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NOTION OF ICE-FOOT WITH SPECIAL REFERENCE TO THE SAINT-LAURENT ESTUARY

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J.C. Dionne

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In the first part, a review of the existing definitions and classification of the icefoot is made, showing that the icefoot notion is inaccurate, often ambiguous and not the same for everyone. In the second part, a definition and a description of the icefoot in the St. Lawrence Estuary are offered. Two main types of icefoot are distinguished: the upper and the lower strand icefoot. The protective and the morpho-sedimentological role of this feature is also emphasized.

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10 Jean-Claude /Dionne

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THE NOTION OF ICE-FOOT WITH SPECIAL REFERENCE TO THE SAINT-LAURENT ESTUARY

By: Jean-Claude Dionne

From Cahiers de Geographie de Quebec, Vol. 17, No. 14, September 1973, pp. 221 - 250

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Introduction

A survey of the literature on ice permits the statement to be made that the concept of icefoot often differs from one author to another, thus leading to a certain amount of confusion. Sometimes there exists substantial differences between the various definitions provided in dictionaries or in works devoted to this subject. In English the spelling of icefoot, equivalent to papied de glace, varies according to the whim of the authors; at different times it is written icefoot, ice-foot or ice foot. Now, according to the Glossary of Geology of the American Geological Institute (Gary et al., 1972, p. 350), ice foot, written in two words should signify the bottom of a glacier front or a bank of snow, hardened or partially transformed into ice, located at the foot of a steep hill. Without exaggeration it can be stated that the expression pied de glace and its English equivalent icefoot are commonly used without rhyme or reason, or at least in a very imprecise way.

The expression pied de glace is a translation of the English term icefoot introduced by Kane (1856), coming from the Danish word isfod used by the Danish explorers. In the strict sense, icefoot corresponds to a narrow edge of ice frozen to the shore by the inside or bottom or by both at once, and located on the upper part of the shore. It is normally made of pure ice, but may sometimes include snow ice in its interior and surface. In principle icefoot in the strict sense is not directly subject to tides during the icy season. It is the result of congelation on the spot of a sheet of water (marine or lake) or of the agglomeration of pieces of drift ice pushed to the shore by waves and then frozen together, or of the congelation of water thrown onto the upper part of the shore when waves break.

The purpose of the present contribution is a critical review of the various definitions and classifications existing and a description and characterization of the icefoot on the banks of the Saint-Laurent estuary.

Part One: The Nation of Icefoot in General

A. Existing Definitions

The expression pied de glace and its English equivalent icefoot have been the object of numerous definitions. An adequate review requires that most of them be given consideration. We shall distinguish the definitions provided in specialized dictionaries[1] from those contained in works devoted partially or totally to icefoot. Since the present literature is mainly in English, we have

[1] The term icefoot is mentioned in Webster's New International Dictionary (1953, p. 1233) and in the Random House Dictionary (1967, p. 705). In the first work it is defined as: "a. A wall or belt of ice that forms along the shore in Arctic regions between high and low watermarks as a result of rise and fall of the tides. b. The ice at the front of a glacier". In the second it is defined as: "In polar regions a belt of ice frozen to the shore, formed chiefly as a result of the rise and fall of the tides."

have preferred for the sake of accuracy to use the definitions in this language; but we shall begin with the literature in French.

1. Definitions from the Dictionaries

Since there are more than a hundred geographies of dictionary, geology, glaciology and oceanography (Dionne, 1973), it would prove difficult to review all of them here; therefore we shall limit ourselves to the definitions in the works used most.

It is curious that there are rare works in French speaking of icefoot. George (1970, p. 324) in the Dictionnaire de la Geographie defines it as a "mass of ice fixed to the foot of a cliff in the Arctic seas. This mass is made of a combination of sea ice, piled snow, and ice from fresh water. Its expansion causes rocks to burst under the effects of freezing and thawing occurring frequently because of the movement of the tide and the daily thermal amplitude. The erosion of the cliff by this process produces a platform of abrasion and possibly a strand flat."

Hamelin (1959, p. 51) distinguishes between a foot of pure ice and a foot of snow ice. He defines the first as "ice in place, frozen to the bank and to the bottom, developed better when the edges of the bed are wide and shallow. There is no free water channel between the icefoot and the shore. The icefoot is practically unaffected by the movement of the tide." The second corresponds to an "edge of ice located along the shore but above the outside of the sheet of water; the ice is not formed by the congelation of the sheet of water, but by the congelation of the water thawing from local snow. This snowy icefoot expands the pure icefoot on the land side."

This author also takes up the notion of icefoot, but in a more ambiguous and incomplete manner (Hamelin and Cook, 1967, p. 100): "the expression icefoot has a double meaning. Strictly speaking it is a glaciological term. The icefoot is not always made up of pure ice coming exclusively from water congelation; it often includes frozen snow (pure snow which has partially absorbed water and then refrozen). The icefoot in general is made up of ice on the spot. When this ice-snow border is located along a tidal shore, it is sometimes spoken of as strand ice or surf ice." The illustration of icefoot presented alongside the definition shows a narrow terrace 1 or 2 m wide at the foot of a steep slope corresponding more to residual icefoot than to real icefoot, so that the reader experiences some difficulty in abstracting a precise idea of the phenomenon.

Many definitions of the term icefoot are found in English. Gary et al. (1972, p. 350), in the Glossary of Geology of the American Geological Institute, define it as "a narrow strip, belt or fringe of ice formed along and firmly attached to a polar coast, unmoved by tides, and remaining after the fast ice has broken away; it is usually formed by the freezing of wind-driven spray, or of sea water during ebb tide. A true icefoot has its base at or below low-water mark."

In the Illustrated Glossary of Snow and Ice of the Scott Plar Research Institute, Armstrong et al. (1966, p. 23) defined the term icefoot as "a narrow fringe of ice attached to the coast, unmoved by tides and remaining after fast ice has broken free."

Stamp (1961, p. 251), in his Glossary of Geographical Terms, adopts the definitions of the Ice Glossary and of Webster's Dictionary. In the first it is a matter of "a narrow strip of ice attached to the coast, unmoved by tides and remaining after the fast ice has broken free"; in the second icefoot has two meanings: "A wall or belt of ice that forms along the shore in the Arctic regions between high and low watermarks as a result of the rise and fall of the tides", and "The ice at the front of a glacier". In Longmans Dictionary of Geography, Stamp (1966, p. 199) is satisfied with a laconic definition of the term: "A belt of ice that forms along a shore, unmoved by tides."

Schieferdecker (1959, p. 58), in the Geological Nomenclature of the Royal Geological and Mining Society of the Netherlands, defines the term icefoot as: "An ice step attached to the coast and unmoved by tides."

Moore (1958, p. 88 and 1967, p. 110) offers a rather elaborate dictionary of icefoot: "A mass of ice projecting into the sea on an Arctic or Antarctic shore. It sometimes becomes very thick, with its upper edge several feet above sea level. The first stage in its formation takes place during the autumn, when snow accumulates along the shore; water thrown up by the waves freezes on to this snow, and forms a mass of ice. This is later augmented by lumps of sea-ice, likewise forced on land by tides and waves. Fragments of rock often collect on the ice-foot, and protect the ice from melting so that parts of it remain till the following autumn."

Swayne (1956, p. 77) provides three definitions for the expression icefoot: "a, A wall of ice at the base of a mountain, formed from snow accumulation, but from converging glaciers. b, A wall of ice formed from sea spray along the shore in polar regions. c, An ice strip attached to the coast unmoved by tides and remaining after the fast ice has moved away."

For the U.S. Navy Hydrographic Office (1952, p. 140), the icefoot has two meanings: 1. "A class of fast ice consisting of ice formed along and attached to the shore. The base of the ice is at or below low water mark. The action of tide, waves and sea spray causes the development of the icefoot during the freezing season. Differences in the causative factors are reflected in the difference in the icefoot." 2. "The ice at the front of a glacier."

For Rice (1940, p. 185) the icefoot is: "A wall of ice formed by sea water and snow frozen at the sea shore in polar regions. Also called ice ledge."

2. Definitions in Other Works

In addition to dictionaries, a certain number of definitions of icefoot are found in various works, scientific and other. The first dates back to the XIX Century.

Actually Kane (1856, p. 175-177) seems to have been the first to use the term ice-foot in an English translation from the Danish expression eis-fod[2], but he prefers the expression ice-belt: "The name is adapted on board ship from the Danish "Eis-fod", to designate a zone of ice which extends along the shore from the untried north beyond us almost to the Arctic circle. (...) ... it is a perennial growth, clinging to the bold faces of the cliffs, following the sweeps of the bays and the indentations of rivers. This broad platform, although changing with the seasons, never disappears. (...)... perched high above the grinding ice of the sea, and adapting itself to the tortuosities of the land. As such, I shall call it the "ice-belt". (...) ... as an agent of geological change, it is in the highest degree interesting and instructive. Although subject to occasional disruption, and to loss of volume from evaporation and thaws, it measures the severity of the year by its rates of increase. Rising with the first freezings of the late summer, it crusts the sea-line with curious fretwork and arabesques: a little later, and it receives the rude shock of the drifts and the collision of falling rocks from the cliffs which margin it: before the early winter has darkened, it is a wall, resisting the grinding floes; and it goes on gathering increase and strength from the successive freezing of the tides, until the melted snows and water-torrents of summer for a time check its progress." The illustrations contained in the work show different types or aspects of the icefoot in the Arctic (Figures 1 and 2).

Figure 1. Type of icefoot in the Arctic. Lithograph taken from Kane (1856).

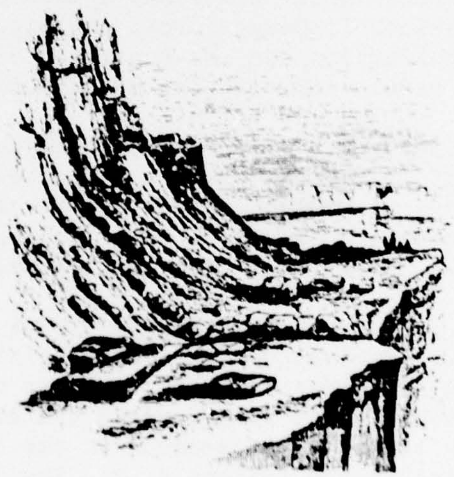

Figure 2. Icefoot at the Cape James-Kent, according to Kane. Lithograph taken from Prestwich (1886, p. 189).

[2]According to Koch (1928, p. 393), the correct spelling of the Danish term would be isfod and not eis-fod; see also Armstrong, et al. (1966), p. 23).

For Ramsay (1878), ice-foot corresponds to the following phenomenon: "Along the shores also, when the sea freezes, the ice becomes attached to the coast. By-and-by, as summer comes on, the ice partly breaks away, leaving what is called an ice foot - still joined to the land."

Geikie (1882, p. 62-64) describes icefoot thus: "Along the coast from near the Arctic Circle, up to Kennedy's Channel, a narrow shelf or platform, varying 60 to 150 feet or so in breadth, adheres to the rocks, accomodating itself to every sweep and indentation of the coastline. In the higher latitudes this shelf never entirely disappears, but further south it breaks up and vanishes towards the end of the summer. It owes its origin to the action of the tides. The first frost of the late summer covers the sea with a coat of ice which, carried upwards along the face of the cliffs by the tide, eventually becomes glued to the rocks. In this position it remains, and gradually grows in thickness with every successive tide until it may reach a height of 30 feet, and sometimes even more, presenting to the sea a bold wall of ice, against which the floes grind and crush, and are pounded into fragments. Its growth only stops with the advent of summer, when it begins to yield to the kindly influence of the sun, and to the action of the numerous streams that issue from the melting glaciers, and lick out for themselves deep hollows in the shelf as they rush outwards to the sea.

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. In the far north, where the ice-foot is perennial, it becomes thickly charged with successive deep layers and irregular masses of rock and debris - the spoil of the summer thaws. And when, as frequently happens, portions of this ice-belt get forced away from the land by the violent impact of massive floes, the current carries southward the loaded ice, which ere long will drop its burden of rock and rubbish as it journeys on, and warmer temperatures begin to tell upon it. Along that part of the coast of Greenland where the ice-foot is shed at the end of every summer, the quantities of rock debris thus borne seawards must be something prodigious.

Prestwich (1886, p. 188) writes the following about the icefoot: "When high cliffs overhand and the water is deeper, a belt of ice is formed at the base of the cliffs by the freezing of the water and the drifting of snow, which is known as the ice-foot. It is this ice, which receives on its surface the angular debris detached from overhanging cliffs, that forms so important an instrument of transport in Smith's Sound and Baffin's Bay." He also provides various illustrations of the icefoot (Figures 2 and 3).

For Nordenskjold and Mecking (1928, p. 290), the icefoot is: "A narrow ledge of sea ice several meters thick that forms in the tidal zone."; while for Bentham (1937, pp. 328 - 329), it corresponds to: "That part of the sea-ice which is frozen to the shore and therefore unaffected by tidal movements. It is separated from sea-ice proper, which moves up and down with the tide, by the tidal crack." According to this author two conditions are essential for the formation of icefoot, namely sufficiently low temperatures and a large difference between the low and high tide levels: "When the waters recede at ebb, the cliffs, or shore become covered with a layer of ice. This process is repeated at every tide until ultimately a continuous rim of ice is formed all along the coast." The author says: "When the shore is shelving, the horizontal distance between the high - and low - tide marks is greater and the ice-foot is wider, while its seaward margin is usually vertical." Therefore he admits that the icefoot covers the intertidal zone.

Koch (1928, p. 394), in a study about icefoot on the shores of Greenland, furnishes the following specific statements: *« In the winter the whole coast of Greenland is girdled with a belt of ice, the so-called ice-foot. (. . .) As a snow-white belt the ice-foot extends along the coast, following even its slightest indentations. Is also forms round stranded icebergs and along the front of quiet glaciers provided that these are not afloat. (. . .) The outermost edge of the ice foot is generally vertical and in line with that point on the coast which is dry at low water, at any rate the front of the ice-foot will never be farther advanced than half a meter from this line, and consequently the ice-foot is always aground. »*

Figure 3. Illustration of the icefoot collecting blocks of strand and dispersing them along the bottom. Lithograph taken from Prestwick (1886, p. 191).

Feyling-Hensen (1953, p. 49) for his part, recognizes that "according to its mode of formation, the ice-foot should cover the shore from high-water level down to low-water level."

For Charlesworth (1957, pp. 174 - 175), the idea of icefoot is more complex: *« This low, flat terrace skirts the polar coasts more or less continuously just above sea-level. It surrounds islands and stranded bergs and fringes quiet glaciers which are aground at the edge of the Antarctic ice-sheet. Its ribbon of ice, firmly frozen to the ground, follows the coastal undulations . . . Its level top marks the highest tide of the year and rises to 3 m or more. It is especially broad on shores which are protected . . . In Kane Basin it is 100 m or even several kilometers broad. It is very narrow on steep and rocky cliffs . . . The outer edge falls steeply or vertically towards sea-ice and coincides with a tidal crack along the line of ebb tide. On gently shelving shores, where the terrace is very wide, the transition to floe-ice is scarcely perceptible and there are many tidal cracks. The ice-foot preceeds the* *formation of sea-ice and survives the disappearance of this ice but is only permanent if the summers are cold. It melts rapidly in spring by waters from the land which erode deep gutters along its edge, by warm sea-water which undermines it and by the sun's rays, aided by grit blown out by the wind.* »

However, the only illustration of an icefoot contained in Charlesworth's work (1957, Pl. VII, p. 192) shows a narrow strip of ice attached to the rocky bank at the limit of high tide, analogous to the examples provided by Bentham (1937, p. 196), the U.S. Navy Hydrographic Office (1952, p. 57), Hamelin and Cook (1967, p. 101) and Armstrong et al. (1967, Figure 50). Thus the reader obtains a different idea of the icefoot, depending upon whether he reads the text or examines the photographs.

Greene (1970, p. 421) distinguishes between the kaimoo and the icefoot proper: "The kaimoo is defined as a bed of ice and frozen sand and gravel extending from the water line shoreward toward the backshore. Icefoot is here defined as a fringe of ice bordering the land and extending seaward from the water line. The icefoot occurs during freeze-up, prior to the development of shorefast sea ice and is well defined until it is incorporated into the fast ice."

In a recent work on the nature of the icefoot along the beaches of Radstock Bay (Ile de Devon, Canadian Arctic), MacCann and Carlisle (1972) make a brief survey of several of the definitions provided above and adopt Bentham's (1937). Following a number of authors they recognized that the tide constitutes an important factor in the formation of the icefoot and that the slope and width of the beach also play a role. For them, "the icefoot is developed in the upper part of the intertidal zone of tidal beaches; it may be built considerably above high-water level by the freezing of swash and spray, and clearly extends well below high-water mark. It is unlikely to contain much interbedded sediment, for the lower part of the beach below the icefoot is likely to be sealed by a cover of ice developed at low tides" (p. 179).

For Cayeux (1969, p. 450) the icefoot corresponds to the ice fixed along the bank: "Along the bank one often sees a tide gap separating the fixed ice, sometimes called icefoot, attached to the bank, from the ice pack subjected to the movement of the tides. (...) In the Saint-Laurent estuary in winter the icefoot, often anchored, is fixed to the gravel and to the plants in the coastal marshes. In the spring, when the heavy tides dislocate it and grind it into floating ice, some of it carries along some of the gravel or of the vegetative cover and deposit it further away."

Icefoot is not exclusive along the coasts of the oceans or of sea borders, although it is best developed along the latter. It also forms on the banks of lakes, rivers, and large streams in cold regions. Thus it corresponds to a sheet of ice fixed to the bank between the limits of high and low water. For some authors it is a matter of a fringe of ice on the upper part of the bank resulting from the congelation of water originating in breaking waves. Zumberge and Wilson (1953, p. 202) specify: "Beginning with the surf-freezing temperature, spray produced in the surf zone is blown onto the foreshore and frozen. Eventually, through a continuation of this process, the frozen spray produced a mass of ice firmly attached to the foreshore. This is called ice-foot".

Marsh et al. (1973, p. 48) thus described the icefoot along the shores of Lake Superior: *« The long, narrow, continuous ridges of grounded ice, separated by broad areas of low-relief ice, that parallel much of the shoreline of Lake Superior and other Great Lakes are called icefoots. They form from fields of small fragments of lake ice and ball ice which have been heaped up by storm waves and grounded. Once stabilized, an icefoot can continue to grow by wave overwash and wave spray. A sequence of up to four ridges of successively increasing size generally forms during the winter, and the outermost ridge is subject to wave action, both erosional and depositional, most of the time. The icefoots are of geomorphic importance, as they protect the shoreline from the high-energy waves of winter and spring, thereby reducing rates of erosion which otherwise might be expected. »*

B. Existing Classifications

Some authors have thought it useful to differentiate the various types of icefoot. This involves classifications sometimes based on major differences and sometimes on minor differences, with a regional or local connotation allowing more precise images on the phenomenon to be achieved.

Wright and Priestely (1922, pp. 295 - 308) distinguished five types of icefoot in the Arctic:

1. the tidal platform icefoot, formed the action of the tide in the zone between the limits of high and low tide;

2. the storm icefoot, formed above the high tide limit by water spray thrown along the bank when waves break;

3. the drift icefoot, formed of snow accumulated along the bank and transformed into ice during the course of years;

4. the pressure icefoot, resulting from the overlapping of drift ice when it is pushed onto the bank by pressures originating in the open sea; and

5. the stranded-floe icefoot, composed of drift ice stranded on the bank.

Joyce (1950) describes two other types of icefoot which form along the Antarctic shores:

1. the false icefoot, situated at or above the high tide mark, and formed of snow and congealed thawed water;

2. the wash and stain icefoot, situated in the intertidal zone and resulting

from the progressive drop in the temperature of the water in the level of the sea in which the surf is the only disturbing element; its formation requires a beach with a slight slope.

The U.S. Navy Hydrographic Office (1952, p. 14), taking up the categories recognized by Wright and Priestley (1922) and by Joyce (1950) mentions without definition six types of icefoot: the tidal platform icefoot, the storm icefoot, the drift icefoot, the stranded icefoot, the false icefoot, and the wash and stain icefoot.

Koch (1928, pp. 398 - 420) describes at length the aspects of the icefoot along the shores of Greenland, particularly from the "traffic" point of view, but he does not propose any particular classification. Still, he speaks of a permanent icefoot and of a icefoot which disappears completely in summer, of a "narrow-icefoot" (30 - 60 m) and of a "broad icefoot" (several kilometers), and occasionally of a "floe pressure icefoot" and of a "glacier pressure icefoot", of a "storm icefoot", of a "drift icefoot" and of a "stranded floe icefoot".

Bentham (1937, p. 329) consecrates part of his study to the types of icefoot, but is content with saying that "the character of the icefoot in any particular locality is dependent on the nature of the coast", specifying that when the strand is wide the icefoot is extensive, and when the shore is abrupt, it is narrow.

For his part, Charlesworth (1957, pp. 174 - 175) distinguishes six types of icefoot, four of which are identical to those described by Wright and Priestley (1922):

1. the drift-ice-foot is fed by snow and eolian contributions coming from the interior (from the land) and has a maximum development at the foot of cliffs and glaciers; it is the last to form and the first to disappear, consequently the least permanent;

2. the spray ice-foot develops from spray and jets of water thrown onto the shore when waves break;

3. the pressure ice-foot forms along deep bays and on coasts exposed to packed pressure; it is made up of rafts of sea ice piled up along the bank by the wind and tide; it has a chaotic appearance due to the overlapping of the flow; snow and recongealed water cement the gaps and produce an agglomerate ice covering;

4. the tidal platform ice-foot is formed in the intertidal zone by congelation and agglomeration of ice floe; it is well developed along shores with large tide amplitude, but can also develop at the foot of abrupt cliffs.

5. the storm ice-foot is formed during Antarctic storms; it is exceptionally high and rises above the level of the sea;

6. the melt ice-foot corresponds to a submerged terrace bordering icebergs and large rasps of ice, and is a result of the melting of ice.

Rex (1964, pp. 392 - 394) distinguishes between storm-icefoot, gravel-sand-icefoot and tidal-platform-icefoot in the Barrow's region (Alaska):

> « *During the period of freeze-up, storms may produce a storm-ice foot. This consists of a shelf or toe of ice near high water mark that results from adfreezing of water as waves wash up the beach. The ice foot runs parallel to the water's edge and has a convex upward cross-section with an irregular, broken-off seaward side. A large amount of gravel and sand is often washed up the beach from the surf zone and included in the storm-ice foot. Crystals of frazil ice also washed onto the beach and incorporated into it. At Barrow this feature should better be called the gravel-sand-ice foot. (. . .) This gravel-sand-ice foot it finely bedded, with beds ranging from 50 to 10 centimeters in thickness and in exceptional cases rises as much as 8 feet above the wave-equilibrium surface. (. . .) The storm-ice-foot mantles the seaward side of the beach in the Barrow area. It thaws in place without breaking away from shore, so sand, and gravel incorporated into the ice foot are dropped on the beach. (. . .) In many areas the ice foot is predominantly a tidal-platform-ice foot . . . When it is present it affords complete protection from wave-erosion* ».

In a lake environment Zumberge and Wilson (1953, p. 202) distinguished between shore-icefoot and off-shore icefoot on the hand and active and inactive icefoot on the other:

> « *At the water-edge of the ice-cover . . . a new ice-foot may develop. Sometimes the new ice-foot is initiated by the presence of an ice ridge formed by the shingling or jamming of broken ice blocks along the open water edge of the sheet ice. Spray on this ridge cements it firmly together, thus producing a new ice-foot . . . This second type of ice-foot is called the off-shore ice-foot in contrast to the shore ice-foot. If the ice-foot borders expanse of open lake water, it is an active ice-foot ; an ice-foot locked firmly in frozen lake ice is inactive . . . In shallow water of the surf zone the off-shore ice-foot may be grounded.* »

Norrman (1964, pp. 151 - 154) describes two types of icefoot common on the banks of the Vattern Lake in Sweden. One, called ice platform, is formed on the upper part of the beach by water congelation coming from the swash; the other, with a more chaotic appearance, is called ice wall and is the result of the piling up of slush, on the upper part of the beach, and cemented by water cast up when waves break: "The suspension sent up the ice front by the swash is rapidly drained to form slush, and the part washed back again is deposited at the outer edge of the icefoot. The drained slush congeals, and a ridge of soft ice with a steep front and a more gentle slope towards the land is built up" (p. 154).

C. Commentaries on the Definitions and the Classifications

What can we extract from these various definitions and classifications except an obvious lack of unity and a certain degree of ambiguity? All of the authors agree in saying that the icefoot corresponds to a fringe or "terrace of ice" on the border of a shore; but as soon as an attempt is made to specify this idea more completely, differences appear.

Some consider the icefoot as a form proper to the polar shores, which is inexact. It would be better to say proper to cold regions, which is not the same thing. In North America, for example, icefoot forms on shores situated south of the 48° of north latitude, while the polar regions are situated north of 60° north latitude.

Some state that icefoot corresponds to the ice covering spread over the intertidal zone, while others claim that it corresponds to a narrow terrace at the upper limit of high sea, while others understand it as covering the entire littoral and prelittoral shallow zone, as long as the ice covering is continuous and attached to the beach.

A number consider the icefoot to be frozen to the bank by the side and bottom, and not subject to tide activity; others state that it is subject to vertical movements of the tide, at least partially, and that it is not always attached at the bottom, even if it rests on the bottom at low tide.

Some definitions even contain contradictory elements, notably those which state that the icefoot covers the intertidal zone and is not affected by tide; this is almost impossible, since the icefoot is rarely completely attached to the surface on which it rests[3] and since the water penetrates below the ice covering at times of flood, particularly during periods of spring tide and raise the ice.

Some claim that the icefoot is formed by the congelation of water passed up to the upper part of the bank from the breaking of waves, and others claim that it is formed by the agglomeration of ice rafts or by the congelation on the spot of the water surface.

Most of the authors state that icefoot lasts for a long time on the shore in summer, but some claim the contrary, that it melts rapidly in the spring; some claim that it melts on the spot, and others that it is fragmented and that the rafts are carried away by the currents.

All in all, the majority of the differences found result both from incomplete definitions and from the existence of several regional types of icefoot which the majority of general definitions do not clearly express.

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[3] The case where it is best attached to the surface is in the littoral marshes. Now these by definition are situated at the upper part of the intertidal zone, so that in the lower part ambiguous to the marsh the icefoot effectively submits to the effects of tides.

Depending upon the authors, regions and the environments (ocean or lake), the existence of several types of icefoot can be demonstrated, so that it is often difficult to find one's bearings. While the various categories of icefoot sometimes allow better understanding of the reality, it is not always easy to distinguish one type from another, and finally the general definition scarcely improves things.

In a general way it is possible to define icefoot as a fringe of ice of varied width at the edge of the shores in cold regions, entirely or partially attached to the shore at the bottom or the side and affected or not by the vertical movements of the water surface. It is also convenient to distinguish two large types of icefoot: the upper and lower strand for tidal coasts, or high and low beach for other water surfaces. The other types of icefoot described by various authors constitute secondary, local or regional types, under these two large categories.

Second Part: Icefoot in the Saint-Laurent Estuary

While there are a number of works devoted to ice in the Saint-Laurent, few authors have dealt with the question of the icefoot. Therefore it appears expedient to specify its principal characteristics.

A. Definition and Classification

In the Saint-Laurent estuary, we have distinguished two types of icefoot: the upper strand icefoot and the lower strand icefoot (Figure 4).

The first corresponds to a narrow strip of ice attached to the upper part of the shore, forming at the beginning of the icy season and disappearing at the end of it. It is attached to the bottom and sometimes by the side, and is practically unaffected by the vertical movement of the tide. It is partially composed of rafts pushed to the shore by the current and of congelation water cast up when waves break; but it also includes hardened snow and ice stemming from the congelation of water from thawing snow. At the beginning of the icy season, it often has a broken or chaotic topography, but in the full of the season it shows an almost uniform surface, horizontal or slightly inclined toward the sea (photographs 1, 2 and 3).

The second is much more extensive; it covers the intertidal zone between the low sea limit and the angle of the strand; it forms later and disappears earlier. It is basically formed of pure ice (marine, brackish or fresh). It is more or less intensely subject to the vertical movements of the tide, depending upon its monthly variations. At low tide it rests on the bottom for the most part, but is rarely attached to the bottom except in depressions where the fronds of the vegetative carpet hold it firmly; its outer part usually ends with a small cliff of ice. In full season it forms a continuous ice covering, almost horizontal, sometimes characterized by eruptions, pressure crests and various other ice forms (photographs 4 and 5).

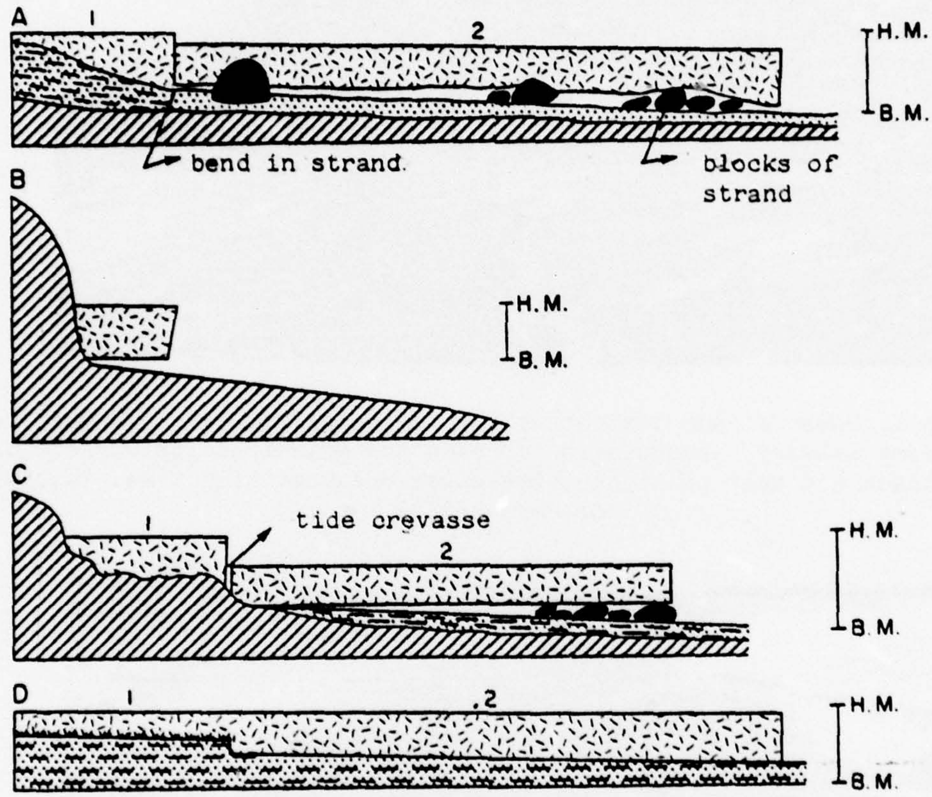


Figure 4. Types of icefoot in the Saint-Laurent estuary. a - in the coves and bays with high and low beaches; b - along abrupt rocky coasts; c - along rocky coasts with erosion platforms in the upper part of the bank and a beach in the lower part; d - in the flat areas.

1 - upper strand icefoot,
2 - lower strand icefoot
hm - high tide level
bm - low tide level

Photograph 1. Upper strand icefoot at the beginning of the ice season in the Saint-Laurent estuary; accumulation of sand and gravel at its surface dragged from the beach and cast up at the time waves break at high tide. Saint-Luce-sur-Mer, 3/4/71.

Photograph 2. Upper strand icefoot during the course of formation; accumulation of small rafts of ice and slush at the upper tide limit frozen together by sea water; incorporation, when waves break, of sand and gravel from the beach into the ice. Saint-Luce-sur-Mer, 1/1/70.

Photograph 3. Icefoot in the strict sense along an abrupt rocky coast; traditional illustration of an icefoot, Rimuski, 10/3/66.

B. Duration

The duration of the icefoot in the Saint-Laurent estuary varies from year to year, from upstream to downstream, from one coast to the other and from one sector to another of the same coast. However, it is possible to describe the duration of the icefoot downstream from Quebec in an approximate way.

In the middle estuary, the upper strand icefoot usually begins to form at the end of November or at the beginning of December, rarely before. Its formation is more or less rapid depending upon the more or less severe climatic conditions prevailing and upon other factors, such as tide and wind. In general the length of formation of the upper strand icefoot covers a period of 15 days to a month.

The lower strand icefoot forms after the upper strand icefoot with a formation taking 25 to 45 days, depending upon the year. Normally, in the middle estuary, an upper strand icefoot exists between the middle and end of December, and the lower strand icefoot is formed for the most part between the end of December and mid-January. The maximum development of the lower strand icefoot, however, is not reached before the end of January; most often it will be between the end of January and the beginning of March.

The "upper or lower strand" icefoot develops first in the more sheltered sections of the bank (coves, bays, depressions and basins); it is 10 to 15 days earlier on the south bank than on the north bank because of gentler slopes and the weaker waves and currents on the south bank.

Photograph 4. Lower strand icefoot marked by spots of mud at the location of drift ice turned over and incorporated in the ice surface. L'Islet, 1/4/72.

Photograph 5. Lower strand icefoot with a chaotic surface. Amse de Saint-Vallier, 3/3/68.

In the downstream part of the maritime estuary (or between Saguenay and the Point of Monts), the formation of the icefoot begins 15 days later than in the middle estuary. The upper strand icefoot forms between mid-December and mid-January, rarely before, and exceptionally later; the lower strand icefoot develops from the end of December to the end of January and reaches its maximum in February or March. Here also there exists an interval of two weeks between the two banks. The north bank becoming ice-covered later. Like the middle estuary, the more sheltered sections are the first covered by the icefoot.

Annual thawing occurs from the end of March to mid-April and frequently coincides with the heavy spring tide periods. The situation is the opposite of ice formation: the middle estuary thaws after the maritime estuary, the south bank after the north bank, and the sheltered sections after the exposed sections. Contrary to ice formation, thawing is progressive from downstream to upstream and the lower strand icefoot always disappears before the upper strand icefoot.

In the maritime estuary the icefoot is broken up gradually from the end of March on, with the process able to continue for a period lasting from a few days to three weeks, depending upon climatic (temperature and wind) and hydrological (tide and currents) conditions. Once the lower strand icefoot is freed of its covering of ice, the waves attack the upper strand of icefoot, which sometimes lasts on the bank until it melts on the spot, especially when the tide cycle does not permit the sheet of water to dislodge and take control of the localized ice rafts on the upper limit of the bank. Generally the depressions are the last sections of the coast to be freed of ice, and very often the icefoot melts on the spot in the upper part of the depression.

The situation is analogous in the middle estuary, but the deicing is produced two weeks later. Thus, on the south bank, it begins at the beginning of April and ends at the end of the same month, rarely later, except for certain years during which the upper strand icefoot can last to the end of the first week in May.

On the north bank of the Saint-Laurent River deicing is generally more hasty and rapid on the south bank. The dispersion of the upper strand icefoot is often a matter of a few days, while the upper strand icefoot lasts for another week or more, depending upon the local conditions and the sector. Still, the section between Beauport and the Cap aux Oies behaves like those of the southern bank of the Saint-Laurent opposite.

Therefore it can be maintained that an icefoot exists on the banks of the Saint-Laurent estuary for a period of between 3 and 5 months per year, depending upon the sections, and that the duration of the upper strand ice wall generally lasts a month longer than that of the lower strand icefoot. In addition, recalling that the Saint-Laurent estuary is a dynamic environment, the lower strand ice wall is the object of constant modification during the ice season. Partial deicing is frequent in certain sections of the Saint-Laurent estuary in the winter, especially on the maritime estuary.

C. Extent and Thickness

On the banks of the Saint-Laurent estuary the extent of the icefoot varies from one point to another, depending upon the slope and the local topography. In a general way it can be stated that it is narrow in steep rocky sections and wide along base, depressions, and basins.

While the upper strand icefoot preserves approximately the same width everywhere throughout the ice season, or several dozen meters (20 to 50 m), the width of the lower strand icefoot is much more extensive, from 100 to 4000 m. Its width varies in time and space, i.e., during the ice season and depending upon the section. Several figures will help in establishing these ideas. Thus, between Pointe-au-Pere and the Bay of Mites, it reaches a width of 800 to 900 m; opposite Rimouski, the ice covering which can be considered as a lower strand icefoot, reaches more than 3000 m, connecting Ile Saint-Barnabe to the south bank; at Bic, Cap-a-l'Orignal and Saint-Fabien-sur-Mer, the icefoot extends for a width of 400 to 800 m; between Saint-Fabien and Cape Marteau, it is very narrow, 75 - 100 m; opposite Trois-Pistoles, it measures 1000 to 2000 m in width; at Isle-Verte it reaches 4000 m and thus joins Ile-Verte on the south bank; at Cacouna it extends between 800 and 1200 m wide, depending upon the place; at the Point of Riviere-du-Loup, it scarcely exceeds 400 to 500 m, but between this point and Le Portage, it sometimes reaches 1000 m; between Andreville and Kamouraska, it reaches between 1000 and 2000 m in width and up to 3000 m opposite Kamouraska; between La Pocatiere and Cap-Saint-Ignace, it measures between 300 and 700 m, but sometimes reaches 3000 m at Montmagny; between this point and Berthier its width is 400 to 500 m, while in the bays of Berthier, Saint-Vallier and Bellechasse, it is 500 to 900 m wide.

On the north bank of the Saint-Laurent the icefoot is much less extensive because of the narrowness of the strands, the absence of deep bays, prevailing winds blowing from the west and northwest, and tide currents which periodically clear the bank. Still, during the ice season, a narrow icefoot 30 to 50 m wide is found at the limit of the average high tide. The lower strand icefoot is exclusive in the sections characterized by a large strand. Thus, in the full ice season it can reach 300 to 600 m wide between Cap aux Oies and Saint-Simeon, up to 4000 m wide at the Pointe aux Alouettes at the mouth of the Saguenay, and from 700 to 800 m wide opposite the Grandes-Bergeronnes and in the Baie des Mille-Vaches. Between Baie-Comeau and Sept-Iles it rarely exceeds 100 to 200 m in width, except in the baie of Sept-Iles where it can reach 1000 m. In the sector upstream from the middle estuary, or between Beauport and the Cap aux Oies, the icefoot has a great extension and often reaches 2000 m in width in full season, especially opposite Montmorency.

The thickness of the icefoot in the Saint-Laurent estuary is much more constant than its width. In general the upper strand icefoot has a thickness between 40 and 100 cm and that of the lower strand between 50 and 150 cm. The latter is ordinarily thinner in its inner part (50 - 75 cm), but thickens in the direction of the sea, where it reaches 100 - 150 cm in full season. However, the thickness of the lower strand icefoot is not constant; it often increases along thresholds, i.e., where pressure crests are formed and in places where there is overlap. In the depressions (Rimouski, Isle-Verte, Cacouna, La Pocatiere, Les Aulnaies, Montmagny, Ile d'Orleans), its thickness is generally from 40 to 80 cm. In the basins (La Pocatiere, L'Islet, Montmagny) it reaches 50 to 90 cm.

The few values relative to the thickness and extent of the icefoot provided here are not at all absolute; they simply show the many variations which exist and indicate the necessity of distinguishing between the upper and lower icefoot, in order to eliminate any misunderstanding.

D. Methods of Formation

We already know that the upper strand icefoot is formed at the beginning of icing and that the lower one is formed later, but still during the first part of the ice season. It remains to specify the various methods and formations of the two types.

1. The Upper Strand Icefoot

The upper strand icefoot generally has a complex origin. It rarely results from rapid congelation on the spot of a sheet of water, but rather from progressive congelation and in multiple phases of tiny quantities of water cast up to the upper part of the shore when waves break. It often begins with an accumulation of slush and crushed ice pushed onto the beach by the current; this mud forms an initial bead at the upper sea limit, the size of which increases gradually with the congelation of water cast up when the waves break. At this stage there is often an incorporation of material from the beach to the ice (photographs 1 and 2). It can also result from the accumulation at the upper limit of the bank of raft ice (young ice) pushed by the current and later frozen together by water splashed when waves break. In this case growth is more rapid than in the previous case. In rocky and relatively steep sections the upper strand icefoot is often the result of the progressive congelation of water thrown against the cliff or the bank when waves break. But in the majority of cases it is composed partially of snow and ice originating in the water thawed from this snow.

2. The Lower Strand Icefoot

The lower strand icefoot is formed either by direct congelation of the water surface in sheltered sections (depressions, for example); in this case it is homogeneous and formed of ice of the same age. But more often it is the result of agglomeration of raft ice and of small crests of slush accumulated on the bank by the combined action of wind and tide and then cemented by the water from the sea (or brackish); in this case it can be formed of ice and fresh water ice of different ages. This initial icefoot generally presents an irregular or chaotic surface which is gradually smoothed with contributions of interstitial water and snow (photograph 6). During the ice season the lower strand icefoot thickens from below by congelation of water at the base at ebb tide, and occasionally by water congelation at the surface, when it is submerged during heavy spring tides.

Photograph 6. Lower strand icefoot in the process of formation; young ice formed partly from slush. Saint-Luce-sur-Mer. 13/12/64.

In addition the precipitation of snow and winter rain can also increase the thickness of the layer of ice by several centimeters sometimes. In this way, by the end of the ice season, the lower strand icefoot forms a homogeneous appearance, or even a continuous and solid covering of ice (photographs 4 and 7).

It should be mentioned that the majority of lower strand icefoot on the Saint-Laurent are composite and complex: their formation takes place in several stages beginning with floe ice of various dimensions and different ages frozen together by sea or brackish water.

E. Methods of Break-up

The deicing of the Saint-Laurent banks generally begins at the end of March in the maritime sector and at the end of April in the middle estuary, and frequently coincides with the heavy spring tides, the most exposed sections being freed of ice first, deep recesses with a gentle slope and well protected being freed of ice with an average dealy of two weeks. In the middle estuary deicing extends from the beginning to the end of April with a maximum around 15 April; in the maritime estuary it extends from the end of March to middle April with a maximum around 5 April, depending upon the sections.

Photograph 7. Lower strand icefoot in the process of destruction in a basin of the Saint-Laurent estuary; note the great smoothness of the surface and the glacial microrelief in the mud at the limit of low tide. Montmagny, 15/4/72.

The deicing process occurs according to three modalities:

1) By marginal detachments, i.e., by gradual reduction of the width of the lower strand icefoot. There are sporadic detachments at the extreme edge of rafts of ice lifted by the tide and dislodged by the waves (photograph 6). This method of linear narrowing of the icefoot also exists throughout the ice season at the extreme margin of the lower strand icefoot, depending upon wind and tide conditions.

2) By mass detachment, coinciding with the heavy spring tides at the end of March or the beginning of April. At this time large sections of ice are raised by the water surface which breaks them up and dislodges rafts of various sizes, which are then carried out to sea with the ebb tide. The essence of deicing takes place in 4 or 5 days, when about 70% of the icefoot is destroyed; the parts carried away by the currents go to feed the floating rafts in the estuary and the gulf (Brochu, 1960). It sometimes happens, depending upon climatic and tide conditions, that deicing stops or is interrupted by a cold spell coinciding with the period between tides. In this case the break-up of the icefoot is retarded by about 10 days, as in 1971. Sometimes in the maritime estuary massive deicing occurs during the ice season when the conditions are favorable, i.e., when the wind blows out to sea, there are heavy tides and the winter temperature is relatively high. The most exposed sections of the coasts are the most affected by these winter removals of ice. The lower strand icefoot thus undergoes reductions and increases during the ice season. It would be erroneous to

believe that it forms at the beginning of the cold season and disappears in spring, thus temporarily but effectively blocking a large part of the shore, such as happens in the polar regions where the packed ice protects the icefoot from any rapid destruction. Along the banks of the Saint-Laurent and the coasts with large tidal amplitude, the lower strand icefoot undergoes multiple derangements throughout the ice season.

3) Through Reduction and Thawing on the Spot

Sometimes conditions are such that part of the lower strand icefoot, and particularly the higher strand icefoot, escape dismantlement by waves and tides. In this case, through the force of the sun, rain, running water from the melting of the snow cover and sometimes from water mining the icefoot from below, the ice melts on the spot. This situation often occurs in depressions.

F. Morphological Aspects

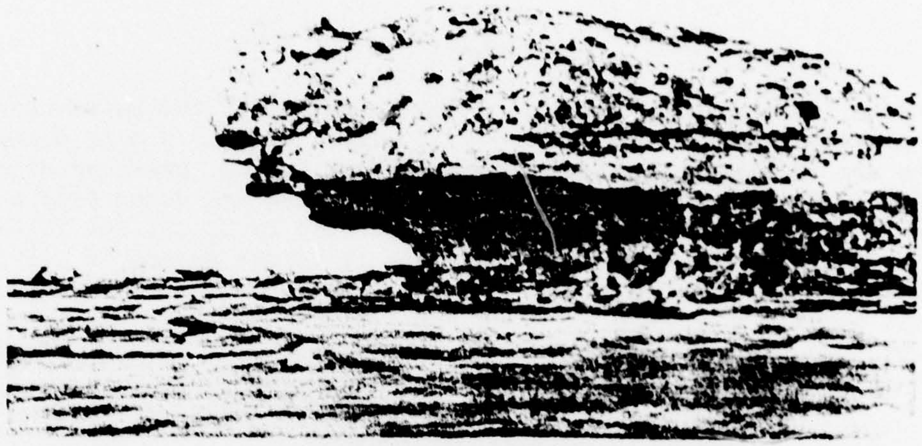
On the banks of the Saint-Laurent the surface of the icefoot, in full season or at the end of the ice season, is characterized by total uniformity and great smoothness (photographs 4 and 7). While the upper strand icefoot is not very broken, the lower one offers a more or less varied microtopography which is largely associated with the action of the tides. It can be stated that the icefoot on coasts with a large tidal amplitude are more broken than those on coasts with weak tides. Since the ice morphology has never been the subject of extensive work, except for the work of Wright and Priestley (1922) and a recent work by Marsh et al. (1973), we have thought it useful to briefly describe here the principal elements of the icefoot.

1. The Ice Cliff

Ordinarily the lower strand icefoot ends toward the sea with an ice cliff several dozen centimeters to several meters in height. This escarpment is generally vertical and sometimes characterized by a dissolving gap at the base, at the level of wave action. In addition some cliffs have sculptured forms, cornices (photograph 8) or caves several meters in thickness analogous to those along rocky coasts. The cliff is a characteristic of the upper strand icefoot only when the latter is very individualized or when there is no lower strand icefoot.

2. Ice Undines and Pressure Crests

The lower strand icefoot is frequently characterized by the presence of lateral beads composed of tilted raft ice which can reach 10 to 15 m in height, 50 to 60 m in width and up to 2 km in length (photograph 9). They are principally formed where there is a shallow bottom, rocky or loose, and beads of beach. Sometimes 2 or 3 are found extended parallel to the bank; these are the ice undines.



Photograph 8. Ice cornice and gap in an ice crest 6 m high, in the intertidal zone. Saint-Luce-sur-Mer. 1/1/70.

Other smaller crests (2 to 4 m in height) are the result of the pressure exerted by the tide where water currents cross the strand or where there are tide fissures, sometimes oblique and sometimes perpendicular to the bank, rarely parallel (photograph 10).

Photograph 9. Ice undine 5 m high at the limit of mean low tide. Saint-Luce-sur-Mer. 9/2/65.

Finally, other crests form 50 to 150 cm in height at the external or internal limit of the icefoot because of the accumulation of slush and small pieces of ice frozen together by water cast-up when waves break. This type of crest seems to be very widespread on the banks of Lake Superior (Marsh et al., 1973).

3. Blisters

A characteristic form of the upper strand icefoot of the Saint-Laurent is the formation of small peaks 1 to 4 m in height by 2 to 8 m in diameter where there are isolated blocks of strand. These conical peaks or blisters (photograph 11) are the result of curling and tipping ice under tide action. In their morphology they recall the forms described by Wright and Priestley (1922, p. 343) in the Antarctic and attribute it to the escape of air and gas present beneath the ice surface, but different from the "cones of ice" in the Great Lakes (Marsh, 1973). They are frequent on the south bank, between Levis and the Baie de Mitis, and in the region of Quebec. They are also found on the shores of the Canadian Arctic (Wilkinson, 1970, p. 45).

Photograph 10. Pressure crest perpendicular to the bank in the lower strand icefoot; note the large quantity of sediment in the tilted blocks of ice. L'Islet. 1/4/72.

4. Chaotic Groups

The lower strand icefoot, especially on the south banks of the Saint-Laurent and in the region of Quebec, often shows a chaotic surface, especially in the first part of the ice season (photograph 5). This irregular relief from 50 to 150 cm in height is the result of tilting or overlapping of ice rafts under the effect of various pressures exerted by tide and wind. The ice chaos is irregularly distributed and its density is extremely variable from one section to another and from year to another. However, it seems less abundant in certain regions of the Canadian Arctic.

Photograph 11. Icefoot blister developed at the location of a large block of strand. Saint-Luce-sur-Mer. 9/2/65.

5. Fissures and Crevasses

Fissures and crevasses characterize the entire lower strand icefoot, while they rarely affect the upper strand icefoot. They exist in two large categories: some due to contraction by cold and others due to tide action. The first are generally narrow of a polygon shape and require an icefoot which is not much affected by the vertical movements of the water surface; the second are wider and grow parallel to the bank (photograph 12); they are produced when the water surface affected by the tide subjects the icefoot to periodic vertical movements. During the ice season water in the crevasses frequently refreezes, resulting in lateral expansion of the icefoot. In rocky sections a crevasse is sometimes found between the upper and lower strand icefeet, generally open at low tide, and able to reach 50 to 200 cm in width.

6. Other Minor Forms

At the surface of the icefoot in spring various minor forms associated with thawing can be observed. These are sometimes small streams on the top of the ice evacuating the melted water, and sometimes gutters or melted holes of various size, sometimes residue cones and residual shapes. These forms, by definition, are ephemeral and last only for the space of one ice season.

Photograph 12. Upper strand icefoot at the end of the ice season; note the numerous tide crevasses parallel to the shore. Baie de Bellechasse, 8/4/69.

It should also be pointed out that during the winter the icefoot is frequently hidden, at least partially, by a covering of snow which itself has various snow and eolian forms: wrinkles, dunes, sastrugi, etc.

G. The Role of the Icefoot in Morpho-sedimentology

The icefoot plays an important role in coastal morpho-sedimentology, being at once an agent of destruction, construction and protection; this is a role which a number of authors have already emphasized briefly (Kane, 1856; Geikie, 1882; Prestwick, 1886; Nansen, 1922; Wright and Priestley, 1922; Zumberge and Wilson, 1953; Charlesworth, 1957; Corbel, 1958; Norrman, 1964; Rex, 1964) and which we ourselves have already specified (Dionne, 1970).

The platform of ice covering the coasts during the ice season (3 to 5 months on the banks of the Saint-Laurent, 8 to 12 months in the Canadian Arctic), constitutes a natural defense effective against the action of waves, currents, tides, and physico-chemical and biological processes. Since the banks are partially defended against the direct action of thse modelling agents, the result is a relatively slow evolution of the shores of cold regions. For some authors (Wright and Priestley, 1922, pp. 322 - 324; Zumberge and Wilson, 1953; Marsh et al., 1973), this is supposed to be the principal role played by the icefoot. But the latter also proves to be an effective agent of erosion, transport and sedimentation (Dionne, 1970). In addition to carrying materials away from the surface of the strand and removing debris which has fallen to its surface from the cliffs, it erodes or directly undermines the loose surfaces and planes or thins the rocky platforms cut into the soft rock. In addition it promotes cryoclasism and the evacuation of debris (Nansen, 1922). Sometimes it causes a suspension of material when the waves break at its front, or controls the formation of a suitable but temporary balanced profile (Zumberge and Wilson, 1953, p. 203; Norrman, 1964; Marsh et al., 1973). In brief it exercises an important morpho-sedimentological action in the cold regions.

Conclusion

The notion of pied de glace or its English equivalent icefoot proves to be more complex than appears at first sight. However, part of this complex comes from the fact that authors do not agree, or more precisely have not tried to agree on the content of the term or expression, necessarily expressed by a certain amount of confusion since, for some the icefoot corresponds to a narrow fringe of ice at the upper limit of the coast, and for others it includes all of the ice platform covering the intertidal zone. One solution consists of distinguishing between an upper strand icefoot (icefoot in the strict sense) and a lower strand icefoot (icefoot in the broad sense), as we have done for the Saint-Laurent. This distinction seems fundamental to avoid any misunderstanding. Since studies referring to the icefoot are relatively few, this statement, in addition to clarifying am ambiguous idea, perhaps will have the virtue of arousing interest in more numerous researchers on a form apparently well known but little mentioned in the majority of works on littoral geomorphology, especially in French.

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