is areal changes in Antarctic pack ice. Using remote sensing data, Kukla and Gavlin (1981) note a 2.5 x 10⁶ km² decrease in
sea ice from 1973 to 1980, which is significant from ice-free
areas or changes in atmospheric circulation patterns. One
crystallographist mentioned that the lower elevation of MI (1400 m a.s.l.) relative to E10 (2305 m a.s.l.)
remained unchanged. This is suggestive of increased
volcanism or increased transport of sulfate from crustal
or volcanic sources.

In this worst case the MI core has greater
concentrations for all species compared to E10. It is likely
that this greater annual input to MI is attributable to its
more coastal location. The actual answer may lie
somewhere between these two extremes and more
investigation is necessary to understand the differences in
concentrations between the two sites.

| TABLE III. DILUTION-ADJUSTED MEDIAN CONCENTRATIONS (μmol a⁻¹) IN CORES FROM SITES E10 AND MI. |
|-------------------------------------------------|-------------------|-------------------|
| E10 | MI | Upper E10 | Lower E10** |
| Cl | 3.07 | 12.11 | 3.16 | 3.11 |
| SO₄ | 2.63 | 10.03 | 5.39 | 2.51 |
| Cl | 0.53 | 2.00 | 1.10 | 0.50 |
| NO₃ | 0.44 | 2.16 | 0.54 | 0.44 |
| Si | 0.21 | 1.29 | 0.94 | 0.19 |
| Cl | * Top meter of core E10. |
| Si | ** Remaining length of core E10. |

ACKNOWLEDGEMENTS

The 1981-82 University of New Hampshire field
party included P A Mayewski (leader), W B Lyons, B
Allen III and P J Feuerbach. The authors acknowledge
the support of US Navy Squadron XVE-6 for deployment
in the field, C I Davidson (Carnegie-Mellon University)
for supplying analytical time on the C-MU ion
chromatograph, and T C Loder III (University of New
Hampshire) and G J Larson (Michigan State University)
for analytical advice and review of the manuscript. We
are also grateful for the comments made on an earlier
draft of this paper by an anonymous reviewer. This
research was funded by NSF grants DPP-8203891 and
DPP-8304801.

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