ICE THICKNESS AND ABUNDANCE OF CONTAMINANTS

By William E. Davies and G. William Holmes

Trace Elements Investigations Report 705

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

ICE THICKNESS AND ABUNDANCE OF CONTAMINANTS*

By

William E. Davies

and

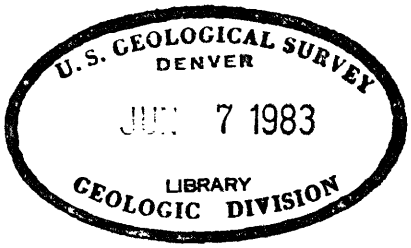
G. William Holmes

January 1958

Trace Elements Investigations Report 705

This preliminary report is distributed without editorial and technical review for conformity with official standards and nomenclature. It is not for public inspection or quotation.

*This report concerns work done on behalf of the Division of Research of the U. S. Atomic Energy Commission.



Distribution	No. of copies
Albuquerque Operations Office (J. E. Reeves)	2
Division of Research, Washington (D. R. Miller)	6
Office of Operations Analysis & Planning, Washington(P. C. Fine)	1
Atomic Energy Division, duPont, Wilmington (V. R. Thayer)	1
Chemistry Division, Argonne National Lab. (W. M. Manning)	1
Chemical Tech. Div., Oak Ridge Natl. Lab. (F. R. Bruce)	1
Health Physics Div., Oak Ridge Natl. Lab. (F. L. Parker)	3
Los Alamos Scientific Laboratory (J. H. Hall)	1
Univ. Calif. Radiation Lab., Livermore (G. W. Johnson)	10
U. S. Naval Ordnance Lab., White Oak, Md. (J. E. Ablard)	1
U. S. Naval Radiological Lab., San Francisco (N. E. Ballou)	1
U. S. Geological Survey:	
C. A. Anderson, Washington	1
J. R. Balsley, Washington	1
Alfred Clebsch, Jr., Albuquerque	1
W. E. Davies, Washington	1
W. H. Diment, Denver	1
Ernest Dobrovolny, Denver	1
D. C. Duncan, Washington	1
E. B. Eckel, Denver	1
James Gilluly, Denver	1
G. V. Keller, Denver	1
M. R. Klepper, Washington	1
J. D. Love, Laramie	1
G. W. Morey, Washington	1
G. W. Moore, New Haven	1
T. B. Nolan, Washington	1
L. R. Page, Washington	1
W. T. Pecora, Washington	1
W. G. Pierce, Menlo Park	1
C. B. Read, Albuquerque	6
Edwin Roedder, Washington	1
E. M. Shoemaker, Grand Junction	1
V. T. Stringfield, Washington	1
C. V. Theis, Albuquerque	1
D. J. Varnes, Denver	1
D. E. White, Menlo Park	1
F. C. Whitmore, Jr., Washington	1
H. H. Waesche, Washington	1
TEPCO, Denver	1
TEPCO, RPS, Washington (including master)	2
	63

CONTENTS

ILLUSTRATIONS

TABLE

ICE THICKNESS AND ABUNDANCE OF CONTAMINANTS

By William E. Davies and G. William Holmes

ABSTRACT

Sixteen ice caps or glaciers in North America, Greenland, and Iceland are known to contain areas of glacial ice more than 1,000 feet thick. One of these - the Greenland ice cap - has ice at least 11,000 feet thick; five others - the Vatnajökull ice cap, Iceland, U. S. Range mountain glacier, Ellesmere Island, Canada, the St. Elias Range mountain glacier, Alaska and Canada, the Hubbard ice field, Alaska, and the Harding ice field, Alaska - have ice as much as 3,000 feet thick.

Ice contains a number of contaminating or englacial materials, the abundance of which varies from glacier to glacier and from place to place within glaciers. Quantitative analyses of these contaminants for the most part are lacking, except for various salts soluble in water vapor. Qualitative knowledge suggests that the most abundant englacial materials are 1) silicates in the form of rock and mineral debris plucked from the sides and bottoms of the glaciers, 2) similar material (loess) of wind-blown origin, and 3) wind-deposited volcanic debris of tuffaceous character.

The most common saline found in ice is NaCl, but in at least one glacier in U.S.S.R. magnesium aluminum sulfate appears as a film on the snow after melting. Analyses of 24 samples from the Juneau ice field, Alaska, showed 0.3 to 4.5 ppm of Cl^- and 0.5 to 7.4 ppm of NaCl. The composition of 16 samples of rime from the Zugspitze mountain observatory, Germany was 0.00005 to 0.0059 grams per liter (g/l) of Cl; 0.0022 to 0.0021 g/l of Mg; SiO_2 was present in 4 samples; Na was present in one sample; iodine also was present in one sample. Iron as oxide or in the ionic state was present in 11 out of 25 samples of Swedish glacial ice.

Tritium concentrations probably vary with the source of the water that formed the ice, but analytical data are scant. Heavy water in Swedish glaciers is 1 to 5 times the amount in ordinary subsoil water. The O^{18} content is variable. Radioactive products from atomic bomb blasts have been identified on European glaciers.

Organic matter is incorporated into ice from organisms native to glaciers such as algae, moss, bacteria, protozoans, diatoms, and snow fleas and also from flying or wind-blown organisms such as grasshoppers and larvae.

INTRODUCTION

The literature on glaciers of the northern hemisphere has been reviewed in order to define those places that might contain ice bodies 1,000 feet or more in thickness and to summarize existing analytical data on composition of contaminants or englacial material.

In general our knowledge of the composition of glacial ice is limited to qualitative data which indicate a heterogeneous distribution of rock and mineral debris within glacial ice, except perhaps in the upper 4,000 feet of the Greenland ice cap and some areas in Antarctica. Relatively low concentrations of such contaminants occur in the glaciers of Baffin Island and Ellesmere Island (fig. 1) whereas relatively high concentrations characterize the glaciers of Alaska, Yukon Territory, British Columbia, Washington, and the Canadian Rockies.

Figure 1.

Index map of the Queen Elizabeth Islands showing permanent land ice areas.

Our knowledge of the thickness of certain glaciers is more quantitative and is based on geophysical measurements and bore holes (maximum depth drilled is 1,438 feet, in the Greenland ice cap, and core has been recovered to 1,040 feet). Great thicknesses (that is, more than 5,000 feet) have been recorded only in Greenland and Antarctica. The variation in thickness of the Greenland ice cap is shown in figure 2.

THICKNESS OF GLACIERS AND ICEFIELDS OF NORTH AMERICA

Sources of information

Comparatively little data are available on the thickness of permanent ice in North America. The ice caps of Iceland and Greenland have been investigated from a reconnaissance viewpoint by the Expeditions Polaires Françaises (Holtzscherer and Bauer, 1954), Snow, Ice, and Permafrost Research Establishment, U. S. Army, Corps of Engineers (1957), and the Transportation Corps, U. S. Army (1954). Studies of ice caps on Baffin Island have been made by Baird (Baird and others, 1950). In Alaska and western Canada data are available on 6 glaciers (Allen and Smith 1953, Goldthwait 1936, Poulter, and others, 1949, Baird and Salt, 1949). Information on other glaciers and ice caps has been interpreted on the basis of the topography of the land mass adjacent to the ice mass and on characteristics of similar glaciers where measurements have been made.

This study is a part of a program that the U. S. Geological Survey is conducting in connection with its Investigations of Geologic Processes project on behalf of the Division of Research, U. S. Atomic Energy Commission. The purpose of the study is to present data for the determination of the suitability of using ice as a medium for confining nuclear reactions. In addition this study outlines the present state of knowledge concerning ice thickness and contamination and the fields in which additional research is necessary if nuclear reactions are to be made in ice.

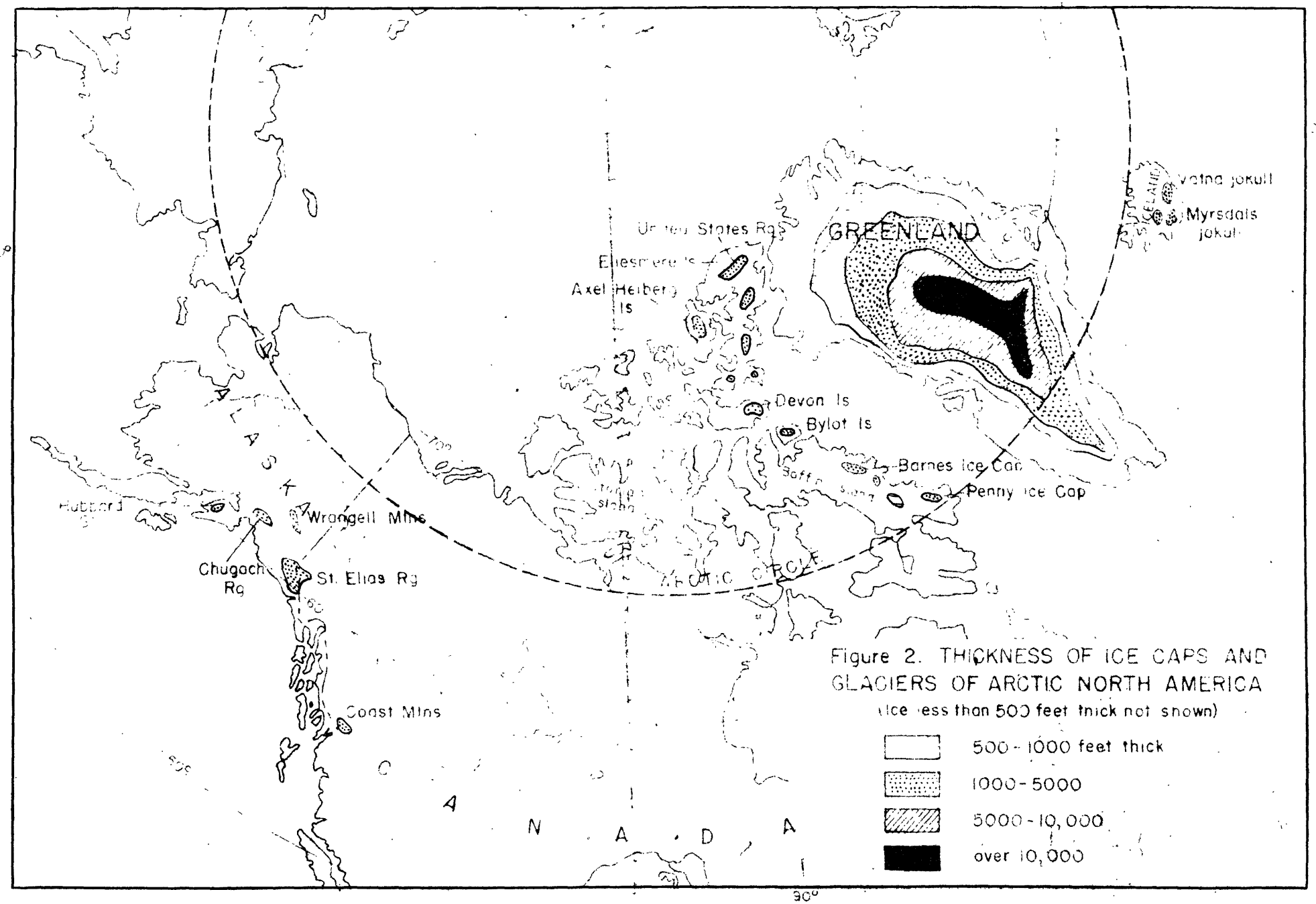


Figure 2. THICKNESS OF ICE CAPS AND GLACIERS OF ARCTIC NORTH AMERICA
(Ice less than 500 feet thick not shown)

- 500 - 1000 feet thick
- 1000 - 5000
- 5000 - 10,000
- over 10,000

The glaciers and ice fields have been grouped into 4 categories. A basin ice cap occurs in Greenland only and occupies a subcontinental-size basin surrounded by mountains or high plateaus. The floor of the basin is relatively uniform and large volumes of ice are contained within various depth contours. Plateau ice caps are relatively thin and are perched on plateau uplands with no confining land areas along their borders. In general they are in the shape of low ice domes. Mountain ice caps are irregular in depth and form a dome-like cover over basins and peaks in areas where the land beneath has moderate relief (1000-5000 feet). Valley glaciers are active glaciers contained between valley walls. Movement is from a few feet to several hundred feet a day. A tabular summary of major ice fields of North America, Iceland, and Greenland is given in table 1.

Table 1.--Summary of major ice fields of North America, Iceland, and Greenland

Name	Location	Type	Thickness in feet	Remarks
Vatnajökull.	Iceland.	Plateau.	1500-3400	Highly contaminated with volcanic ash.
Myrdalsjökull.	do.	do.	1500	Do.
Langjökull.	do.	do.	1000	Do.
Ice cap.	Greenland.	Basin.	11,000	Negligible contamination where more than 4000 feet thick.
U. S. Range.	Ellesmere Island.	Mountain.	3000	Moderate contamination from glacial debris.
Victoria-Alberton.	do.	do.	1000	Do.
3 small ice caps.	South part of Ellesmere Island.	Plateau.	1000	Moderate contamination with concentration because of melt.
Ice cap.	Devon Island.	do.	2000	Do.
Ice cap.	Axel Heiberg Island.	Mountain.	2000	Moderate contamination from glacial debris.
Ice cap.	Bylot Island.	Plateau.	1000	Do.
Barnes ice cap.	Baffin Island.	do.	1000-1350	Hard ice.
Penny ice cap.	do.	do.	1000	Do.
St. Elias Range (Malaspina Glacier).	Alaska-Canada.	Mountain.	1000-3000	Moderate contamination from dust and volcanic ash.
Hubbard ice field.	Alaska.	do.	1000-3000	Do.
Wrangell Mountains.	do.	do.	1000	Do.
Harding ice field.	do.	do.	1000-3000	Do.
Chugach Mountains.	do.	do.	1000	Do.
Coast Mountains.	Alaska-Canada.	do.	1000	Do.

Melt conditions produce large quantities of water on most of the ice caps and glaciers cited. Permanent firn condition is only on the Greenland and Baffin Island ice caps at elevations above 5,000-6,000 feet.

ENGLACIAL SUBSTANCES

Introduction

Sources of information

The following brief review deals with englacial materials (materials contained in the ice) with emphasis on substances other than till or glacio-fluvial and glacio-lacustrine materials because the nature of englacial till, outwash, and lake deposits is relatively well known.

Sources for the following discussion are few, and speculation on the nature and concentrations of englacial materials must be based in part on inference from knowledge of the size, volume, geographic setting, and regime of glaciers in the Northern Hemisphere. Review of the standard bibliographies indicates that very few analyses of glacial ice have been made, most of which were incidental to geophysical studies of widely scattered glaciers. In contrast, a moderately large literature on englacial organisms and organic materials exists, and representative studies of englacial till, loess, or volcanic ash have been reported.

In this study data are presented covering as many aspects of contamination of ice as are known. The data pertain to numerous glaciers throughout the northern hemisphere and are intended as a guide to the type of contamination that probably is present in large ice caps. Before sites can be chosen for utilization of ice caps for any purpose, extensive testing must be carried out to determine the chemical nature and extent of contamination in a specific area.

Physics and geography of glaciers in relation to englacial materials

The character and degree of concentration of englacial substances depends largely on: 1) the physical character of the glacier, 2) the relation of the glacier to its surroundings, and 3) the regional and local climate.

Concentration of contaminants.--The degree of concentration of airborne contaminants depends on such interrelated factors as the rate and nature of flow, the thermal profile, the regime or nature of accumulation and ablation, the area and volume of the glacier, and the relative extent of the zones of accumulation and ablation.

For example, foreign materials in the ice theoretically will be present in relatively high concentrations in glaciers that are very slow or stagnant, in glaciers with low rates of firn accumulation and high rates of ablation, and those with large areas of accumulation in relation to areas of ablation. Glaciers with large quantities of meltwater that accumulate as refrozen meltwater should also contain higher concentrations of contaminants.

On the other hand, glaciers that flow rapidly from their accumulation zones, glaciers that accumulate large volumes of firn, and those with small accumulation areas and large ablation zones, by inference, should have low concentrations of contaminants. "Temperate" glaciers (Ahlmann, 1948, p. 66) whose temperature is near the pressure-melting point during the ablation season, and which produce or contain large quantities of meltwater, may concentrate foreign material in the firn of the ablation zone by the compaction, recrystallization, and refreezing of snow, but this concentration may be lessened by the activity of meltwater. "High

polar" glaciers (Ahlmann, 1948), which are below freezing at depth throughout the year, may also contain small percentages of contaminants, owing to the absence of meltwater concentration, and to low precipitation.

Geography of the glacier.--The geographic setting has important bearing on the degree of contamination. The proximity of the glacier to the sea or to arid regions with evaporite beds, or to source areas of loess or dust, such as weathered rock surfaces, floodplains, or dry lakes, and to volcanoes, is obviously a primary consideration. Similarly, the form of the glacier, whether it is a valley glacier in a region of actively eroding alpine peaks, or a great continental ice sheet whose accumulation zone is far from sources of foreign materials, is also a major factor.

Climate.--The regional and local climate is another major consideration. The amount and form of precipitation, the direction and velocity of wind, the source regions of the air masses, the air temperature, humidity, and radiation control such factors as the sources of contaminants, the amount and type of accumulation and ablation, the meltwater activity, and the thermal profile of the glacier.

In contrast to the amount of information concerning analyses of foreign materials in glacial ice, the factors listed above are relatively well known. The physics of glaciers, although it is a young science, is well enough known so that general assessment can be made on the basis of widely distributed glaciological studies in Scandinavia, Iceland, Greenland, Baffin Island, western Canada, and Alaska. Likewise, geographic and climatologic factors can be readily evaluated.

MATERIALS FROM LOCAL SOURCES

The nature of locally derived debris in glaciers can be readily determined and its general composition is well known, at least qualitatively, in the study of glacial deposits. Most of this material is from the bedrock floor, valley walls, or cirques of the glacial system and consists primarily of rock fragments. Unconsolidated deposits such as lake beds, soils, loess, or alluvial materials and, rarely, vegetation, may also be incorporated. The concentration of englacial material generally increases in the direction of glacial movement, but obviously the degree of concentration within corresponding parts of different glaciers varies widely, owing to such factors as the vigor of glacial erosion, the resistance of the subglacial rocks, the abundance of source rocks from valley sides, or the regime and thermal character of the glacier.

Rock fragments and finer material eroded by glaciers are common in all valley glaciers and along the edge of ice fields. In the central parts of ice fields, when the ice is over 1,000 feet thick, this material is absent and the only contaminants are eolian or meteoric dust and small organic materials.

TRANSPORTED FINE-GRAINED OR MICROSCOPIC CONTAMINANTS

Quantitative data on the nature and concentration of fine-grained, microscopic, submicroscopic, or dissolved materials in glacial ice and firn are few and scattered. However, the presence of several types of contaminants in various glaciers, discussed below, is well known; and, lacking comprehensive quantitative data, an evaluation of the degree of contamination might be inferred from glaciologic, climatologic, and geographic information.

Loess

Although eolian silt may be derived from local sources, it can be transported considerable distances. Loess probably falls on most valley glaciers and at least on the margins of ice caps and ice sheets. Contrasting conditions are reported by Sharp (1949), who describes an abundance of fine-grained debris on the stagnant ice of Wolf Creek Glacier, Yukon Territory, and by Wilson (1955) who reports only traces of mineral dust in the Greenland ice cap approximately 60 miles from the margin. Sedimentation rates of loess vary widely, depending on abundance of source materials, the direction and persistence of the transporting wind, and on glaciologic factors listed in the foregoing sections.

Loess consists mainly of silt-sized particles, with some sand and clay sizes, and is composed primarily of quartz, with small variable fractions of clay minerals, feldspars, micas, hornblende, pyroxene, and carbonate minerals. A very large literature exists on the composition, stratigraphy, and distribution of loess, and much of this information is germane to the loess or dust deposited directly on glaciers. Flint (1957, p. 181-194) has a general treatment of this subject.

Measurements of loess accumulation in glaciers in the Tien Shan Mountains, U.S.S.R. (Glazovskaia, 1954), are cited as representing a relatively high rate of accumulation. The dust deposition ranged from 130,000 to 270,000 particles per square centimeter per day on clear days, and about three times that rate on hazy days. The high periods of accumulation were associated with dust storms in adjacent deserts.

Airborne micro-organisms

Plant materials, primarily pollen, spores, and minute plant parts or fragments probably occur in most valley glaciers but seem to be rare in the accumulation zone of large ice sheets. Wilson (1955) found no pollen of undisputed eolian origin in the Greenland ice cap 60 miles from the margin. Benninghoff and Robbins (1954, p. 127) reported that no pollen was found in ice samples taken near the margin of the Greenland ice cap northeast of Thule, although a few fragments of plant tissues were present.

On the other hand, plant materials are present in sufficient quantities in glaciers such as the Taku, southeast Alaska, to warrant palynologic investigations (Heusser, 1954).

Meteoric dust

Minute quantities of cosmic or meteoric dust accumulate in glaciers, as well as in oceans and lakes. Concentration of cosmic dust was once believed to absorb solar radiation to form cryoconite holes (cylindrical holes 6 inches to 2 feet in diameter, a few inches to 2 feet in depth) but this is now known to be a deposit, called cryoconite, composed mainly of algae (Wilson, 1955). If cosmic dust occurs in cryoconite, it is masked by other constituents. However, even in view of the absence of analytical data demonstrating the presence of meteoric particles in glaciers, they must be assumed to be present in extremely low concentrations, by inference from astronomic, oceanographic, and geologic information.

Volcanic ash

Airborne products of vulcanism, including dust, ash, and larger particles, as well as precipitation enriched by volcanic gases are incorporated in glaciers. Although heavy concentrations are usually associated with local vulcanism. world-wide distribution of ash occurs. The 1912 ash from the Mt. Katmai, Alaska, explosion was reported from a bore hole in the Greenland ice cap, and it is expected that the 1883 ash from the Krakatoa, East Indies, explosion will be found at greater depth (Odishaw, 1958, p. 124).

Extremely high rates of accumulation are represented by pumice layers blanketing the Knife Creek glaciers in the vicinity of Mt. Katmai, Alaska (Muller and Coulter, 1957). High concentrations of ash in glaciers may be expected in other Alaskan glaciers, including those on the Wrangell Mountains, in the Chugach Range and on the Aleutian volcanoes. Glaciers in Iceland, New Zealand, the Andes Mountains, and in East Africa, associated with volcanoes, may be expected to contain volcanic products. Analyses of volcanic ash are available from widely distributed localities, which would provide a basis for estimating at least the qualitative composition of englacial ash.

In general, over large ice caps such as Greenland, the horizontal distribution of volcanic ash is uniform. In layers of ice that correlate with large volcanic eruptions, such as Krakatoa, the material is in the form of dust particles scattered throughout the annual layer. The dust is primarily feldspar and quartz with small amounts of mica and hornblende. Traces of garnet, pyroxene, magnetite, rutile, and sillimanite are present. Particles are smaller than 0.2 mm in diameter. Concentrations are probably less than 0.001 percent by weight.

Ice fields near active volcanoes (Iceland and Alaska) have higher concentrations of volcanic ash. In general this contamination is distributed throughout the ice mass because of melting of the ice and frequent volcanic eruption. Concentrations may be as high as 70 percent by weight in layers reflecting years of intense volcanic activity.

Salts and other compounds

Snow and ice samples from the Juneau ice field, Alaska, located near the sea, were analyzed for sodium chloride and chloride in the expectation of detecting differences with depth or character of the ice or snow (Miller, 1953, p. 35-36). The total range of 24 samples was: chloride, 0.3 to 4.5 ppm; and sodium chloride 0.5 to 7.4 ppm. Summer snow contains more salines than winter snow, but no significant differences in saline content with depth were noted.

Many other glaciers, even those far from the sea, may contain salines and other compounds as suggested by analyses of rime from the Zugspitze mountain observatory, Germany (Lipp, 1932). Analyses of 16 samples indicated the following:

Cl	0.00005 to 0.0059 g/l
Mg	0.0021 to 0.0022 g/l
SiO_2	present, 4 out 16 samples
Na	present, 1 sample
I	present, 1 sample

Snow analyses indicated that the contained Cl^- was 0.00099 g/l, and Mg^{++} was 0.0013 g/l.

Traces of iron were present in 11 of 25 samples of Swedish glacial ice (Sandström and von Gegerfelt, 1945). It is believed the iron originated from surrounding rocks or in the ionic state as condensation nuclei. It remains as iron ion or iron oxide in the ice until melting occurs, when it changes to hydroxide in colloidal form.

An unusual crust has been reported from a glacier in the Turkestan Mountains, U.S.S.R. (Tagantsev and Zil'bermints, 1914). A film of pickeringite, a hydrous magnesium aluminum sulfate, appears on the ice after the snow has melted. It is ascribed to airborne evaporites from adjacent arid regions and is concentrated on the ice surface after a summer of great evaporation and aridity.

Tritium and radioactive materials

Comparison of tritium analyses of glacial meltwater from the Mendenhall Glacier, Alaska, with rain water and water from Long Island Sound showed glacial water to contain significantly less tritium than other samples (Fireman and Schwartzer, 1954). Tritium concentrations of the samples varied widely, and high concentrations were not ascribed to bomb tests but to the history of the rain sources. Rain from continental water or rain from water that has been at high altitudes has greater concentrations than rain from recently evaporated ocean water. Radioactive materials in ice previous to 1943 are of such small concentrations that they are seldom detected. In post-1943 accumulation, concentrations are less than 0.0001 percent by weight and are significant only where geochronology is concerned.

INDIGENOUS ORGANISMS

In contrast to studies of trace elements in ice, a large literature exists concerning organisms native to glaciers and snow fields, especially algae. These plants live throughout the surface layers of the snow or firn, and also in segregations in pits and depressions. Other inhabitants include moss, bacteria, protozoans, diatoms, and snow fleas. Grasshoppers, larvae, and flying insects (false cryobionts) commonly are buried in firn or snow but are not normal and permanent inhabitants.

Algae exist in firn and snow, appearing in the ablation season as discolorations of red, yellow, green, and brown (Huber-Pestalozzi, 1926). Concentrations of algae in pits and basins, described as cryoconite, are dark brown or black. Representative studies of snow algae have been made in the Alps and in Alaska by Kol (1934, 1938, 1942).

Cryoconite, or a concentration of algae in pits, tubes, or shallow depressions (called cryoconite holes), with variable amounts of mineral and humic matter has been described from glaciers. A general treatment is presented by Steinbock (1936), and recent studies in Greenland have been reported by Wilson (1955) and Benninghoff and Robbins (1954). Cryoconite exhibits growth during the ablation period. The dark color of cryoconite intensifies the heat transfer from sky radiation and sunlight, and the algae become the locus of accelerated ablation.

Mosses may grow on glaciers in the form of polsters (glacier mice) surrounding pebbles or accumulations of sandy silt and pebbles (Benninghoff, 1955).

Bacteria from high alpine snowfields, including aerobic, anaerobic, and gas-forming types, have been identified (Kursteiner, 1923) and probably also exist in glaciers.

The most common type of insect native to glaciers is the snow flea Isotoma (Zschokki, 1928), which may occur within layers up to 0.5 meter thick at the surface (Kol, 1938). Counts of 120 fleas per square foot have been made on Alaska glaciers. No concentrations of these insects are reported at depth within the glacier, and it is probable that decay at the surface on death removes all traces.

Organic substances in snow and ice would tend to increase the nitrogen content (Bordoni-Uffreduzzi, 1887), but no specific analyses are available of such concentrations. Based on the presence of organic nitrogen in glacial dust, concentrations of about 0.0005 percent by weight may be anticipated for organic material at depth.

STRATIGRAPHY OF ICE FIELDS

Stratigraphy of large snow and ice fields has been investigated in Alaska, Baffin Island, Greenland, and Iceland. These investigations have shown that in areas of permanently dry snow (when all precipitation is in the form of snow, and surface melt is insignificant) systematic stratigraphy can be established. In areas where summer melt and rainfall are extensive and on active glaciers stratigraphy is not uniform and the ice consists of heterogeneous, nonsystematic layers mixed with rock debris, dust and organic material, which form from 5 to 90 percent of the mass.

Dry snow occurs in Greenland above 4,000 feet altitude. It is also probably present in small areas in Ellesmere Island and northern Baffin Island above 6,000 feet. In Alaska the ice fields are large moving glacial masses subject to extensive summer melt. In Iceland melt during the summer is very extensive.

The typical stratigraphy in the dry snow of the Greenland ice cap is directly related to snow density, time, and climate. The seasonal deposition of snow can be determined with fair reliability in Greenland. Each annual bed consists of a zone of thin ice crusts representing summer thaw glaze and deposition underlain by a compact layer of winter snow free of ice glaze.

The thickness of the layers varies with depth. Near the surface annual beds are 6 to 10 feet in thickness. At 100 feet the annual layers are in the order of 6 inches to a foot in thickness. Below this the thickness of annual layers remains relatively constant. Temperature is also constant below this depth and is about $0^{\circ}F$ to $15^{\circ}F$ depending on the altitude of the surface of the ice cap.

The amount of contamination is well preserved in the snow and the percent by weight remains constant as depth increases, but the percent by volume rises greatly in the upper 100 feet because of compaction of the snow at depth. At 100 feet the ice approaches a density of 0.83 and is impermeable. Gas in the snow is trapped and compressed below this depth. At 800 feet the snow has a pressure of 20 Kg/cm^2 and the gas a pressure of 14 Kg/cm^2 which is equal to the tensile strength of ice. Below this depth core recovery from drilling is difficult or impossible and maintenance of open shafts and cuts requires considerable support. This condition becomes worse with depth. Drilling in the Greenland ice cap has been done to 1,438 feet and core has been recovered from 1,040 feet.

Significant stratigraphic zones (200 miles east of Thule) in the Greenland ice cap are:

97 feet - Annual layer with ash from 1912 Katmai eruption

150 feet - Annual layer with ash from 1883 Krakatoa eruption

9,000 feet - Zone of plasticity (?) which absorbs seismic waves.

ENGLACIAL WATER

Meltwater

Water in glaciers should be considered as an englacial substance, because of its abundance, its relationship to glacial processes, and its role in concentrating or dispersing contaminants. Water in the form of films in intergranular spaces, or percolating and flowing in ice cavities, is present in all glaciers during the melting season, except for some "high polar" glaciers. Some "temperate" glaciers, such as those in Iceland, are melting all or nearly all year, and many others contain bodies of water in cavities at depth during all or part of the winter period.

Heavy water

An excess of heavy water (D_2O) has been reported from Swedish glaciers (Sandström, 1951), amounting to 1 to 5 times the amount that occurs in ordinary subsoil water.

GASES

Analyses of gases in a "temperate" glacier in Sweden (Coachman, Hemmingsen, and Scholander, 1956) showed the following: 1) Gas pressure increased from atmospheric pressure near the firn line to three

atmospheres near the terminus. 2) There was no general loss of gas from the glacier; but 3) the oxygen content decreased down glacier. 4) The oxygen content varied from bubble to bubble, and the variation increased down glacier. 5) The oxygen loss occurred without an increase of carbon dioxide. The loss of oxygen is ascribed to chemical oxidation of dust within the individual bubbles. The gases are atmospheric gases, trapped during the formation of ice from snow.

Studies of the ratio of O^{18} to O^{16} in glacier ice indicate the O^{18} content of summer snow is higher than winter snow, but the oxygen isotope composition of the samples is not uniform, even within a single glacier. The samples from the Saskatchewan Glacier, Canada contained more O^{18} than the Malaspina Glacier, Alaska samples, and both contained more than samples from the Greenland ice cap (Epstein, 1956).

CONCLUSIONS

Analytical data on the quantitative aspects of englacial material are sparse, scattered, and, with rare exceptions, inconclusive.

The presence of a wide variety of englacial materials is known, especially locally derived rock debris, loess, volcanic ash, and saline substances. Organisms and organic substances are also known to occur in many glaciers.

The concentration of englacial materials can be only roughly estimated, on the basis of scattered analyses, and on glaciological data, climatology, and geography of the glacier.

The rate of addition of contaminants to glacier ice varies widely. Locally derived rock debris, loess, saline materials from the atmosphere, airborne micro-organisms, meteoric dust, atmospheric gases, and water will be added at a more or less regular rate, but varying in some cases throughout a single year, or from year to year depending on meteorological conditions. The addition of volcanic products and radioactive materials from bomb blasts naturally will be episodic.

The rate of concentration of contaminants also varies. Aside from factors resulting from long-term changes in the regime of the glacier, concentration depends on the relationship of the volume of material available to the volume of firn or ice added each year, the action of meltwater through the glacier, and the rate of wastage.

Large glaciers and ice fields in North America with relatively large concentrations of contaminants occur in Alaska and the Canadian Rockies. Glaciers and ice fields with low concentrations of contaminants include those on Baffin Island, Ellesmere Island, and Greenland. However, no glaciers will be free of airborne contaminants such as saline substances, meteoric dust, volcanic ash, and radioactive substances from bomb blasts.

For experimental purposes the Greenland ice cap and the ice fields of Ellesmere Island are the most suitable. In these the ice is a minimum of 1,000-5,000 feet thick and contamination is very low. Access to them, however, is difficult.

REFERENCES

Ahlmann, H. W., 1948, Glaciological research on the North Atlantic coasts: Royal Geog. Soc. Research ser. no. 1, 83 p.

Allen, C. R., and Smith, G. I., 1953, Seismic and gravity investigation on the Malaspina Glacier, Alaska: Am. Geophys. Union, Trans., v. 34, p. 755-760.

Baird, P. D., and Salt, D. J., 1949, Report on Expedition Snow Cornice [Yukon]: Natl. Research Council of Canada, Assoc. Committee Soil and Snow, Mechanics Tech. Memo. 14, p. 1-13.

Baird, P. D., Ward, W. H., and Orvig, S., 1952, The glaciological studies of the Baffin Island expedition, 1950, Pts. 1 and 2: Jour. Glaciology, v. 2, p. 2-23. London.

Baird, P. D., and other members of the expedition, 1953, Baffin Island expedition, 1953, a preliminary field report: Arctic, v. 6, p. 227-251. See p. 234-237.

Benninghoff, W. S., 1955, "Jökla mýs": Jour. of Glaciology, v. 2, p. 514-515.

_____, and Robbins, H. C., 1953, Botanical investigations, Operation Ice Cap: Department of the Army, Transportation Corps, Transportation Research and Development Command, Ft. Eustis, Va., p. 119-130.

Bordoni-Uffreduzzi, Guido, 1887, Biological investigation of ice and its relation to public hygiene: Centr. Bakterio. Parsitenk, v. 2, p. 489-497.

Coachman, L. K., Hemmingsen, E., and Scholander, P. F., 1956, Gas enclosures in a temperate glacier: Tellus, v. 8, p. 415-423.

Corps of Engineers, U. S. Army 1957, Greenland Ice Cap research program, Studies completed in 1954, 2 vols.

Epstein, Samuel, 1956, Variations in the O^{18}/O^{16} ratios of fresh waters and ice: In Nuclear processes in geologic settings, Rept. 19, Natl. Acad. Sci., Nat. Res. Council, Nuclear Sci.. Ser., July 31, 1956. NAS - NRC Publ. 400, p. 20-28.

Flint, R. F., 1957, Glacial and Pleistocene geology: 553 p., New York, John Wiley and Sons.

Fireman, E. L., and Schwarter, D., 1954, Measurement of the tritium concentration in natural waters by a diffusion cloud chamber: Physical Rev., v. 94, p. 385-388.

Glazovskaia, M. A., 1954, Eolian deposits on Tien Shan glaciers: Priroda, v. 43, p. 90-92. /Text in Russian/

Goldthwait, R. P., 1936, Seismic sounding on South Crillon and Klooch glaciers: Geogr. Jour., v. 87, p. 406-517. See p. 496.

Heusser, C. J., 1954, Palynology of the Taku glacier snow cover, Alaska and its significance in the determination of glacier regimen: Am. Jour. Sci., v. 252, p. 291-309.

Holtzscherer, Jean-Jacques, and Bauer, Albert, 1954, Contribution à la connaissance de l'inlandsis du Groenland: Expéditions Polaires Francaises, Résultats scientifiques, Paris, 56 pp.

Huber-Pestalozzi, G., 1926, Die Flora von Schnee und Eis, in Schroeter, C., Das Pflanzenleben der Alpen, Zürich, Albert Raustein, p. 942-949.

Kol, Erzsebet, 1934, Biology of the cryovegetation of the Valais Alps and the Mont Blanc Massif: Bulletin Soc. Botan. Geneve, Ser. 2, v. 25, p. 287-292.

Kol, Erzsebet, 1938, Biological research of the snowfields and glaciers of Alaska, 1936: Smithsonian Inst. Expl. and Fieldwork, 1938, Publ. 3525, p. 69-74.

_____, 1942, Snow and ice alga of Alaska: Smithsonian Misc. Coll., v. 101, no. 16, p. 1-36.

Kursteiner, J., 1923, The bacterial count of soil samples from high Alpine and snow regions: Jahrb. Schweiz. Alpenclub, v. 58, p. 210-226.

Lipp, H., 1932, Chemical composition of rime at Zugspitze: Jahresber. Sonnblick-Ver, v. 40, p. 27-32.

Miller, M. M., 1953, Juneau Ice Field Project, 1951 winter season, J.I.R.P. report no. 8, American Geographical Society, New York, 51 p.

Muller, E. H., and Coulter, H. W., 1957, The Knife Creek Glaciers of Katmai National Monument, Alaska: Jour. Glaciology, v. 3, p. 116-122.

Odishaw, Hugh, 1958, International Geophysical Year, a report on the United States program: Science, v. 127, no. 3290, p. 115-128.

Poulter, T. C., Allen, C. F., and Miller, S. W., 1949, Seismic measurements on the Taku Glacier in Geophysical Studies in the Antarctic, Appendix 3, p. 150-179, Stanford, Calif., Stanford Research Institute.

Sandström, A. E., 1951, On the concentration of heavy water in glacier ice: Arkiv för Fysik, Band 3, nr. 35, p. 549-556.

_____, and von Gegerfelt, Maud, 1945, Traces of iron in glacier ice: Arkiv Mat., Astron. och Fysik, Band 32B, nr. 6, 4 p.

Sharp, R. P., 1949, Studies of superglacial debris on valley glaciers: Am. Jour. Sci., v. 247, p. 289-315.

Steinbock, O., 1936, Cryoconite holes and their biological significance: Z. Gletscherkunde, v. 24, p. 1-21.

Tagantsev, V. N., and Zil'berminta, V. A., 1914, Desert weathering in a glacier area of the Turkestan Range: Izvestia, Ak. Nauk S.S.S.R., ser. 68, p. 1041-1052.

Ward, W. H., and Baird, P. D., 1954, A description of the Penny Ice Cap, its accumulation and ablation, Pt. 1 of Studies in glacier physics on the Penny Ice Cap, Baffin Island, 1953: Cambridge, England, Jour. Glaciology, v. 2, no. 15, p. 342-355.

Transportation Research and Development Command, U. S. Army, 1954, Final Report, Scientific Program, Operation Ice Cap 1953.

Wilson, L. R., 1955, Snow and ice residues: cryoconite: Project Mint Julep, Investigation of smooth ice areas of the Greenland Ice Cap, 1953, Part II, p. 94-100, Air University, Maxwell AFB, Alabama.

Zschokii, Fritz, 1928, Snow animals: Die Alpen, v. 4, p. 122-132.