THE

AMERICAN JOURNAL OF SCIENCE

[FIFTH SERIES.]

ART. XVIII.—*Observations on Ice-Borne Sediments by the Canadian and Other Arctic Expeditions*;[1] by E. M. KINDLE.

CONTENTS.

INTRODUCTION.

One of the incidental results of the explorations of the Canadian Arctic Expedition has been a very substantial increase in our knowledge of Arctic ice and its geologic work. The drift of the Karluk and the ice journeys of Stefansson, Storkerson, and other members of the Canadian Arctic Expedition have, taken together, given us a knowledge of a stretch of the Arctic sea extending from Banks island to Wrangel island, a distance of about 1,100 miles in an east-west direction. The tragic fate which befell five of the six members of the scientific staff of the Karluk and the loss of their extensive collections, when the vessel was crushed off Herald island, has limited the published data relating to this part of the C. A. E. to Captain Bartlett's story of the drift.[2] It contains references to various things of interest, such as "pebbles almost perfectly round and very smooth," which the dredge brought up from near the edge of the continental shelf, all of which returned to the sea bottom with the Karluk.

[1] The photographs used in this paper are published with the permission of the Director of the Canadian Geological Survey.

[2] Bartlett, Robt. and Hale, R. T., Last Voyage of the Karluk. Diary of Captain Bartlett, Department of Naval Service.

Stefansson's unique journey across the ice of the Beaufort sea made known an extensive area of previously uncharted Arctic seas on the western side of the Arctic archipelago. Stefansson staked his life on his theory that it was possible to live off the Arctic floes, and won. His ability to live off the life found on the ice enabled him to make important contributions to our knowledge of the Arctic ice pack and the oceanography of the Polar sea during his three months' expedition over the ice from Alaska to Banks island.

These have been published, however, under a title[3] not likely to catch the attention of geologists and the data of geologic interest in the volume needs to be brought into touch with comparable data from other sources.

Mr. Frits. Johansen, who accompanied Mr. Stefansson on the Beaufort sea ice journey to a point beyond the margin of the continental shelf, has kindly given the writer access to his journal containing many important observations on the extensive area of sea ice traversed in going from Martin Point, Alaska, across the continental shelf and back to Kamakok, Alaska. The writer is also indebted to Mr. Johansen for bringing to his attention certain Danish reports dealing with arctic ice.

The data relating to this subject recorded by various other expeditions will be included in this paper, which has been written from the viewpoint of sea ice as a distributor of sediments within the Polar basin and the North Atlantic.

Climate.

Most, if not all, of the Arctic sea and all of the immediately adjacent lands are characterized by the tundra climate,[4] not the climate of perpetual frost as is rather generally supposed. The difference between these two climates is highly important from the geologic viewpoint. A climate of perpetual ice and frost, such as that of the

[3] Stefansson, Vilhjalmur, The Friendly Arctic. Pp. xxxi, 784. Illustrations and maps. New York, 1922 (The Macmillan Co.).

[4] Ward, R. deC., A new classification of climates: Geogr. Rec., vol. 8, pl. II, 1920.

Köppen, W., Versuch einer Klassification der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt: Geogr. Zeitschr., vol. 6, pp. 593-611, 657-679, with pls. 6, 7; 1900.

interior of Greenland and the Antarctic icecap, completely checks the operation of the agencies of erosion throughout a geologic cycle while a tundra climate stimulates them throughout two months or more of active stream erosion each year. During the thawing season in a tundra climate land degradation proceeds at a rapid rate.

The dates given by Parry indicate that active land erosion by water is in progress at Melville island during the last week in May, and Stefansson's observation about the mouth of the Mackenzie shows the ice at the mouths of arctic rivers to open sometimes even in April.

The following figures permit comparison of the minimum winter temperatures of the arctic coast of Canada and three widely separated points in the Canadian northwest. The lowest temperature[5] recorded for the winter of 1915-1916 at three interior stations were

Fort Simpson,	lat. 61° 51′ N.	—48
Hay River,	lat. 60° 50′ N.	—45
Edmonton,	lat. 53° 33′ N.	—45

The minimum temperature at Bernard Harbour, Arctic coast of Canada in lat. 68° 47′ N. for the winter of 1915-1916 was —46,[6] or two degrees milder than the temperature at Fort Simpson, 550 miles to the south of Bernard Harbour. This is only 1° colder than the lowest temperature recorded for New England during a 30-year period preceding 1918 and the same as the lowest temperature observed in northern New York for the same period.[7] The comparison of arctic coast temperature records with those from the interior of arctic America makes evident the relatively mild character of the winter climate of the coast. The lowest temperature recorded at Point Barrow, arctic coast of Alaska, during a period of 5 years was —50°, while a temperature of —76° has been observed at Fort Yukon, 340 miles further south, where the temperature mean for the entire month of

[5] From Canadian Weather Bureau. See Geogr. Rev., vol. 10, p. 389, 1920.

[6] Johansen, F., Vegetation along the Arctic coast between Point Barrow and Bathurst Inlet. Can. Arctic Exped. Rept., vol. V, pt. C. (MS.).

Anderson, R. M., Recent Explorations on the Canadian Arctic coast, Amer. Geogr. Rev., vol. 4, p. 258, 1917.

[7] Memo. from U. S. Weather Bureau.

December, 1917, was nearly 49° below zero.[8] The minimum temperatures[9] recorded for the year 1900 at Herschel island at the mouth of the Mackenzie, McPherson 130 miles, and Good Hope 270 miles, south of Herschel, were respectively — 49.4°, — 60°, and — 62°, increasing in severity, it will be noted, from north to south as in the comparison between Point Barrow and Fort Yukon.

These figures hardly bear out Professor Chamberlin's view that the Smith Sound and Kane Basin region of Northwest Greenland is an area of relatively mild climate,—"an oasis in the frigid desert of the north."[10] The temperature records available appear to show that the Kane Basin region enjoys a climate milder, taking minimum temperatures as an index, than the interior of Arctic America and far milder than the interior of Arctic Siberia which is much further to the south, but not milder than the Arctic archipelago. At Anniversary Lodge at the edge of this "oasis" Peary[11] has recorded as late as March 21 a temperature of — 50°F. for the average of 34 hours with the estimated minimum for part of this period "certainly not higher than — 60°." With this may be compared the mean minimum temperature of 51.2°F. for three years[12] in King Oscar land. Minimum temperatures for other Arctic coast points already cited,—Bernard Harbour, Herschel island and Point Barrow,—are all below this northwestern Greenland record with the exception of the Point Barrow five-year minimum record of — 52°.

Stefansson's opinion that northeastern Montana has a winter climate "14° colder than the north coast of North America and 10° colder than the North Pole" will appear less improbable if it is understood that reference is made to minimum temperatures and if one remembers that latitude is only one factor, and often the least important one, in controlling temperature. It must not be inferred from this statement, however, that any point in

[8] Memo. U. S. Weather Bureau.

[9] Preble, E. A., North American Fauna, No. 27, p. 35, 1908.

[10] Chamberlin, T. C., A Veteran Climatic Fallacy, Jour. Geol., vol. 31, p. 188, 1923.

[11] Peary, R. E. (E. B. Baldwin), Northward over the Great Ice, vol. II, p. 190, 1898.

[12] Sverdrup, Otto (Herman G. Simmons), Summary of the Meteorological Observations: New Land, vol. II, pp. 484-494, 1904.

the northern part of the United States has a mean annual temperature even approximately as low as points on the Arctic coast generally show.

Captain Bartlett states that during the drift of the Karluk north of Point Barrow the days were frequently mild and springlike with temperatures above the freezing point late in September. On the 4th and 5th of October he records the weather as delightful with the temperature up in the forties. Bartlett records that not until December did the temperature reach the minus thirties. On November 10th the temperature was up to 23°F. and "almost like a spring day,"[13] although the sun left them for the winter on November 11th.

The temperature records of Captain W. E. Parry,[14] who wintered at Melville island a century ago, show the lowest temperature reached to have been 55° below zero, while northeastern Montana is credited with a minimum temperature of — 68°. Facts of this kind do not appear so surprising if, as it now appears, the cold pole of the world, where the mean winter temperature is — 48° in January, is located at Verkhoyansk, Siberia,[15] about 1,400 miles south of the North Pole. It became evident as far back as the fifties of the last century, when Dove's charts of the isotherms for the northern hemisphere were published, that the North Pole and the pole of maximum cold were probably separated by a considerable distance.

Baron von Wrangel records that at his winter quarters at Nishne Kolymsk the temperature rose in winter with north winds. Dr. Kane noted the same fact at Renssalaer Harbour in Kane Basin, North Greenland. The most interesting feature connected with Captain Parry's temperature observations is the reported rise of temperature with a north wind. On December 31st Parry records that, with a north wind changing to east, temperature rose from — 28° to + 5° at midnight.[16] Again with a light breeze from the northward the temperature rose

[13] Bartlett, Robt., Last Voyage of the Karluk, pp. 45, 49, 63.

[14] Parry, Sir W. E., Three Voyages for the Discovery of a northwest passage from the Atlantic to the Pacific and narrative of an attempt to reach the North Pole. Vol. 1, p. 169.

[15] Danckwortt, P. W., Sibirien und seine wirtschaftliche Zukunft: Ein Rückblick und Ausblick auf Hendel und Industrie Sibiriens (1921), Geogr. Review, vol. 13, p. 314, 1923.

[16] Parry, Sir W. E., Op. cit., vol. 1, p. 147.

from —55° in a. m. to — 34° at midnight. People who have wintered at Kola in Lapland state that a north wind always promptly causes a rise in temperature, thus supporting the theoretical deduction that the location of the North Pole in a deep ocean should give it a higher temperature than land areas south of it.

Hayes,[17] as early as 1858, argued for a relatively mild climate at the North Pole.

The relative climatic conditions in the Arctic archipelago and the upper Mackenzie valley may be inferred by comparing Captain Parry's records concerning early Spring in Melville island and McConnell's records made at Fort Simpson on the upper Mackenzie river. At Winter Harbour, Melville island, thawing began in the last three or four days of April in 1820.[18] At Fort Simpson, McConnell states that "on the 20th of April the temperature rose above freezing point for the first time in nearly six months."[19] A photograph taken by Mr. Johansen, of the Canadian Arctic Expedition, shows that on the 24th of May the snow was sufficiently melted to show patches of bare ground at Bernard Harbour on the Arctic coast of Canada. J. G. McMillan, who wintered on Melville island in 1909, notes[20] that "caterpillars were observed crawling about on the ground in sheltered places" a few days after May 10th. Stefansson states that a very light snowfall characterizes the Arctic islands and that 74% to 90% of the surface of Arctic lands is nearly free of snow at all seasons since the little that falls is swept into the lee of hills.

Concerning the summer climate of the far north we have, comparable with Stefansson's record of 90° in the "Arctic prairies" of northern Canada, statements such as the following from Sverdrup which refers to the summer weather in Ellesmereland, the most northerly island yet discovered:—"The sun now (July 3) burnt just as it does on the Norwegian mountains on a really hot summer

[17] Hayes, Isaac J., Observations on the practicability of reaching the North Pole, this Journal, vol. 26, p. 310, 1858.

[18] Parry, Sir W. E., Op. cit., vol. 1, p. 178.

[19] McConnell, R. G., Rept. of an exploration in the Yukon and Mackenzie Basins, N. W. T., Ann. Rept. Geol. Surv. Can., vol. 4, p. 86d, 1885-1889.

[20] Bernier, J. E., Report of the Dominion of Canada Government Expedition to the Arctic Islands and Hudson Strait on board the D. G. S. Arctic, p. 407, 1910.

day."[21] In northeastern Greenland near lat. 81, Peary[22] found bumblebees, butterflies, numerous flowers and a temperature at times "almost tropical."

On the Arctic coast of Canada the rivers open surprisingly early. The western mouth of the Mackenzie delta has opened at various dates between the 10th and 25th of April. Herschel Island river (Firth river) opens a little earlier.[23] On May 4th, 1912, the waters of the Firth river compelled Stefansson to make a detour five miles off shore to avoid them.[24]

Even in northeastern Greenland the Danmark expedition found the rivers breaking up in June and remaining open till September. In 1908 the breakup occurred June 18.[25] Dr. R. M. Anderson records that about ten species of plants were in bloom near his camp August 13, and that the "freeze-up" of the rivers south of Coronation Gulf occurred October 5 in 1915.[26]

The weather records of Dr. W. Brand[27] and various other Arctic expeditions support those cited in indicating a climate in which stream erosion is active throughout the summer.

Wind Transportation of Sediment to Sea Ice.

There can be no doubt that the work of the wind is a most important factor in moving the lighter products of erosion near arctic coasts on to the sea ice. The very light snowfall over some, if not all, of the islands in the arctic archipelago affords particularly favourable conditions for the wind transport of silt and fine gravel on to the ice even in winter. Leffingwell[28] reports having seen pebbles on near-shore sea ice which had been carried off the land by the wind.

Stefansson shows in the following statement[29] that at certain localities the air currents furnish exceptionally favourable conditions for the transport of sediments from

[21] Sverdrup, Otto, New Land, vol. I, p. 185.
[22] Peary, R. E., Op cit., vol. 1, pp. 334, 352.
[23] Stefansson, V., Personal communication.
[24] Stefansson, V., Personal communication.
[25] Trolle, Alf., Meddel. om Grön., vol. 41, pp. 392-393, 1913.
[26] Op. cit., p. 254.
[27] Brand, Dr. W., Meddel. om Grön., vol. 42.
[28] Prof. Paper, U. S. G. S. 109, 1909.
[29] Personal communication.

the land on to sea ice. "There are certain localities in the Arctic where there are terrific offshore winds. One such place is described in "My Life with the Eskimo." It is between Horton River and Langton Bay where there are cliffs from 500 to 1000 feet high. These elevations are reached anywhere from a few hundred yards to three miles inland. This is really the escarpment of a plateau. When you are coming from the interior in winter and are about ten miles from the sea-coast, you begin to notice light airs blowing at your back. The closer you come to the edge of the plateau the stronger the wind, and when you finally begin the descent it is blowing a gale of fifty to seventy-five miles an hour. This terrific wind keeps that velocity for a mile or two out on the ice, when it begins to slacken, and ten miles away from the coast there will be a calm again. I have thought that the wind was like a great Niagara of cold air, pouring over the edge of the plateau into the vacuum created by upward currents of air from the comparatively warm water of Franklin Bay. What we are interested in here is that the strong wind carried sand and gravel far out on the sea ice. Roughly circular pieces of slate as much as two or three inches in diameter are sometimes found spinning along like cartwheels out on the ice a mile or two away from land. As I remember it, I have found some of them as much as three miles out on the ice. Some of the water of Franklin Bay (Arctic coast of Canada) is deep inshore. It is likely, therefore, that each year a considerable quantity of this sand and gravel will float away on the surface of the ice cakes, possibly to a great distance from land."

Peary has given the following significant description of the winds which descend from the inland ice of Greenland: "The vicious but fortunately short-lived fury of the 'Great Winds' of Northern Greenland is astonishing. A sudden local tilting of the atmospheric balance, perhaps its own accumulated weight, starts a section of the cold heavy air of the interior ice-cap towards the nearest point of the coast. Gravity constantly accelerates its motion as it moves down the incline of the ice-cap, till at last it plunges, a roaring snow-laden torrent, down the steep landward slopes of the ice, and falling into the deep bays or fjords is compressed between their precipitous and frequently converging cliffs, and goes screaming and hiss-

ing to the open sea, a huge air-jet under a pressure capable of moving all but the heaviest objects, and comparable in its effects to the destructive water-jet from the monitors of Western hydraulic mining.''[30]

On one occasion Baldwin,[31] meteorologist of Peary's '93-'94 expedition, recorded an average wind velocity of 48.1 miles per hour for a period of 33¾ hours.

Captain Bernier[32] states that ''High winds carry across the country sand, gravel and soil, some of which, in the passage, lodges upon the surface of the ice and is covered in the ice-forming periods by new ice from rain or melting snow and the water from the sea. Polar icebergs are formed in this way and may be forty or fifty feet thick. They differ from glacier icebergs in appearance and weight with less of confined air, and, therefore, sink deeper in the water in comparison.''

On the northwest coast of Greenland the writer has seen a heavy fishing dory drawn up on the rocky shore broken beyond repair by being rolled, like a straw hat, over and over by a late summer gale.

No one who is familiar with the ''Great Winds'' of Northwestern Greenland is likely to question the important rôle which they play in transporting to the sea ice any light fragmental material sand or dust which happens to lie in their path. In many localities the sea ice remains packed against the shore till midsummer when the snow has completely disappeared, giving the wind a long period in which to sweep sand and dust on to it. Johansen[33] records that the ice remained at Collinson Point, Arctic coast, till July 20, 1914.

Relative Efficiency of Marine and Non-Marine Ice in Transporting Sediments.

Salt and fresh-water ice possess markedly different physical characters which make the former a more efficient carrier of sediments than the latter. They differ ''as much as statuary marble does from crystal'' accord-

[30] Peary, R. E., Northward over the ''Great Ice'': vol II, footnote, p. 238.
[31] See Peary, Op. cit., p. 189.
[32] Bernier, J. E., Report of the Dominion of Canada Government Expedition to the Northern Waters and Arctic Archipelago of the D. G. S. Arctic, p. 28, 1910.
[33] Ms. Journal.

ing to one author. Fresh-water ice, when it thaws in the spring, behaves in a manner fundamentally different from salt-water ice. It divides into separate needle-like crystals with little cohesion which causes masses of it to crumble readily and makes the crossing of lake and river ice in late spring hazardous when the ice is two feet thick. "Salt-water ice, when it thaws, never disintegrates into separate crystals."

A striking example of the amazing rapidity with which fresh-water ice disintegrates has been recorded by J. G. Totten,[34] who described in detail the complete disappearance in a single night of an ice sheet, one foot or more thick, covering practically the whole of Lake Champlain. On the arctic coast of Canada, Johansen[35] has noted the speedy disappearance of ice in a large lake. The writer has observed in Great Slave Lake the nearly complete disappearance of extensive fields of very thick ice in the course of a couple of days. When the prismatic structure has developed to the proper stage the agitation of the water and consequent friction of adjacent ice cakes incident to a moderate breeze is sufficient to detach the feebly united vertical prismatic crystals and cause them to fall asunder. Then the vastly greater surface exposed to the sun and water causes them to quickly melt. Sea ice, on the other hand, may travel for hundreds of miles from its place of origin and in parts of the Arctic seas probably survive the heat of many summers.

It may be seen from these facts that lake and river ice is not capable of carrying sediment for any considerable distance, although it moves great quantities of sediments short distances. Compared with sea ice it is an inefficient agent in the transportation of sediments. Glacier or snow-made ice, because of the great bulk of its sea-borne masses, is a very efficient type of ice in the dispersal of sediments.

The physical peculiarities of sea ice which result in making it an efficient long-lived carrier of sediments have been well described in some detail by Dr. Kane[36] and by Captain Scott.[37]

[34] Totten, J. G., On the sudden disappearance of the ice of our northern lakes in the spring, this Journal, vol. 28, pp. 359-364, 1859.

[35] Johansen, F., Rept. Can. Arctic Exped., vol. VII, pt. N. p. 11, 1922.

[36] Kane, Elisha K., The First United States Grinnell Expedition in search of Sir John Franklin, Philadelphia, 1857.

[37] Scott, Robt. F., Voyage of the Discovery, vol. II, p. 458.

Lieutenant J. M. Wordie[38] has prepared a good brief discussion of sea ice nomenclature which could be used advantageously by authors who have observations on sea ice to record.

The characteristics which make sea ice a dependable source of fresh water to explorers travelling over the floes are pointed out in Stefansson's description of it.

"It is a fact not generally understood," he writes, "that old salt-water ice is always fresh. When ice forms in the fall it is as salty as the water out of which it is made, and if you take a chunk of it and melt it you get brine unfit for the ordinary uses of water. The ice remains salty all winter, but the following spring, as soon as the warm weather comes, it begins to freshen enough for use in tea-making or other cooking by the end of the summer. But the lagoon ice, which has never been over six feet thick to begin with, thins down to a few inches by July and cakes of it are perfectly fresh by that time, as we abundantly proved at Oliktok."[39] Stefansson found the water between the ice cakes in Beaufort sea frequently fresh enough to drink and estimates that 12 or 15 feet of fresh water often overlaid the salt water in some of the ice fields.

Storkerson records that the seals which he shot frequently sank 10 feet or more through this fresh water and remained floating near the contact line between it and salt water.[40] Stefansson also at times failed to secure the seals killed, as a result of this tendency.[41]

Alf Trolle,[42] of the Danmark expedition, has shown a distinct connection between increase in the surface salinity and the increasing thickness of the ice in the course of the winter. He has recorded a large number of observations on the salinity and temperature of the sea between the east coast of Greenland and the Faroes islands. They show that "both surface temperature and salinity increase greatly from the ice edge out towards the Atlantic water."

[38] Shackleton, Sir Ernest, South: The story of the 1914-1917 Expedition, pp. 344-347, 1919.

[39] Stefansson, V., My Life with the Eskimo, pp. 115, 116.

[40] Storkerson, S. T., Appendix to The Friendly Arctic, p. 697.

[41] Stefansson, V., The Friendly Arctic, p. 196.

[42] Trolle, Alf., Hydrographical observations from the Danmark expedition. Meddel. om Grönland, vol. **41**, pp. 311, 392, 1913.

Ground Ice.

The puzzling but common phenomenon known as fossil or ground ice, which is a common feature of the Alaskan coastal plane, has been described by various authors. The entire literature relating to the subject of ground ice has been summarized by Leffingwell,[43] who has studied this type of ice more exhaustively than any one else. During his earlier work along the Arctic coast Stefansson made some observations on ground ice and explained many of these occurrences as due to the landward thrust of sea ice under wind pressure. "Under such conditions tongues of ice may slip up on the beach and be shoved inland two or three hundred feet beyond the limit of high tide and thirty or forty feet above sea level. (See figs. 1 and 2.) This is a common phenomenon. A rather less common one, but by no means rare, is that the tongue of ice is stabbed like a dagger into the ground. When the ice thaws the following summer and drifts away to seaward, these daggers are broken off in the wound, as it were, and left behind, covered with more or less earth according to the circumstances of the case. I have seen this happen on the gravel beach between Cape Smyth and Point Barrow and on the first sandspit east of Pitt Point."[44]

It is probable that ground ice may, at times, become a minor factor in the transportation of sediments through the undercutting of sea cliffs or river banks in which it occurs.

Floe and Berg Ice.

Any ice made from salt water is called floe ice, while berg ice is derived from glaciers and is the product of consolidated snow. In Baffin Bay floe ice has ordinarily a thickness of only 5 or 6 feet, according to Lieut. Greely. Direct freezing probably seldom, if ever, produces ice more than 8 or 10 feet thick on the Polar sea.[45] Most of the "big ice" or "palaeocrystic ice" of the Arctic floes, which may be 50 feet or more in thickness, results from the telescoping or "under-running" of one ice field by

[43] Leffingwell, Ernest de K., The Canning River Region, Northern Alaska, U. S. Geol. Survey, Prof. Paper 109, pp. 179-243, 1909.

[44] My Life with the Eskimo, p. 384.

[45] Peary, Robt. E., The North Pole, p. 195-196.

another. The thickest floes under-run the lighter ice and huge masses are piled up near the contact which freeze together into a mass often many times the thickness of either of the colliding floes.

Mikkelsen and Leffingwell[46] were pioneers in the exploration of the ice floes north of Alaska by travel over the sea ice. Their relatively short journey over the "big ice" of the whalers accomplished the very important result of locating the edge of the continental shelf with its soft, blue mud within forty miles of the coast, in addition to recording the salient features of the ice floes north of Flaxman island. These included pressure ridges 25 feet high, the "old ice" with hills 30 feet high, and rubble ice of extraordinary roughness. One of Mikkelsen's photographs shows a mass of floe ice thrust ashore which is 25 feet thick.

Stefansson's long expeditions over the sea ice gave him unprecedented opportunities for seeing all phases of its work and behaviour. His 700-mile journey with two companions over the ice of Beaufort sea to Banks island occupied 93 days and is without a parallel in the annals of arctic exploration.[47]

Although written from the autobiographic rather than the scientific viewpoint, geologists interested in the transportation of sediments by ice will find many illuminating passages scattered through "The Friendly Arctic." Most of the books on Arctic exploration make few or no references to the land-derived sediments on sea ice unless the author's attention has been called to them by some unusual incident such as MacMillan[48] relates, when he mistook patches of dirt-covered ice in Smith Sound, which he was passing in a blizzard, for sleeping men and dogs and tried to waken them by yelling at them.

[46] Mikkelsen, Ejnar, Conquering the Arctic Ice, p. 261, 437-440, 1909.

[47] *Note:*—The unique feature of Stefansson's ice journey to Banks island lay, not in the hazards of the over-ice journey, but in the dependence of the expedition on the theory that large mammals would be found far from land in numbers adequate for its food supply. Aside from starvation the hazards of sea-ice travel are not so great as generally supposed, provided it is done under competent direction. This conclusion is justified by the record of 1830 when 22 whaling ships were crushed in the Baffin Bay ice floes (Macmillan, Four Years in the White North, p. 16). Out of the thousand men representing the crews of these ships all but two, who died from the effects of liquor, reached the Danish settlements of Greenland in safety.

[48] MacMillan, Donald, Four Years in the White North, p. 285, 1918.

Stefansson has taken pains to record such observations. In spite of the reassuring title of his book, most geologists will prefer getting this kind of data second-hand from Stefansson to experiencing themslves the terrific phenomenon of the "grinding" of the ice-packs when heavy floes moving in opposite directions meet. "Then," Stefansson writes, "the rending and tearing and crushing of the floes was almost deafening, and pieces of ice larger than an ordinary house would be tumbled about like corks in the water. Ridges thirty feet high and more would be formed in one moment, and tumble back into the sea the next as the pressure from the moving field was abated. Huge pieces are then torn rapidly off the edges of both floes if they are of similar thickness, or off the edge of the weaker. If you happen to be camped on the weaker it behooves you to move quickly. Pieces of your floe the size of a city lot will rise on edge and tumble towards you, and the ice around camp will begin to groan and buckle and bend."

Bartlett[49] describes severe shocks like those of an earthquake which accompany the formation of these ridges and states that in one instance a crack two or three feet wide, resulting from one of these, opened inside one of the igloos of his party.

Scoresby has calculated that one of the immense ice fields which he mentions is capable of delivering a blow or shove equal to 10,000,000,000 tons. When it piles against a shore cliff 80 feet high, as a member of the Karluk crew reports, its efficiency in rock abrasion is evident. The ability of ice floes to scour the bottom and transport material in shallow arctic seas when driven by currents or the wind is comparable with that of glaciers. The former, it must be remembered, may move at one to two miles an hour during and shortly after gales, while the latter move only a few feet per annum. Concerning sea ice movement Stefansson states,[50] "I am inclined to think that the movements of ice a hundred miles away from land average less than a mile per day. I have never tabulated my various observations to get an average, but I have made a rough estimate of half a mile per day for the movements of ice distant from land."

[49] Bartlett, Robt. and Hale, R. T., Last Voyage of the Karluk, p. 148.
[50] Personal communication.

When the land-fast ice, which is often forty or fifty miles wide between islands, lifts off the bottom under the influence of a gale as it did during the early stages of one of Stefansson's journeys,[51] it may carry with it vast quantities of bottom and shore materials which are widely distributed over the sea bottom. From the standpoint of sediment transportation the sea ice, which is in winter attached to the shore, is of primary interest. Its width varies greatly as the following statement from Stefansson indicates:[52] "The so-called floe or line of usual fracture where in a hard gale the sea ice separates from the land ice, is, in an average year, between one and three miles away from the Alaskan coast, at Cape Smythe. East of Point Barrow to Barter island the floe in average weather is anything from three miles to eight or ten miles northwest of the island. On the whole coast just described an exceptional gale accompanied by a considerable rise of tide may break off the ice within half a mile of the coast in many places. From Herschel island to Cape Brown special conditions prevail. This is the great Mackenzie delta with shoals extending far to sea. There is no white man or Eskimo, so far as I know, who can give any reliable information about the location of the floe in this district. From Cape Brown to Cape Bathurst there are many bays, and the location of the floe varies accordingly. At Cape Bathurst it is usually between a mile and three miles from land. At Cape Parry it is anything from a few hundred yards to a mile or two, and the same applies at Cape Lyon and east beyond Pierce Point—where the strait begins to narrow so that the floe runs across towards Victoria island. Both just north and just south of Prince Albert Sound, Victoria island, the floe may come almost up to the land and is seldom more than four or five miles to seaward. It curves then up into the Prince of Wales Straits. On Banks island the floe is in my experience likely to be about a mile away from the coast at De Salis bay. None has been seen at Nelson Head, the ice breaking off flush against the cliff. As you proceed up the southwest coast of Banks island, the floe becomes wider, but in the bight east of Cape Kellett it is seldom as much as five miles from land, and more likely

[51] The Friendly Arctic, p. 151.
[52] Personal communication.

three miles. Beyond Cape Kellett the landfast ice along the west coast is from five to twelve miles wide, the distance being measured from the sandbars and islands rather than from the mainland coast. Turning east around the northeast coast of Banks island, the floe again comes right up to the land until beyond the middle of the north coast, when it widens again. Up to Christmas the floe will be from five to fifteen miles away from the land as far east as Mercy Bay or even beyond. But in most years the ice in McClure Straits sets fast after midwinter, so that in March the floe ordinarily runs in a curve across from the north tip of Banks island to the south tip of Prince Patrick island. No one has observed the floe along the south and southwest of Prince Patrick island, but from Land's End eastward it is from five to ten miles wide. We cannot say, however, whether this depends on local shoals that hold it by coming nearly or quite out of the water or whether it is the sea ice resting on a shallow bottom, as is the case north of Alaska. From this point on the floe is so irregular that I do not care to generalize from memory. At no place do I think it extends to more than ten miles in width. There are capes where it comes close to the land."

The excavating power of the floe ice and the varied character of the débris picked up by it when driven ashore by the wind are shown by figs. 1 and 2. Koch, who has observed this phenomenon in northeastern Greenland, writes that "The force with which the wind crushes the ice against the shore is very impressive. I have, in one case, seen how the fjord ice, during a summer blizzard, was crushed a long distance in across the land, while at the same time pushing a wall of pebbles and gravel before it."[53]

Johansen[54] describes a case in which he observed the ice floe driven ashore July 2, 1914, at Camden Bay, Alaska. "First some ice was screwed up close to the beach here and there; then came an immense and continuous pressing of the ice from far off-shore onto the beach. Like the movement of a glacier the whole body of sea ice moved eastwards; without regard for shallow water the coastal ice was pressed up on the beach and during this slow but

[53] Koch, I. P., Meddel. om Grönland, vol. 46, p. 422, fig. 107, 1917.
[54] Johansen, F., Ms. Journal, pp. 87-88.

FIG. 1.

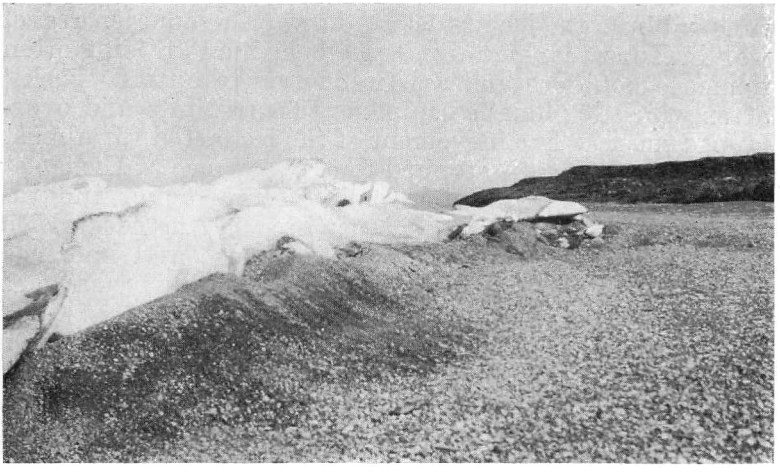

FIG. 1. Ice pack digging into the beach under wind pressure. Arctic coast, Alaska. Photograph by F. Johansen.

FIG. 2.

FIG. 2. Shore debris picked up by floe ice when driven ashore. Arctic coast, Alaska. Photograph by F. Johansen, July, 1914.

continuous movement the ice ploughed down in the sand where this was the beach material and on the coast of tundra-bluffs the ice first shoved away the boulder gravel wall in front, tearing it up, going over it and raising often immense boulders and driftwood trunks on its "back" after which it ploughed into the tundra-bluffs and overlapped these. The movement of the ice lasted for almost an hour and when it stopped the appearance of the coast was quite changed. Some parts of the higher tundra-bluffs had their seaward side covered by the coastal ice stretching to the upper margin of these and immense blocks of ice, boulders or tree trunks from the beach were raised and pushed still further in on the tundra."

Concerning 1923 ice conditions on the Arctic coast of Alaska, Sidney Paige writes (personal communication), "Before July 25 the pack was close against the shore from Icy Cape to Point Barrow. After that date the ice went out to stay until late in the fall."

The bottom load of the floe ice is never seen from the surface except through the overturning of the cakes in pressure ridges or rafters, as they are sometimes called. Ice masses of considerable thickness are developed in these ridges. One, which was measured by Stefansson, rose 78 feet above the water level. This is more than twice the maximum height given by Nansen for such ridges, but Stefansson quotes still larger figures from other observers of the ice north of Beaufort sea. The enormous size of the pressure ridges reported by Stefansson in the Beaufort sea is equalled by "a huge rafter from 25 to 100 feet high and about three miles wide" which the shipwrecked Karluk party encountered north of Herschel island.[55] Johansen crossed a number of these in his trip to the northern edge of the continental shelf in Beaufort sea. He states that seven hours were required to cover ¼-mile in crossing the rough ice of one pressure ridge. Much "dirty ice" was seen in some of these pressure ridges, and mud was collected from a cake of ice 20 miles north of the Canadian-Alaskan boundary. Near shore only smooth ice was found.[56]

[55] Bartlett, Robt. A., Diary of Bartlett, Rept. of the Dept. of Naval Service, Canada, p. 48, 1915. Bartlett and Hale, The Last Voyage of the Karluk, p. 150.

[56] Johansen, F., Ms. Journal.

The absence of a definite current to remove the ice from Beaufort sea which remains unthawed at the end of the summer has been suggested as a reason for the conditions which produce "palaeocrystic" or old ice and the greatly thickened beds resulting from overthrust pressures which are of exceptional thickness in the region west of Banks island and Melville island. Leffingwell names twenty years as the least time in which "old ice" can be formed. McClure believed that the age of some of it ran into centuries. The enormous thickness of some of this old ice is indicated by Stockton's record of a "very large, hummocky floe, at least 10 miles in length, several miles in breadth, and aground in 80 feet of water,"[57] off Cross island on the Alaskan coast. The modifications which such masses of very thick ice moving before a gale can produce in soft bottom deposits are obviously prodigious.

Captain Hooper[58] found the ice aground at Herald island, Wrangel island, and Cape North in Siberia in about 10 fathoms. McClure[59] generally found the ice aground in 6 or 8 fathoms around the north coast of Alaska. Lieutenant Stockton's hydrographic survey of the anchorage near Point Barrow "demonstrated that the contour of the bottom is constantly changed by the plowing and planing done by the heavy ice grounded and driven up by the pressure of the mighty ice-pack, under the influence of northerly winds and gales."[60]

While the plowing or excavating work of ice is limited to shallow water the transportation of sediments is coextensive with the distribution of floe ice. The rivers are important factors in furnishing sediment to sea ice. Koch's account of the spring break-up of the rivers in northeastern Greenland makes it clear that much debris from the land must be carried on to the sea ice at this time. He states that "During the latter half of June the rivers break up and send a flood of water out across the ice, and soon there is in front of every river mouth a

[57] Stockton, C. H., Arctic Cruise of the U. S. S. Thetis: Nat. Geog. Mag., vol. 2, p. 185, 1890.

[58] Hooper, C. L., Rept. of the Cruise of the U. S. Revenue Steamer Thos. Corwin in the Arctic Ocean, 1881. 48th Cong. Ex. Doc., No. 204, p. 128, 1884.

[59] Osborn, Sherard, The Discovery of the Northwest Passage, p. 71, 1857.

[60] Stockton, C. H., Natl. Geog. Mag., vol. 2, p. 182, 1891.

smaller or larger lake with quite open water, which quickly spreads over larger areas.''[61]

MacMillan noted that at Melville island ''the streams began discharging in great volume upon the shore ice,''[62] in early spring.

Johansen has noted a rather novel feature in connection with sea ice which is still attached to, or in contact with, the shores. In the more or less landlocked areas like Dolphin and Union strait, where his observations were made July 1, 1915, ''the sea ice in early summer was full of channels and pools with melting water, often in connection with a crack or seal-hole and thus with the sea water below. The tide was falling when I was out, and the water streamed along in the channels on top of the ice, until a hole in the ice was reached, where the water in a violent whirl rushed down, increasing the size of the hole.

The mixture of the warmer tide-water and melting water rushing down into the hole probably is responsible for the great variation in the temperature measured (around 0° C.).''[63]

It is evident that in the shallow coastal waters where this type of down-rushing current was observed either pot-like holes or shallow trenches would be likely to develop as a result in soft bottom deposits.

In Beaufort sea, Stefansson states that ''Ice with a certain amount of earth or gravel upon it and sometimes fragments of rock or small boulders'' was found on all the ice trips ''at every distance from shore'' (p. 514, The Friendly Arctic). A gravel, mud and boulder ridge 18 paces long and 5 feet high was seen at one point on the floe ice. ''This and other similar mud heaps found by us on the ice in the vicinity probably show that the general current in Beaufort sea probably takes a circuitous route and thus around the polar basin, eventually to melt in the Gulf Stream north of Iceland and Norway, which seems to be the fate of most of the old polar ice.''[64]

The drift of the ill-fated Karluk, the Jeannette, Fram,

[61] Koch, I. P., Survey of Northeastern Greenland: Meddel. om Grönland, vol. 46, p. 418, 1917.

[62] Report of the Dominion of Canada Government Expedition to the Arctic Islands and Hudson Strait on board the D. G. S. Arctic, p. 407, 1910.

[63] Johansen, F., Ms. Journal.

[64] In a footnote, p. 185, Stefansson has stated briefly his views concerning the different directions in which currents move in Beaufort sea and westward.

and other vessels beset off the Alaskan and Siberian coasts appear to support his inference of a westerly drift, although Storkerson's remarkable journey over the ice floes north of Alaska seems to indicate areas where the westerly movement is wanting or negligible. Storkerson, after spending 238 days on the ice floes north of Beechey Point, Alaska, reports that "We discovered that no permanent current exists in the Beaufort sea between the North latitudes 72.5° and 74°. All drifts of ice in that territory have been proven by our astronomical observations and our meteorological records to be governed by the wind exclusively. So far as we could judge we could have lived on the ice eight years as easily as eight months." Storkerson's ice journey, which took him north from his starting point on the Alaskan coast approximately 225 miles without notable east or west drift beyond zigzags due to shifting winds, strongly supports his contention, at least for the particular region and season represented by his traverse. There can, however, be little question, in view of all the evidence, that the prevailing direction of coastwise currents north of Alaska *near* the coast is westward. "There is usually a movement of the ice south along the west coast of Prince Patrick and Banks island and west along the north coast of Alaska. This westerly drift is probably not very noticeable except during or after great storms."[65] The westward trend of such sand spits as Demarcation and Collinson Point and the one at the west end of Flaxman island affords even more convincing evidence of this to the writer than the western drift of the Karluk or the case of the umiaks caught in the ice off Cape Smythe which reached Cape Lisbourne, 230 miles to the southwest, five weeks later.[66]

The 2,500 mile drift of the oaken cask which was placed on floe ice northwest of Point Barrow, Alaska, and picked up 5½ years later on the north coast of Iceland is perhaps the most convincing experiment yet recorded concerning the westerly drift in the Arctic basin west of Beaufort sea.[67]

Mikkelsen gives the following summary of his observa-

[65] Personal communication from V. Stefansson.

[66] Stefansson, V., Am. Geogr. Soc., vol. 42, p. 460, 1910.

[67] Bryant, H. G. Some results from the drift cask experiment in the Arctic ocean: Bull. Am. Geogr. Soc., vol. 38, pp. 105-107, 1906.

tions on the movement of the ice north of Alaska. "The set of the ice in Beaufort sea is very puzzling, and we could not arrive at a satisfactory explanation of it. With calm or an easterly wind the ice would open up, long and broad lanes would appear, and the ice would drift westward at a rate of almost ten miles in twenty-four hours. When the conditions were reversed and the wind was west we found that all lanes closed up and that the ice was exposed to very severe pressure, but the drift to the east was very small and generally nil, even when a west wind was blowing at a rate of twenty to twenty-five miles an hour. In the spring of the year there is a permanent and strong westerly set to the north of Alaska, but all the whalers agree that in the summertime an easterly set is predominant close to the land."[68] This near-shore easterly set of the summer season was noted by McClintock.[69]

Both the sediment carried by ice from the Arctic archipelago and its eastward movement through the various straits of the archipelago have been noted in the following passage by Captain Bernier,[70] who has had a long experience of Arctic waters. "The ice of all kinds, from ice that had formed the previous winter to ice showing several years of growth, was at the time being discharged from every channel on its way eastward. This great discharge occurs in cycles of years. Old ice is known by the discoloration caused by soil or sand which marks the years of accumulation."

Markham[71] and various other Arctic explorers have called attention to the mud and other land-derived sediments which the sea ice carries. Greely[72] has figured a flat topped berg 900 feet long with two moraines across the top.

The 1000-mile ice drift of Dr. Kane's[73] ship from Wellington channel through Barrow strait eastward through Lancaster sound, then southward down the Baf-

[68] Mikkelsen, Ejnar, Conquering the Arctic Ice, p. 438.

[69] McClintock, Capt., Narrative of the Discovery of the Fate of Sir John Franklin and His Company, p. 72, 1868.

[70] Bernier, J. E., Report of the Dominion of Canada Government Expedition to the Northern Waters and Arctic Archipelago of the D. G. S. Arctic, p. 28, 1910.

[71] Markham, Albert Hastings, The Great Frozen North, p. 339, 1878.

[72] Greely, A. W., Three Years of Arctic Service, vol. II, p. 53, 1886.

[73] Kane, Elisha K., Arctic Explorations: The First United States Grinnell Expedition in search of Sir John Franklin. Philadelphia, 1857.

fin Land coast to latitude 66°, longitude 58°, has furnished more definite information than any other Arctic expedition concerning the currents in the northeastern part of the Arctic archipelago. Kane recognized, on the opposite side of Baffin Bay, a current trending in the opposite direction up the west coast of Greenland. Tarr[74] has called attention to the relatively mild climate on the Greenland side which is doubtless the result of this current. Dr. Kane speaks of the great ice pack which occupies the middle area of Baffin Bay, lying in the eddy between the north flowing current on the east and the south flowing current on the west side of the bay. The great majority of the west Greenland ice is eventually carried south, it would appear, by the Labrador current and the bergs deposit much of their débris in the Grand Banks region east and southeast of Newfoundland. Here they meet the Gulf Stream where a ship's length may give a temperature contrast of 22°. Concerning the effect of grounded bergs in altering the bottom Kane wrote as follows:—"The berg is beyond all doubt a most important agent in modifying the soundings upon the coast. The grounded bergs off Disco are known to leave troughs, plowed by their projecting tongues, as they float and ground with the rise and fall of the tides. Where the bottom is of mud and till, as is the case on the west coast generally, this action must be very marked; for on a berg I surveyed trigonometrically in July, which had grounded in soundings of five hundred and twenty feet, the great tap root that anchored it to the bottom admitted of an easy rotation, and the berg swung upon its axis with each change of the tide."[75]

Kane's extraordinary opportunities for observing the part played by bergs as bearers of rocks and sediment were well improved during the months his ship was drifting through the Baffin Bay ice floes. He speaks of bergs studded all over with angular or rounded rocks and the depressions filled with a detrital paste resembling till. "Of nearly five thousand bergs which I have seen, there was, perhaps, not one that did not contain fragmentary

[74] Tarr, R. S., Difference in the climate of the Greenland and American sides of Davis and Baffin's Bay, this Journal, vol. 3, pp. 315-321, 1897.

[75] Kane, Elisha K., Arctic Explorations, this Journal, vol. 24, p. 242, Sept., 1857.

rock. A walk over the berg would disclose them, either clinging partially imbedded in their slopes, or in the form of pebbles and still smaller fragments, penetrating in cylindrical cavities deep into the substance of the berg.''[76] Kane figured and described (pp. 454, 455), but was unable to explain, some very curious bergs which were marked all over with circular depressions ten inches or a foot in diameter and nearly in contact.

R. W. Coppinger[77] has described from the floes of the Kane Basin region, old floe ice of similar character in which the circular pits contained snow and some dark powder. The presence in the depressions of dark-colored powder indicates them to be the product of differential surface melting which any dark body is apt to induce on ice. The Swiss Greenland expedition[78] found similar cylindrical tubes or dust wells covering in places a quarter of the surface of the Jakobshavn glacier.

Some of the peculiar bergs and floe ice described by Kane and Coppinger may represent the sikosak of the Danish geologists. Koch states that ''On long stretches of Northeast Greenland, between the parallels 78° and 82°, the inland ice does not form icebergs, but spreads itself beyond the sea and gradually loses itself in the fjord ice. The deep layer of snow contributes towards making the transition between the inland ice and sea ice so imperceptible, that on long stretches it is often impossible to know whether one finds oneself on glacier ice or on sea ice. Very large portions of this continuous glacier ice float in the sea and therefore partake of the rise and fall of the tide.''[79] The conditions essential to the formation of the sikosak are described as follows: ''Where the fjord ice remains throughout the summer and thus becomes perennial, the first condition for the formation of the sikosak—i. e. ice on the sea formed on the spot, simply by the fall of snow—is present.

[76] Kane, Elisha K., The U. S. Grinnell Expedition in Search of Sir John Franklin, p. 457, 1854.

[77] Nares, G. S., Narrative of a voyage to the Polar Sea, vol. II, p. 347, 1878.

[78] Brooks, Chas. F., Physiography and Glaciology of Middle West Greenland. Abstract of part of results of Swiss Greenland Expedition, Review, Jour. Geol., vol. 31, pp. 436-438, 1923.

[79] Koch, I. P., Survey of Northeast Greenland: Meddel. om Grönland, vol. 46, pp. 406, 407, 1917.

When the weight of the deposited snow has pressed the fjord ice down to a certain depth, presumably about a couple of metres, the latter cannot, even during the hardest winter season, increase downward by freezing, and in case the ice is weighed further down, melting will take place throughout the year on the under surface. The original fjord ice, formed by the freezing of the sea water, must consequently melt off, and that which remains is entirely due to the fall of snow."[80]

In the Cape York district sikosak occurs according to the descriptions of Freuchen and their interpretation by Koch[81] who writes:

"From a letter from Freuchen I learn that the formation of the sikosak is a well-known phenomenon among the Eskimos in the fjords of the Cape York district. Here fjords may be met with into which no glaciers debouch, but which are nevertheless filled with a glacier having a well-developed system of crevasses. The Cape York Eskimos know that glaciers of this kind do not continue to exist, but that after an interval of many years they disintegrate and go adrift, but only to form again in the years to come."

Lauge Koch[82] states that the greater part of the bergs of West Greenland originate from only a few glaciers but these are exceedingly productive. The most productive glaciers are near lat. 69 N.

The writer's observations on the margin of the Greenland ice cap north of the Cornell glacier in lat. 74° 15′ have convinced him of the correctness of Kane's estimate of the importance of the bergs as transporters of rock. North of the margin of this glacier the inland ice is in places separated from the land by small lakes with vertical ice cliffs 60 or 70 feet high from which miniature bergs are calved. At a locality where a recently drained ice front lake permitted examination of the vertical walls of the margin of the ice cap the lower 10 feet contained an abundance of boulders, gravel and shell fragments. At another locality north of the Cornell glacier the inland ice meets the land with a gently sloping surface on which

[80] Koch, I. P., Op. cit., p. 423.
[81] Koch, I. P., Op. cit., pp. 423-424.
[82] Koch, Lauge, Some New Features in the Physiography and Geology of Greenland, Jour. of Geol., vol. 31, p. 52, 1923.

morainal material is accumulating on the surface of the ice 50 to 100 feet from its margin. This is the result of the stratification of the ice and the upward inclination of the layers as the ice approaches the margin of the ice free land. Masses, 50 feet across, of boulders, gravel, and mud with some Pleistocene shell fragments were accumulating on the surface of the ice cap margin at this locality.[83]

The Swiss West Greenland expedition found the banding (annual layers) of the Jakobshavn glacier ice near the frontal margin becoming steeper until it was nearly vertical near the frontal moraine.

The stratification of glacial ice which is often associated with sediment accumulation is clearly shown in Johnstrup's photographs and résumé of Stenstrup's description.[84] The excellent photographs of the Danmark expedition show well the large quantities of morainal material held by the stratified glacial ice of northeastern Greenland.[85] Vast quantities of morainal material are brought to the sea front of some glaciers. The Jakobshavn glacier with its several lateral moraines[86] is an example of this type of glacier. Much of this morainal material is no doubt dumped in the sea during the calving of bergs but considerable quantities should be carried away by large flat-topped bergs.

The Eisblink, one of the largest of the West Greenland glaciers, forms a cape pushing out into the sea thirteen miles. It is bordered by a semicircular mass of submarine débris known as the Tallert Bank which may be regarded as a frontal submarine moraine.[87]

Professor Chamberlin[88] has noted sediment bearing layers in some West Greenland glaciers studied by him. Kindle[89] has listed the Pleistocene fossils which the lower

[83] These observations were made while the writer was a member of a Cornell University Greenland expedition under the leadership of the late Professor R. S. Tarr.

[84] Johnstrup, M. F., Résumé des Communications sur le Grönland: Meddel. om Grönland, vols. 4, 5, p. 266; pl. 3, fig. 3; pl. 4, fig. 3; 1883.

[85] Koch, I. P. and Wegener, A., Die glaciologischen Beobachtungen der Danmark-Expedition, Meddel. om Grönland, vol. 46, figs. 34-44, 1917.

[86] Engell, M. C., Undersogelser og Opmaalinger ved Jakobshavns Isfjord og i Orpigsuit i Sommern 1902, Meddel. om Grönland, vol. 26, pl. 4, 5, 7; 1904.

[87] Reclus, J. J. Elisée, The Earth, vol. 1, p. 181 (D. Appleton & Co.), 1886.

[88] Chamberlin, T. C., Glacial Studies, Jour. Geol., vol. 2, p. 778, etc., 1894.

[89] Kindle, E. M., Pleistocene fossils from Baffinland and Greenland: Science, vol. 6, pp. 91-93, 1897.

layers of the ice cap carry in latitude 74° 15′ West Greenland.

E. Mikkelsen has published a photograph (lost in the Arctic, London, 1913, p. 76) showing a sediment-bearing berg observed on the east coast of Greenland.

Edv. Bay[90] has found mud, clay, fine dust and diatom deposits common features of the sea ice off the coast of East Greenland. He states that the flat bergs in Scoresby Sound, East Greenland, are sometimes completely covered by stones. Boulders, he found, were more common on ice near shore than far out, while mud and clay are more common on floe ice somewhat remote from the coast. Much of the latter he infers from the evidence of the associated molluscs to have been derived from the Siberian coast. He sometimes found sand present in floe ice by melting where it was previously invisible. Bay has discussed at length Nordenskiold's view that the boulder reef of the east coast of Greenland disclosed by dredging between 69° and 74° N. lat. is the result of sea ice transportation.

The relics of Wellman's ship, the Ragnvald Jarl, crushed in the ice north of Spitsbergen and found near Julienshaab, southwest Greenland in 1921,[91] together with the fragments of the Jeannette, which was crushed north of Siberia and found in the same locality in 1884, strongly support the evidence of the ice-borne molluscs cited above concerning the Siberian source of much of the ice floe sediments seen east of Greenland.

No comprehensive consideration of the work of icebergs in relation to sedimentation is complete without mention of the huge waves produced by the calving of large icebergs. The writer has seen a series of these waves in Greenland strike the shore at a distance of about 10 miles from the berg which produced them with greater violence than ordinary storm waves would. Commander R. E. Peary relates an example of the work of an iceberg wave near the Bowdoin glacier in northwestern Greenland which burst through solid ice near shore and stove in a steam launch hauled up for the winter. This wave carried a whale boat a hundred yards inland and in receding took with it into a vortex of grinding ice cakes, all of the

[90] Bay, Edv., Den Östgronlandske Expedition udfort i Aarene 1891-92 under Ledelse af C. Ryder, Meddel. om Grönland, vol. 19, pp. 177-187, 1896.

[91] Rabot, Chas., Geographic Review, vol. 13, p. 625, 1923.

oil barrels, several bales of hay, several puppies, and a dory.[92] Every fjord with a large active glacier must have had its shores swept hundreds or thousands of times by such waves which would be most effective in removing the trains of lateral morainal material which might otherwise have persisted along the sides of a valley with a retreating glacier. Narrow fjords where large storm waves could not develop would thus be subjected to wave action of a most effective type.

Sir George Nares made various important observations on the sediments carried by the Polar ice. He refers to the loading of sea ice with land débris by small streams thus: "Since the first melting of the snow we observe that several of the floebergs near the mouths of the large ravines are covered in parts by pebbles and débris carried down by the rapid streams. We had previously supposed that the mounds of pebbles met with formed part of the actual shore, but the tidal movement has lately tilted some of the pieces of ice and so displayed the lower stratum below the gravel."[93] Nares quotes the observations of Dr. Moss, a member of his expedition, on the character of the atmospheric dust. "Occasionally deposits of atmospheric dust were to be met with throughout the stratified ice. Similar dust was to be found on the present surface of the floes occasionally greatly magnified in appearance by the growth amongst it of an Alga, identified by Professor Dickie as *Nostoc aurem.* The dust often occurred in little granules, so that in mass it formed an öolite. All the specimens of ice-dust obtained by me from the floebergs are undoubtedly the air-carried débris of crystalline rock not traceable to the neighboring shore."[94]

An important part of the floe ice from the standpoint of sediment and shore-derived materials is the portion which has been derived from the narrow collar of shore ice known as the ice-foot, which has its best development on coasts with a considerable tidal range like the Baffinland region.

MacMillan gives the following description of the ice-foot: "The ice-foot proper, however, never exceeds in

[92] Peary, R. E., Northward over the "Great Ice": vol. II, p. 76, 1898.
[93] Nares, Sir G. S., A Voyage to the Polar Sea, pp. 55, 56; 1878.
[94] Nares, Sir G. S., Op. cit., p. 61.

height that of the highest tide, and it is slowly built up from low-water mark by accretion, each receding tide leaving its congealed deposit. An ice-foot may form in the same way on the perfectly vertical face of a cliff where snow could not possibly lodge. And in the same fashion it may furnish passing sledges with a good, but often dangerous, highway.''[95]

Koch[96] has discussed the several factors concerned in the formation of the ice-foot and published a photograph of it in northeastern Greenland. He observed considerable quantities of pebbles and gravel on the ice-foot.[97]

Although Geikie appeared to underestimate the amount of rock material transported by icebergs, he fully recognized the importance of ice from the ice-foot in this capacity. ''During summer vast piles of rock and rubbish crowd the surface of the ice-foot. These are, of course, derived from the cliffs, to the base of which the ice-foot clings. To such an extent does this rock-rubbish accumulate, that the whole surface of the shelf is sometimes buried beneath it and entirely hidden from view. Along that part of the coast of Greenland where the ice-foot is shed at the end of every summer, the quantities of rock débris thus borne seawards must be something prodigious.''[98]

The coast line of Arctic and sub-Arctic Canada has been generally elevated 200 feet to 500 feet in Post-Glacial time from the Straits of Belle Isle to the Mackenzie delta. A vast amount of glacial morainal material has been stripped from this shore by various agencies among which the ice-foot has been prominent and distributed over the Arctic and northern Atlantic sea floors. Throughout the thousands of miles of this shore line the glacial boulders, which nearly everywhere abound above the line of maximum submergence, have been almost completely removed from all steeply sloping parts of the shore. A large share of these boulders have probably been carried away by the ice floes in the grip of ice cakes derived from the ice-foot.

[95] MacMillan, Donald B., Four Years in the White North, p. 154, 1921.
[96] Koch, I. P., Survey of Northeast Greenland: Meddel. om Grönland, vol. 46, p. 404, fig. 97, 1917.
[97] Koch, I. P., Op. cit., p. 418.
[98] Geikie, Jas., The Great Ice, pp. 68, 69, 1874.

The writer's observations during cruises along the Labrador and Greenland coasts have impressed him with the sharp contrast in the amount of fine sediment carried by different parts of the ice floes. Low apparently considered all the discolored pans which he saw in Hudson Strait to have come from Fox Channel.[59] The writer has seen great areas near Hudson Strait where 90% of the ice was discolored by fine sediment which had probably been blown on to the ice floes. More often, however, the ice floes of Baffin Bay will for hours show scarcely any sediment visible on the surface. Any attempt to evaluate the quantity of sediment transported by floe ice, however, if based only on the sediment seen on the surface above water would be as faulty as an estimate of the number of barnacles on the bottom of a ship inferred from the number visible above the water line. Much of the land-derived material carried by ice is held in the bottom layers and is seldom visible. This is eminently true of icebergs which, to the casual observer from the deck of a ship, rarely give any visible hint of the load of land-derived sediments, both coarse and fine, which nearly all of them doubtless carry.

Anyone who has collected fossils in the Arctic at the foot of cliffs during the thawing season has experienced the steady barrage of falling and rolling stones which keep one dodging. There is nothing comparable with this in southern latitudes where the loosening effects of thawing last but a few days. On Arctic coasts such material would land on the ice floes whenever the wind caused them to hug the shore, resulting in loading the ice with great quantities of rock débris for transportation to remote parts of the Arctic or even the Atlantic. In the north the thawing process is never completed and the dislodging of rocks resulting from it lasts all summer though less active in the latter part of the season. Because of the depth of frost penetration, rock disintegration from this source is far more rapid in the Arctic than in temperate latitudes.

Arctic sea ice is at times an important factor in the dissemination of volcanic dust. The volcanoes near Bering sea and of Iceland have doubtless supplied vast

[59] Low, A. P., The Cruise of the Neptune, p. 39, 1906.

quantities of fine dust to adjacent ice fields. In the early part of June, 1908, the writer passed through 300 miles of ice floes in Bering sea, about 80% of which bore small amounts of fine dust. Some of this dust was a fine black magnetic powder presumably of volcanic origin. It probably represented a fall of dust which covered an extensive area in the Seward peninsula, Alaska. This fall is reported by residents of Nome to have occurred on November 2d, 1907. This dust was conspicuous on the surface of snowbank remnants in the Nome district throughout the following June. Although it must have averaged only a small fraction of an inch in thickness, wind drift and subsequent melting of the snow caused its local segregation into very conspicuous masses. The source of this black dust which covered much of the sea ice and coast of north-western Alaska during the winter of 1907-1908 is not known. A. H. Brooks believes that it came from a volcano in the vicinity of Petropavlovsk and states that it was noted by dog-sledge drivers who found that it considerably decreased the efficiency of their teams.[100] There have probably been many eruptions of this kind in Alaska which are without record. Brooks got a trace of one from Mount Redoubt which fell as far north as the Skwentna river, Alaska, in 1902.[101]

Life on Sea Ice.

Various explorers have recorded evidence of the interesting algal flora which is doubtless present nearly everywhere in the Arctic sea. One of the most interesting kinds of algae and probably one of the rarest was reported a century ago by Captain Parry who states that "in the course of our journey on the 2nd of August we met with a quantity of snow, tinged to the depth of several inches, with some red colouring matter."[102] "Today, however, we observed that the runners of the boats, and even our own footsteps, exhibited the same appearance; and on watching it more narrowly afterwards, we found the same effect to be produced, in a greater or less degree, by heavy pressure, on almost all

[100] Brooks, A. H., Personal communication.
[101] Brooks, A. H., U. S. Geol. Survey, Prof. Paper, No. 70, p. 111.
[102] Parry, Sir W. E., Modern Voyages of Discovery, vol. 4, p. 214.

the ice over which we passed, though a magnifying glass could detect nothing to give it this tinge.''[103] Charles Hollick[104] reports having seen this variety of algae off the Labrador coast in a large gothic iceberg of opaque dead white whose facade was crossed by a transverse vein of brilliant crimson.

The foraminifera are among the minute forms of life which the ice floes assist in distributing. Johansen collected six species from the mud on an ice cake in Beaufort sea.[105]

The Danmark expedition secured large collections of marine plankton from the East Greenland sea, some of which was collected from the drift ice.[106] F. Johansen[107] has described shallow ponds in Alaska where fresh-water and marine diatoms live in association. The fresh-water in such lakes is often sharply separated from the salt water as shown by Alf Trolle[108] in northeastern Greenland.

Nansen has described[109] the rich algal flora which is found in the fresh-water ponds on the ice floes north of Siberia. The writer has found diatoms abundant on the floe ice of Bering sea,[110] and they are probably present nearly everywhere on the ice floes. Low found diatoms so numerous as to discolor large areas of the sea in Arctic waters where he states that they are propagated in the fresh-water pools of pan ice and thrive best in the comparatively fresh surface water near melting ice.[111] These minute plant organisms appear to supply the chief basic food for the higher forms of life in the Polar sea. They furnish food for the crustaceans and pteriopods on which, in turn, the fishes, seals, and whales largely live. Some fishes, including the sardine and menhaden, feed directly upon diatoms and dinoflagellates.[112] The vast number of

[103] Parry, Sir W. E., Op. cit., p. 215.
[104] Hollick, Chas., Am. Microscopic Journal, vol. 7, pp. 42-43, 1886.
[105] Cushman, J. A., Rept. Can. Arctic Exped., vol. 9, pt. M, p. 4m, 1920.
[106] Ostenfeld, C. H. and Paulsen, Ove, Marine Plankton from the East Greenland Sea, Meddel. om Grönland, vol. 43, p. 328, 1917.
[107] Johansen, F., Rept. Can. Arctic Exped., vol. 7, pt. N, pp. 3n-4n, 1920.
[108] Trolle, Alf., Hydrographical Observations from the Danmark Expedition, Meddel. om Grönland, vol. 41, pp. 384-390, 1913.
[109] Scientific Results, North Polar Expedition, vol. 5, 1906.
[110] Kindle, E. M., Diatomaceous Dust on the Bering Sea Ice, this Journal, vol. 28, pp. 175-179, 1909.
[111] Low, A. P., The Cruise of the Neptune, p. 257, 1906.
[112] Fisher, W. K., Ocean Life, Pop. Sci. Monthly, vol. 17, p. 375, 1923.

Arctic diatoms annually transported south by such ice streams as the Labrador current may be imagined when it is recalled that a single vertical haul through 65 feet of water in Keil bay contained 273,000,000 diatoms. Various other marine animals of larger size, notably the jelly fish, occur in almost incredible numbers in the Arctic seas in late summer. "Heckel tells us that he met with such enormous masses of the jelly fish *Limacina* to the northwest of Scotland that each bucketful of water contained thousands.[113] The sediment from melting ice must be, in some areas, a factor in burying and preserving these abundant forms of marine life.

Stefansson found seals throughout the sea area which he traversed, with the exception of certain belts of ice which he calls ice deserts, where the ice is too thick for the seals to keep open air holes. North of 76° no bear tracks were seen although often abundant south of that. The foxes appear to have a commensal relationship to the bears, according to Stefansson, keeping always near them in order to feed off the parts of seal carcasses left by the bears.

Previous to the exploration of the region west of the Arctic archipelago by the Canadian Arctic Expedition the existence of life on or among the ice floes far from land was generally denied by the best known authorities on Arctic exploration. As late as 1909 Sir Clements Markham wrote that Prince Patrick island "forms the boundary between the Arctic Paradise of Mellville island and the Polar ocean without life."[114] In the future the "lifeless Arctic pack" will belong in the same limbo with that other myth of an earlier period, the "lifeless abyss" of the deep sea.

The bones of large Arctic mammals must be left on the floe ice in considerable numbers, and the southward drift of the polar ice into the North Atlantic doubtless results in the transport and deposition annually of a considerable number of their bones to the sea bottom several hundred miles south of their normal habitat. Their distribution as fossils would therefore greatly exceed their habitat limits. The same observation applies to

[113] Brooks, A. H., The origin of the oldest fossils, Jour. Geol., vol. 2, p. 464, 1894.

[114] Markham, Sir Clements, Life of Admiral Sir Leopold McClintock, p. 172, 1909.

the distribution of the shells of Arctic molluscs. Even the remains of land animals must often be transported south by the ice floes. Kane saw the skeleton of a muskox firmly imbedded in the ice of the ice-foot.

Stefansson's statement that "bushels of small shells were heaped on the pressure ridges,"[115] at one point is an item of interest to palaeontologists since it indicates a means of distributing shells far from their habitat by sea ice seldom considered by them. The discovery of shallow water shells in deep water has sometimes been cited as evidence of sea bottom subsidence.[116] Icebergs which originate from the west Greenland coast in the neighborhood of latitude 74° doubtless carry in their lower layers considerable quantities of Pleistocene fossils southward, which are picked up from Pleistocene deposits over which the ice cap of parts of West Greenland is now moving. This conclusion is based on a collection of Pleistocene fossils which the writer made from the moraine at the western edge of the inland ice and from the ice itself near the Cornell glacier in west Greenland.[117]

Floe and berg ice is the most highly efficient agent concerned with the wide distribution over the sea bottom of the detritus of the circumpolar lands. Much of this material is being transported to the north Atlantic and deposited in rather definite belts determined by the position and direction of ocean currents. In the maze of channels in the eastern two-thirds of the Arctic archipelago this movement is clearly eastward or southeastward and south along the coast of Baffinland and Labrador. In the Greenland sea east and northeast of Iceland the movement of current-borne bottles thrown overboard by the Danmark expedition has been interpreted to indicate a division of the south-moving polar current on the east coast of Greenland into two parts,—one following the coast around Cape Farewell and then trending north up the west coast of Greenland; the other, flowing east of Iceland and outlining a course resembling a great horseshoe between

[115] The Friendly Arctic, p. 515.

[116] Jensen, A. S., Vidensk. Meddel., p. 229, 1900.

[117] Kindle, E. M., Pleistocene Fossils from Baffinland and Greenland: Science, vol. 5, pp. 91-93, 1897.

Norway and Greenland, open to the north.[118] Elsewhere in the Arctic sea the movement is in general from east to west. The two great routes along which the ice and its load of sediment moves out of the Arctic sea are along the east coast of Greenland and the Baffinland-Labrador coasts. It is to these coasts that Low's[119] "law of Arctic currents" applies. Ward[120] has shown the circuitous drift which certain icebergs have taken in the Grand Banks region, where the complex interplay of varying eddies and currents resulting from the contact of the Labrador current and the Gulf Stream hold many bergs till they go to pieces under the influence of the relatively warm water and contribute their sediments to the growth of the Grand Banks.

[118] Trolle, Alf, Hydrographical Observations from the Danmark Expedition: Meddel. om Grönland, vol. 41, pp. 411-413, pl. XL, 1913.

[119] Low, A. P., Report on the Dominion Government Expedition to Hudson Bay and the Arctic Islands on board the D. G. S. Neptune, 1903-1904: p. 289, 1906.

[120] De C. Ward, Robert. A cruise with the International ice patrol: Geogr. Rev., vol. 14, fig. 3, Jan., 1924.

NOTE: Certain important articles which were overlooked in the preparation of this paper are cited below.

Robert Bell found all of the floe ice of the north coast of Labrador "discoloured or foxy" toward the end of July. "The dust or mud, with which it was covered, was mostly yellowish and greyish in colour. Gravel, angular stones, patches of stoney mud, and an angular bowlder were occasionally observed." Many of the pans of field-ice off Big Island in Hudson Strait had gravel strewn upon them. On ice-pans farther up the coast, or to the northwestward, fragments of shaly marl and limestone with *Receptaculites Oweni* and other fossils were seen. Shells and bryozoans, belonging to moderately deep-water species, were found on the same pans. (Observations on the Geology, Zoology, and Botany of Hudson's Strait and Bay made in 1885: Geol. Surv. Can., Ann. Rept., vol. 1, pp. 7DD, 9DD, 1885.)

Bell's opinion that floe ice "does not shove or pile itself on shore pushing up bowlders and gravel" is negatived by the photographs (figs. 1 and 2) of this paper. Bell's view that ice bergs transport only a very small amount of bowlders and other land debris is probably best explained by the fact that he had never seen the bowlder- and dirt-carrying basal layers of the Greenland ice cap from which the bergs came. His explanation

of the abrupt disappearance of most bergs and the occasional survival of a berg far south of their usual southern limit is based on the great difference in temperature of the outer and inner parts of a berg which develops when it enters the Gulf Stream and leads to speedy disruption by cracking. This disruption does not occur quickly if a berg has been long enough stranded just before entering the Gulf Stream for the whole mass to have slowly risen in temperature to a point approximating that of the sea water off Newfoundland. (On some points in reference to ice phenomena: Trans. Roy. Soc. Can., vol. **4**, sect. III, pp. 85-91, 1887.)

See also Nordenskiold's explanation of the bursting asunder of bergs (Voyage of the Vega, p. 319). Nordenskiold has described (op. cit., pp. 250-251, 1882) from the inland ice of Greenland, the snow of Spitzbergen and other northern regions, dust with magnetic particles of iron. This dust (kryokonite) is considered to be of cosmic origin and capable of adding half a million tons to the earth's bulk per annum. The magnetic dust collected by the writer in Alaska (p. 281 this paper) appears to be an example of Nordenskiold's kryokonite. Nordenskiold has also made numerous observations on ice-transported terrestrial sediments. "Off the large rivers the ice, when the snow has melted, is generally covered with a yellow layer of clay." (Op. cit., p. 144.)

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