CHEMICAL MIGRATION IN MID LATITUDE SNOW PACK

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ABSTRACT

Snow pack provides an inviting reservoir of accumulated chemical and water precipitation. Hypothetically, one should be able to reconstruct a winter's precipitation history through analysis of snow strata. Under nearly ideal conditions Warburton (1978) was able to reconstruct the scale of storms on the Ross Ice Shelf, Antarctica, through analysis of the physics and chemistry of deposited snow strata. During the winter 1981-1982 we quantitatively collected falling snow for chemical analysis, near Glen and at the 600 M level of Whiteface Mountain. We frequently measured snow stratigraphy, temperature profile within the snow pack, and chemical composition of the snow pack at Glen. We performed one major analysis of these parameters at Whiteface, at the time of near maximum depth, 12 Feb 1982. The chemical composition of freshly fallen snow was compared with the chemical composition of resulting strata within the snow pack. Surface snow was collected for several days after snowfall and compared with the new fallen snow.

Synthesis of the chemical structure of snow pack from chemical chronology of freshly fallen snow does not approximate the observed chemical strata. This synthesis fails even when glaze crusts, depth hoar, and other reference horizons are available to fix the chronology of the strata within the pack.

These results are from but a single season and the experiment should be repeated. We hypothesize from them, that the large temperature gradient which usually occurs between relatively warm soil, and a very cold snow surface, causes migration of dissolved ions and gases within mid latitude snow pack.

Introduction

The snow, firn and glacial ice of the polar regions, and even some near equatorial glaciers [Thompson, et al. 1979], have provided climatic histories, through analysis of trace chemicals stored in the ice. Vickers (1966) was able to extract precipitation history from both Antarctic and New England snow pack through analysis of snow pit stratigraphy. Warburton and Linkletter (1978) succeeded in defining areal extent of storms on the Ross Ice Shelf through neutron activation analysis of marine elements collected from snow pit strata.

It is inviting to apply similar snow stratigraphic analysis to North American snow pack. If one assumes crystal and chemical conservation within the snow pack, the water and chemical conservation within the snow pack, the water and chemical precipitation rate of storms can be studied after the event. Schaefer (personal communication) found that snow crystal habit was conserved for about 24 hours in snow pack from heavy snowstorms occurring in the Great Lakes. Several investigators [Cadle, et al. 1983; Feth, et al. 1962] have attempted to integrate a winter's chemical precipitation through analysis of snow strata. Hornbeck and Likens (1974) found chemical loss to occur in aging snow pack.

It is necessary to test the hypothesis of chemical conservatism of snow pack to determine if such analysis may be realistically applied. Several tests are necessary, to determine what conditions allow chemical stability in snow pack and what conditions cause dispersion or loss of chemical material in snow pack.

Site Location and Instrumentation

Two sites were used to obtain snowfall chronologies and snow pit analysis during the winter of 1981-82. These were a relatively high, cold site at Marble Lodge at the 600 M level at Whiteface Mountain, New York, designated by a W in Figure 1. The second was a more southerly, lower site (200 M) near Glen, New York, designated by C in Figure 1, which experiences frequent mid winter thaws.

There is a permanent meteorological station at Marble Lodge, Temperature and precipitation records are obtained from shielded instruments conforming to USWB specifications. One author (DW) maintains a log of daily observations, including snow cover and precipitation type.

A second set of precipitation gauges collects precipitation for chemical analysis as part of several national precipitation programs. Another author (MduB) retrieves these samples daily or following cessation of precipitation. Preliminary analysis are performed at Marble Lodge, and the specimens are then shipped to Battelle NW Laboratories for chemical analysis. The area about Marble Lodge is wooded, mostly as second growth following logging 75 years ago. The snow stratigraphy was obtained from a snow pit in open hardwood 100 M from the two precipitation gauge sites.

The Glen site is located on an abandoned field overlooking the Mohawk Valley. One author (AH) maintained a series of precipitation and occasional meteorological observations during winter 1981-82. The precipitation gauge was not shielded, but lay in a basin known for light surface winds. Stratigraphy was frequently examined. Chemical analysis of new fallen snow and snow strata were preformed at the ASRC laboratory using ion chromatography by another author (AMP). The largest errors extant in this study appear to be in the relative "catch" of the plastic containers used to collect precipitation for chemical analysis.

Results of Experiments

A snowfall which occurred on 5-6 December 1981 began snow cover for both stations. DW's log of precipitation events, major event dates, and non snow precipitation occurrences at the Marble site are shown in the left side of Figure 2. Significant amounts of rain or freezing rain occurred on 24 December, 3 January and 2 February. The temperature exceeded freezing for a few hours on 4 January and 1 February, and the only day during the period that had a mean temperature above freezing was 4 January.

The snow stratigraphy obtained on 12 February 1982 is shown on the right side of Figure 2. The ice lens, formed by the freezing rain of 3 January was used as a reference horizon in

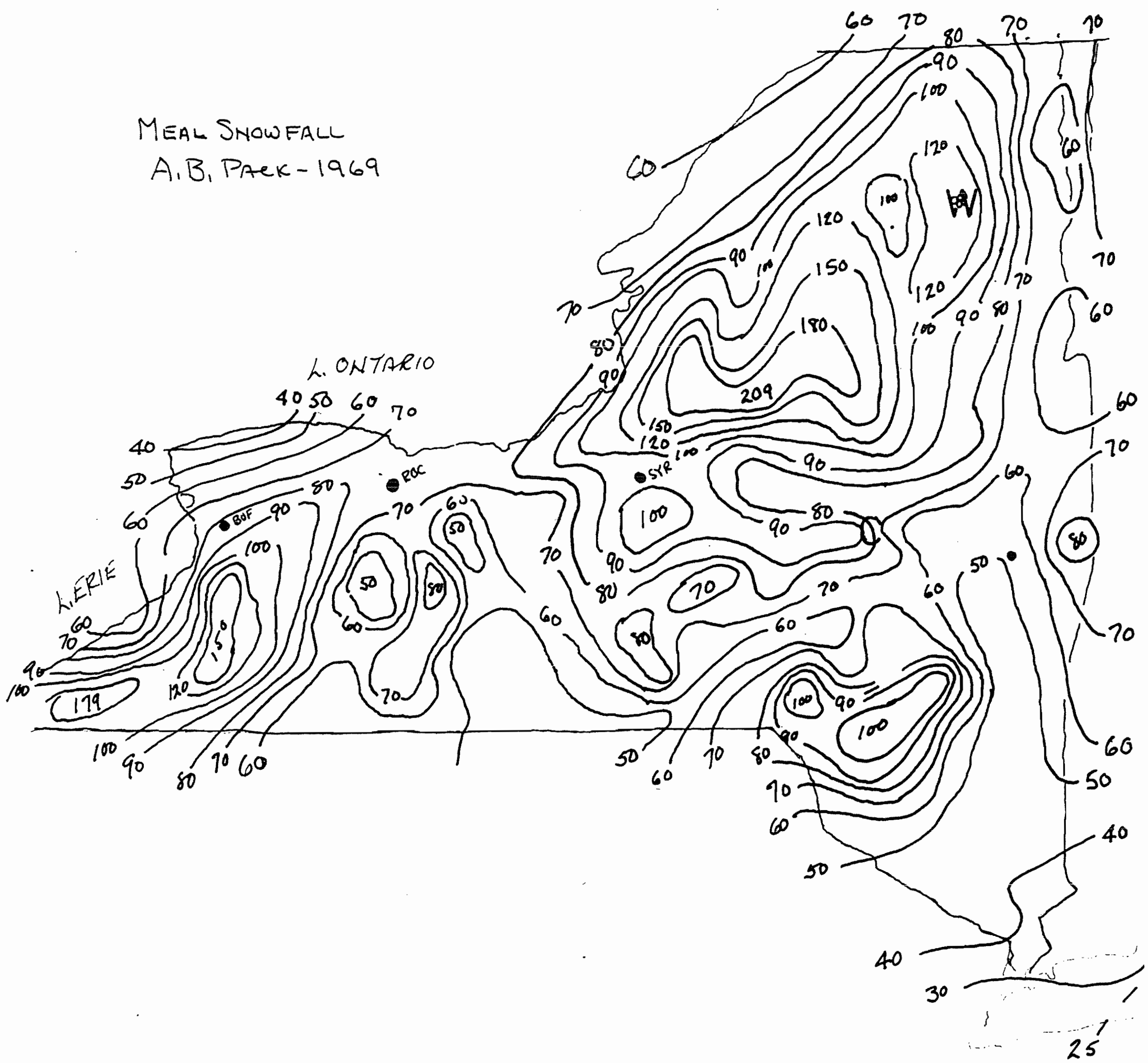

Figure 1. A map showing mean snowfall in New York, traced from original data of A.B. Pack (1969). Whiteface Mountain is noted by W, and Glen, NY by C on the map.

in the analysis. The freezing rain of 2 February left an easily identifiable ice crust. Two rather distinct layers (D&F) of sugar snow or depth hoar were found. Depth hoar is not common here, but apparently formed in a prolonged cold period during January. The depth hoar formation process apparently thinned the reference ice lens of horizon E.

The snow pit was located by examining several corings with an Adirondack snow tube. The pit represents the mean value of snow pack in the area, and corings at each corner were quite similar. The comparison of accumulated precipitation, as registered by the precipitation gauge and the snow pit data indicate some loss of water occurred. If horizon E is indeed the freezing rain of 3 January, most loss occurred through sub surface melting early in the season.

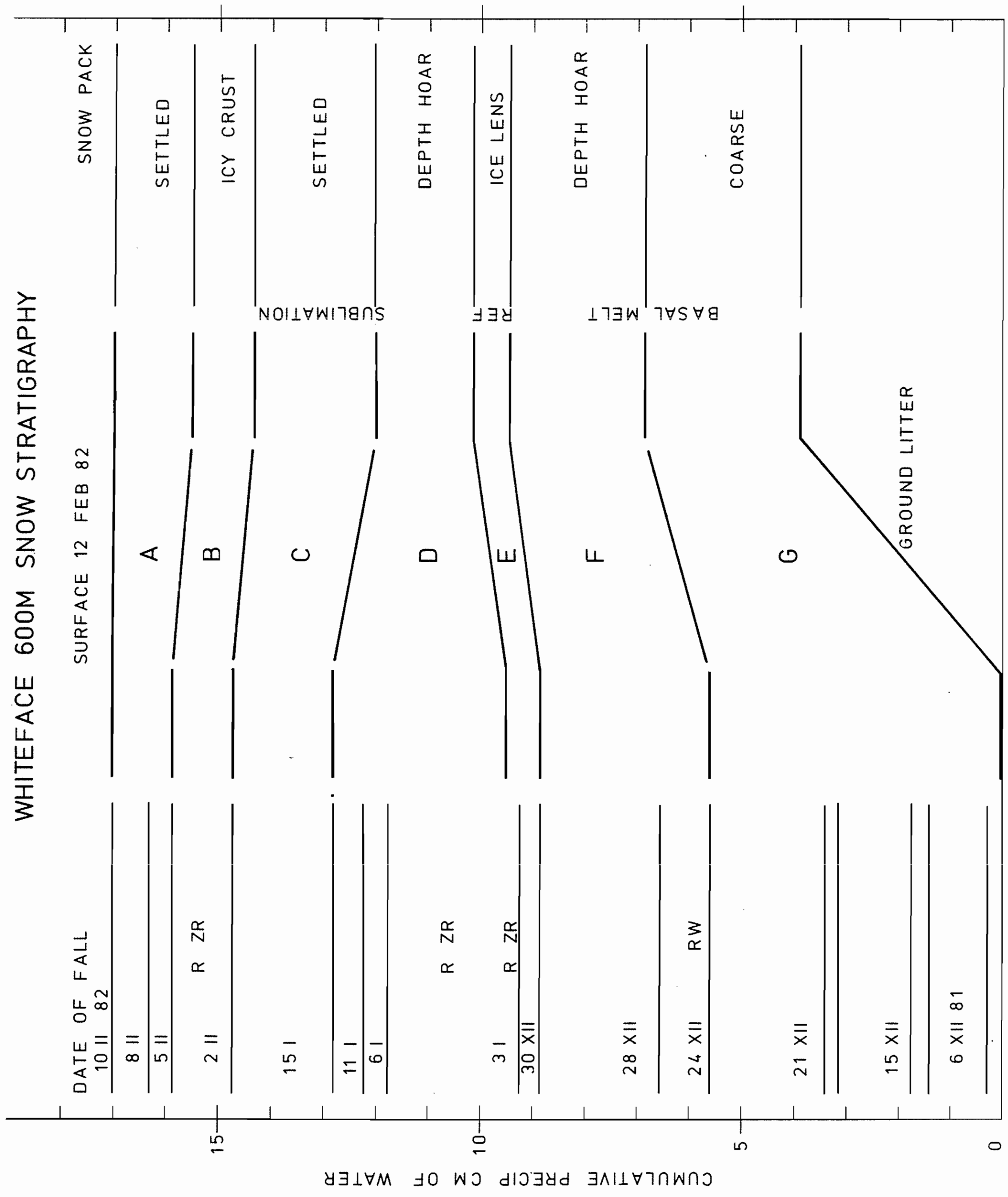

Figure 2. Chronology of precipitation events at Marble Lodge, at the 600 M level of Whiteface Mountain, presented as a pseudo snow pack. The snow strata observed on 12 Feb 1982 are shown at the right of the figure, sharing a common upper reference with the precipitation record. The capital letters and connecting lines in the center indicate the snowfalls apparently incorporated in the strata of 12 Feb.

The cumulative chemical precipitation, for sulfate and nitrate ion, as a function of water precipitation for Whiteface Marble Lodge, is shown in Figure 3. The water amount was taken from gauge observation and DW's notes, while concentration was taken from Battelle analysis. The pack data adjacent was taken from the on-site weight of collected strata and subsequent ion chromatographic analysis by AMS. The strata are denoted by the same letters as in Figure 2.

Comparison of the pseudo stratigraphy obtained from fall chronology [fall] with the chemical stratigraphy of the pack of 12 February 1982 [pack] indicates a general smoothing of the chemical horizons. The cumulative water content of the pack is .25 less than the cumulative amount calculated from the precipitation gauge, but the accumulated ion concentration is .15 to .30 greater. This may be due to sampling and analytical errors, which cannot be precisely evaluated from the data.

The depth hoar of strata D and F seem to have accumulated both nitrate and sulfate. The dense, frozen snow of the lowest strata is comparable in both sulfate and nitrate concentration with the antecedent precipitation. The fairly new snow in layers B and C seems to have lost nitrate and sulfate, while the surface strata A, seems to have gained concentration of both ions.

Field notes showing snow strata and the temperature and ion concentration within the snow pack at Glen are shown in Figures 4 and 5. Ion strata for major storms, as fallen, are shown in the center panel of Figure 4. The air above the snow was quite cold on both 27 and 30 January, but the ground beneath remained quite warm. The temperature 10 feet (3 M) beneath the surface was 42F (6C) on 27 January, and 38F (4C) on 30 January. These temperatures were measured in a covered well 100 M from the snow pit.

The snow pack ripened at Glen during mid March. The snow strata and temperature profile with the pack obtained on 10 March 1982 are shown in Figure 5. There was liquid water present in the pack, and the ground, all strata, and the air in contact with the snow were all within 1F (.5C) of freezing.

The depth hoar observed at Glen on 27 and 30 January 1982 is unusual, but temperatures as low as -27C were observed during the preceding week. The relatively high soil temperatures may have contributed to the depth hoar formation. The depth hoar obtained at Glen 27 and 30 is compared with that collected at Marble on 12 February in Table 1. This depth hoar formed from different precipitation events, according to the stratigraphy. The nitrate and sulfate ion concentrations are quite comparable in the collected depth hoar specimens from both sites.

Table 1

COMPARISON OF DEPTH HOAR

	Amount	Density	Cl^-	NO_3^-	SO_4^{--}
Glen 27 Jan			.4 ppm	2.5ppm	2.1ppm
Glen 30 Jan	3.65cm	$0.41 gm/cm^3$	.32ppm	2.0ppm	1.5ppm
Whiteface 12 Feb	2.57cm	$0.32 gm/cm^3$	.05ppm	2.0ppm	1.7ppm

A comparison of ionic concentration in fall and pack at Glen is given in Figure 6, from the stratigraphy of 14 March which is quite similar to that of 10 March in Figure 5. Notice that the water column scale for the pack in Figure 6 is foreshortened to facilitate comparison. Because of this foreshortening, the concentration is plotted in terms of μgm ion/cm^2 as an attempt at conservative units.

The snow pack strata again seem to smooth the pseudo strata of the precipitation record. In this warm case, the surface layers show a reduction in ionic strength in pack relative to precipitation, in opposition to the cold air increase shown in Figure 4. The cumulative ion and water quantities of 14 March are given in Table 2, showing nearly half of the water was lost prior to ripening of the pack at this warm site.

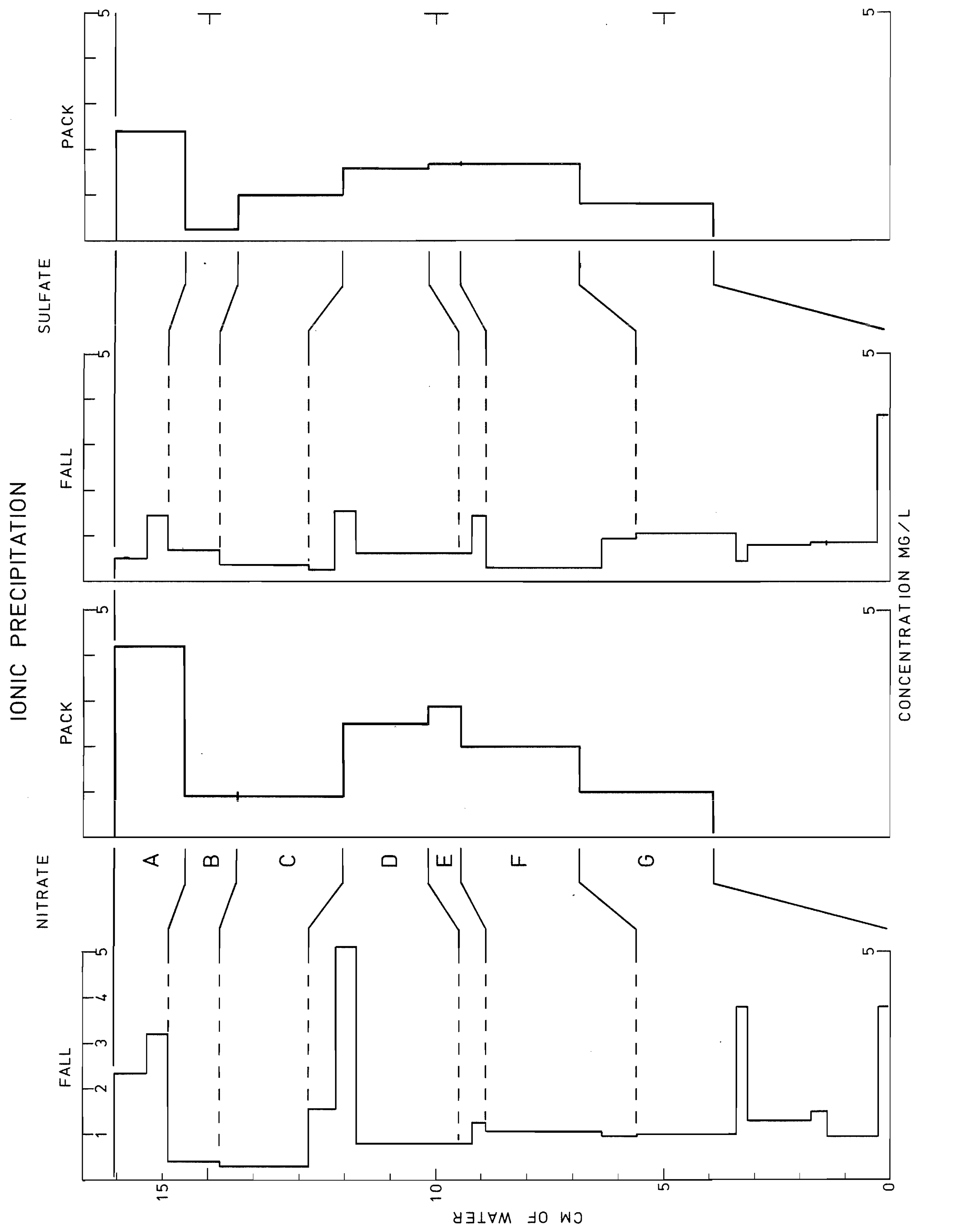

Figure 3. Pseudo stratigraphy of nitrate and sulfate precipitation, prepared from fall and analytical records, compared with chemical strata measured in the snow pack of 12 Feb 1982. The letter designators can be used to correlate the strata with Figure 1.

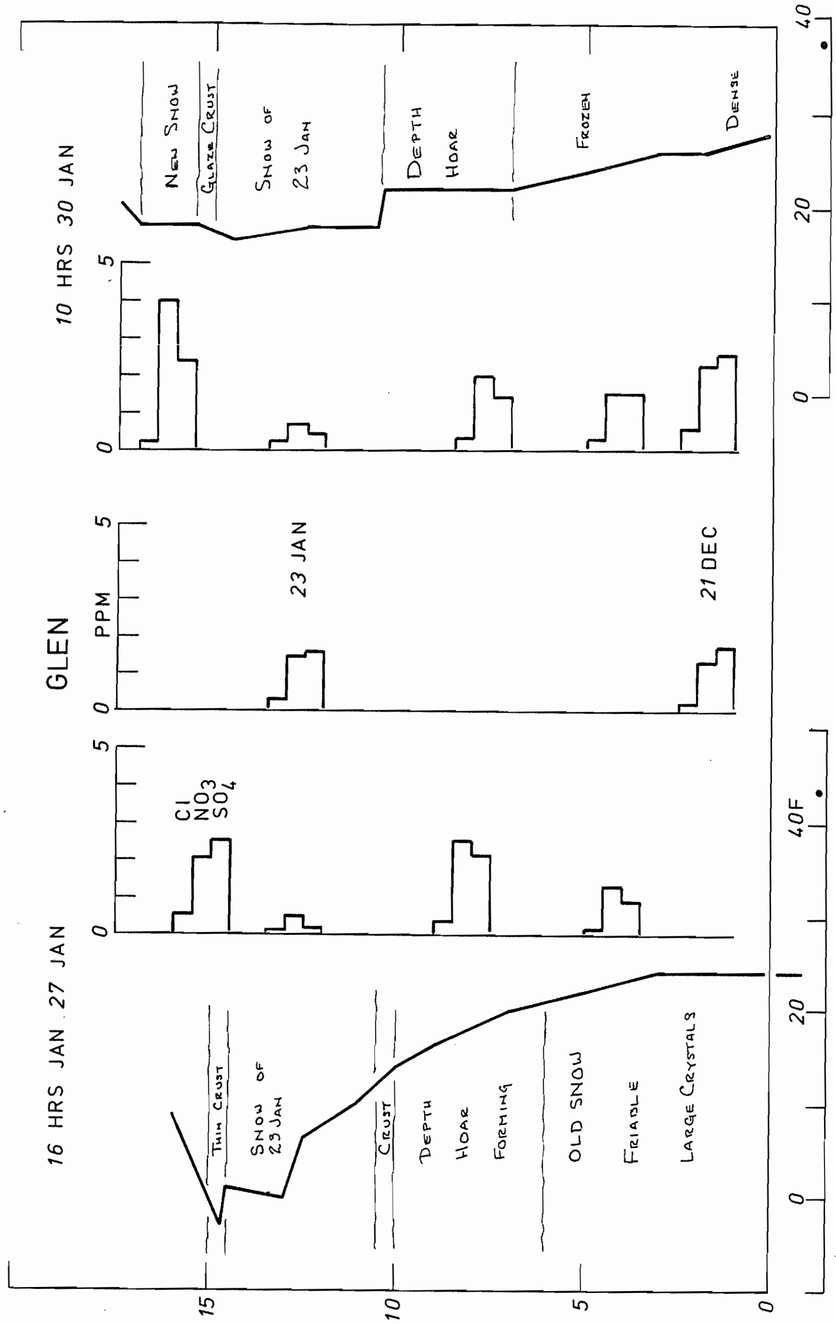

Figure 4. Field notes showing the temperature profiles and major strata in the Glen snow pack of 27 and 30 Jan 1982. Concentration of chloride, nitrate and sulfate ion in the strata are shown adjacent to the temperature profiles. The chloride, nitrate and sulfate ion concentrations obtained from the new fallen snow of 21 Dec and 23 Jan are shown in the center of the figure.

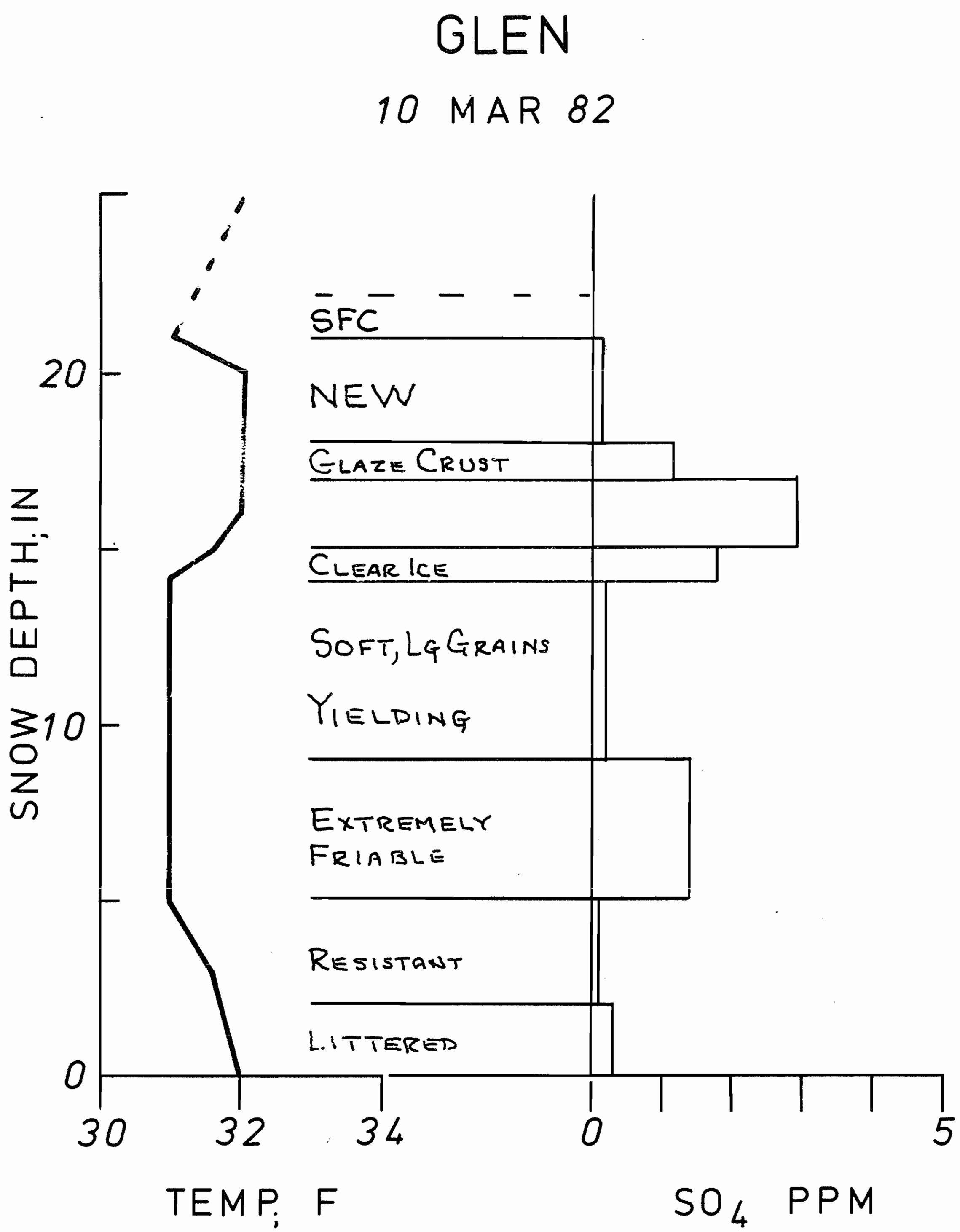

Figure 5. Field notes describing the Glen snow pack on 10 Mar 1982, as the pack began to ripen. The glaze crust is probably the freezing rain of early February.

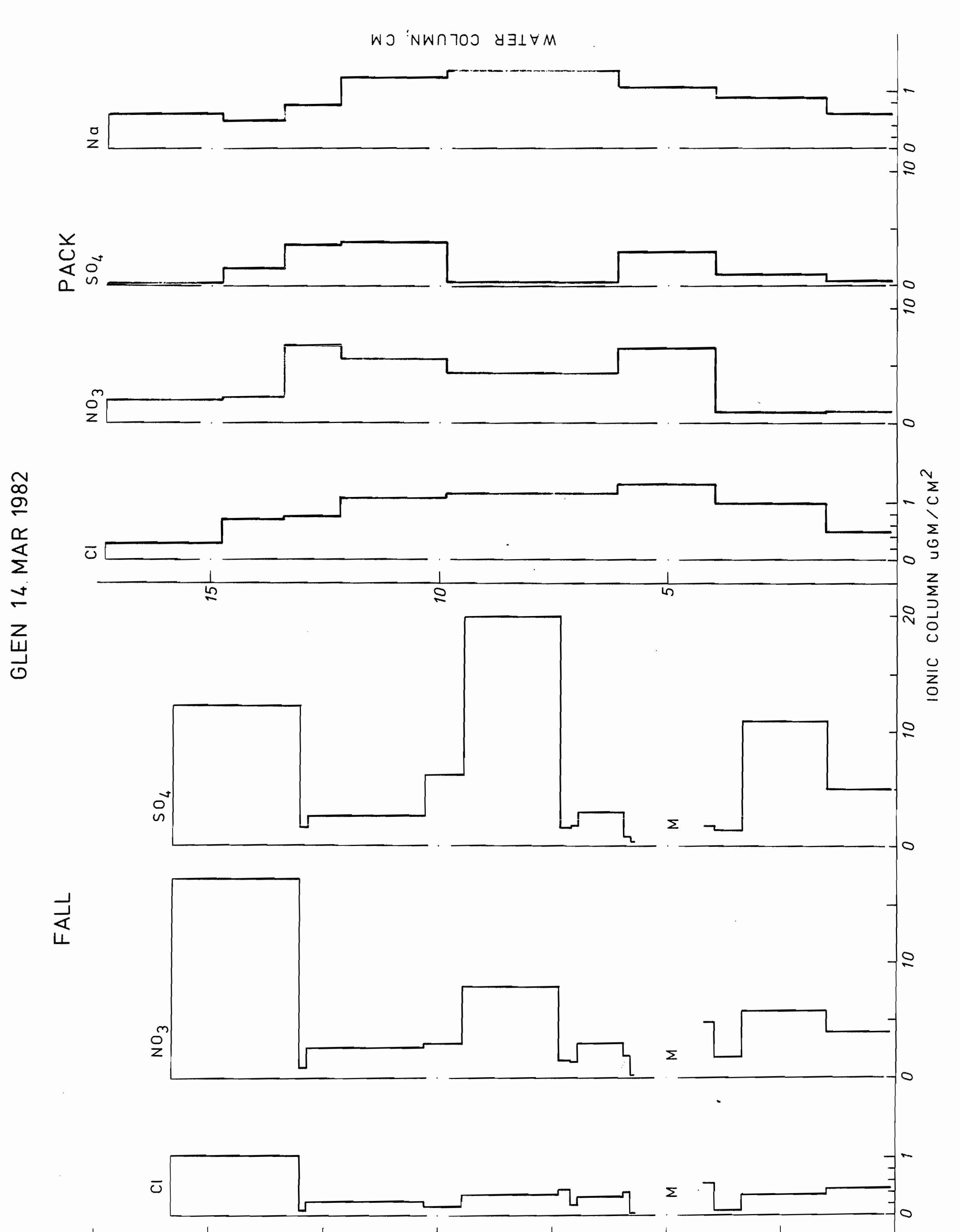

Figure 6. Pseudo strata prepared from precipitation records, and chemical strata observed in ripening snow pack at Glen 14 Mar 1982. About one half of the water in the pack has been lost during the winter, and the pack scale has been adjusted to compensate.

Table 2

Glen
RIPE SNOW PACK 10-14 MAR 82

	Water gm/cm^2	Cl	NO_3	SO_4	Na
		Micro Grams/cm^2			
Sum of Precipitation 5 Dec 81 - 10 Mar 82	31.6	8.2	62.7	70.0	
Sum of Pack 10 Mar 82	17.4	6.6	29.0	13.1	7.0
Percent Retained	55%	81%	45%	19%	

About one half of the nitrate was lost, and only 19% of sulfate retained. The greatest loss in sulfate seems to have occurred in the strata from the sleet and freezing rain of 31 January and 3 February (15-20 cm) and the newest snow (26-32 cm). With respect to amount remaining, nitrate seems comparable to water but the profiles within the strata do not seem to compare with pseudo strata prepared from the precipitation record.

Discussion

A comparison of depth hoar layers in Table 1 shows them to be quite comparable in chemical characteristics, even though formed 200 Km apart, from snow of different storms. Some additional strata which appear to be quite similar in chemical content at the two sites are tabulated in Table 3.

Table 3

COMPARISON OF WHITEFACE/GLEN EVENTS + STRATA
Snow-Sleet-Freezing Rain of 1-2-3-4 Feb

Event	Cl	NO_3	SO_4
Glen 1,2,3 Feb Snow, Sleet, Fr.	.05	0.5	0.5
Glen 10 Feb Ice Crust	.05	0.7	0.5
Whiteface 12 Feb Ice Crust	.08	0.9	0.3
Glen 10 Feb New Snow	.13	2.2	2.0
Whiteface 12 Feb New Snow	.12	4.2	2.4

Many measurements of the snow, sleet and freezing rain of 30 January and 3 February 1982 were made at Glen, and described in the accompanying paper (Hogan 1985). An integration of the chemical characteristics of this mixed precipitation is given in Table 3 as Glen snow, sleet and freezing rain, 1,2,3 February. The late hours of sleet, and the following snow and freezing rain that formed the Glen ice crust are next noted. The same storm produced less sleet at Whiteface, but did include sufficient rain and freezing rain to produce a similar ice crust, listed third in the table. New snow, occurring as light snow and flurries between 4 and 10 February at both stations completes the tabulation.

The ice crusts and surface snow of these strata are chemically quite similar at Glen and Whiteface. Referring again to Figure 3 as well as Table 3, we find the ice crust is chemically comparable to its antecedent precipitation. The surface snow at both stations (strata A) is chemically comparable, but exceeds its parent precipitation in both nitrate and sulfate content by 2 to 5 fold.

The snowstorm of 23 January at Glen did not reach Whiteface. Referring again to Figure 4, the chemical concentration of the new fallen snow of 21 December and 23 January are shown in the center of the Figure, and the chemical and composition of the resulting strata of 27 and 30 January, are shown adjacent. Note that the chemical concentration of the 23 January snow rapidly decreases while in the pack, and the adjacent depth hoar and wind crust show enhanced concentrations. This is during an extremely cold period when no melting occurred. Similar behavior was observed several times during the winter, as new fallen snow decreased in chemical concentration while in pack, while the surface layer increased in concentration.

One might preliminarily hypothesize that the increase in chemical concentration of the surface layer is simply due to precipitation of soluble sulfate, nitrate and chloride bearing aerosol to the exposed surface, or that acid ion vapor permeated the surface from above. These hypotheses cannot be dismissed, or tested easily.

The decrease in chemical concentration that frequently occurs, beneath the surface in cold snow with cold air overlying as in the aging of the snow of 23 January, shown in Figure 4. Considerable chemical migration seems to coincide with depth hoar formation as shown in Table 1, but little chemical migration occurs in cold frozen or glazed crusts as shown in Table 3. Ripening of the snow pack as shown in Figure 6, appears to thoroughly redistribute chemical substances through the pack.

These observations lead to an alternative hypothesis to describe chemical migration and redistribution in cold snow pack. Snow pack in this area often overlies unfrozen ground which may be as warm as 5C, a few centimeters below the snow ground interface. Simultaneously, air above the snow may be as cold as -25 to -30C, and the coldest air is at the radiating surface of the snow. Temperature gradients of more than $1^{o}C/cm$ have been measured in the pack during these conditions. If chemical substances such as sulfate, nitrate and chloride ion are present in the pack as acid vapors, these vapors may well migrate toward the surface in such a temperature gradient. If these chemical substances exist as submicron particles, they may also migrate along with water vapor through the pack, during recrystallization processes such as depth hoar formation. This hypothesis is not applicable to spring snow pack which has little temperature gradient, and may include liquid water.

Conclusions

Cold snow pack is relatively conservative of chemical properties on the gross, total pack scale, but migration among strata may occur. This migration is especially noticeable during depth hoar formation, and toward surface layers during cold clear periods. Frozen and glaze crusts seem most conservative of chemical properties.

Temperature gradients, induced from unfrozen ground beneath the snow, and strong radiation from the surface of the snow seem to supply the driving force causing upward migration of chemical components within the pack. This migration seems strongest in early shallow snow pack.

There seems to be little conservation of the season's chemical precipitation in ripening snow. Further research might be directed toward identifying a conservative tracer within snow pack, as an aid to determining the migration of other components.

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Figure Legends

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