Géographie physique et Quaternaire

Freeze-thaw and shore platform development in Gaspé, Québec

Le rôle de la gélifraction dans la formation des plates-formes littorales en Gaspésie, Québec

Gefrieren und Auftauen, und die Entwicklung der Küsteplattform in Gaspé, Québec

A. S. Trenhaile and P. A. Rudakas

Volume 35, Number 2, 1981

Morphologie littorale et marine

URI: https://id.erudit.org/iderudit/1000435ar
DOI: https://doi.org/10.7202/1000435ar

See table of contents

Publisher(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (print)
1492-143X (digital)

Explore this journal

Cite this article

Trenhaile, A. S. & Rudakas, P. A. (1981). Freeze-thaw and shore platform development in Gaspé, Québec. *Géographie physique et Quaternaire*, *35*(2), 171–181. https://doi.org/10.7202/1000435ar

Article abstract

The role of freeze-thaw action in coastal environments, with particular reference to the formation of sub-horizontal shore platforms in Gaspé, Québec, was investigated experimentally. Rock cores and crushed rock samples were subjected to: two freeze-thaw cycles of twelve and twenty-four hour durations; fresh water and three artificial sea water solutions of about half, one and a half, and 'normal' salinity; and two drainage conditions representing rock pools and vertical well drained surfaces. These variables were selected to simulate some of the local environments which exist between the cliff top and low tide level in coastal Gaspé. Shales were the most susceptible to frost breakdown, followed in turn by argillites, calcisiltites and dolomitic silty argillites, and graywackes. Greatest disintegration tended to be associated with sea water solutions of about half-normal salinity. The data suggest that breakdown is greatest in the lower portions of the cliff. Freeze-thaw may produce the moat-like pools commonly found at the back of shore platforms. Although the process undoubtedly facilitates wave erosion of the platform and cliff, however, there is no evidence to suggest that it causes shore platforms to assume subhorizontal gradients.

Géographie physique et Quaternaire, 1981, vol. XXXV, n° 2, p. 171-181, 2 fig., 3 tabl.

FREEZE-THAW AND SHORE PLATFORM DEVELOPMENT IN GASPÉ, QUÉBEC

A.S. TRENHAILE and P.A. RUDAKAS, respectively, Department of Geography, University of Windsor, Windsor, Ontario N9B 3P4, and Petro-Canada, Calgary, Alberta

ABSTRACT The role of freeze-thaw action in coastal environments, with particular reference to the formation of sub-horizontal shore platforms in Gaspé, Québec, was investigated experimentally. Rock cores and crushed rock samples were subjected to: two freeze-thaw cycles of twelve and twenty-four hour durations; fresh water and three artificial sea water solutions of about half, one and a half, and 'normal' salinity; and two drainage conditions representing rock pools and vertical well drained surfaces. These variables were selected to simulate some of the local environments which exist between the cliff top and low tide level in coastal Gaspé. Shales were the most susceptible to frost breakdown, followed in turn by argillites, calcisiltites and dolomitic silty argillites, and graywackes. Greatest disintegration tended to be associated with sea water solutions of about half-normal salinity. The data suggest that breakdown is greatest in the lower portions of the cliff. Freeze-thaw may produce the moat-like pools commonly found at the back of shore platforms. Although the process undoubtedly facilitates wave erosion of the platform and cliff, however, there is no evidence to suggest that it causes shore platforms to assume subhorizontal gradients.

RÉSUMÉ *Le rôle de la gélifraction dans la formation des plates-formes littorales en Gaspésie, Québec*. Le rôle de la gélifraction en milieu littoral, en particulier dans la formation des plates-formes subhorizontales en Gaspésie, a été étudié d'une façon expérimentale. Des carottes et des fragments de roc ont été soumis à des cycles gel-dégel de 12 et de 24 heures, les uns dans de l'eau ordinaire et les autres dans de l'eau de mer à salinité normale, à demi-salinité et à salinité et demie, dans des conditions d'humidité correspondant à celles des cuvettes rocheuses et des escarpements verticaux. Les conditions furent déterminées en regard des milieux naturels locaux prévalant dans la zone comprise entre le haut de la falaise et le niveau des basses mers, sur la côte nord de la Gaspésie. Les schistes se sont révélés les plus sensibles à la gélifraction; viennent ensuite dans l'ordre de plus grande sensibilité, les argilites, les calcshistes, les argilites dolomitiques et les grauwackes. La gélifraction maximale s'est produite dans une solution correspondant à la demi-salinité de l'eau de mer. Les résultats indiquent que la gélifraction est plus importante dans la partie inférieure de la falaise. Elle pourrait être à l'origine des cuvettes superficielles entaillant les plates-formes littorales. Bien que la gélifraction soit un processus favorisant l'érosion par les vagues des plates-formes et des falaises, rien ne permet d'affirmer qu'elle soit à l'origine des plates-formes littorales subhorizontales en Gaspésie.

ZUSAMMENFASSUNG *Gefrieren und Auftauen, und die Entwicklung der Küsteplattform in Gaspé, Québec.* Die Rolle der Gelifraktion in Küstengegenden, mit besonderem Hinweis auf die Entstehung von subhorizontalen Küstenplattformen in Gaspé, Québec, wurde im Experiment untersucht. Bohrungskerne und zermahlene Gesteinsproben wurden folgenden Kräften ausgesetzt: zwei Gefrier-und Auftauzyklen von zwölf und vierundzwanzig Stunden Dauer, Frischwasser, und drei künstliche Salzwasserlösungen von ungefähr halber, anderthalber und "normaler" Salinität, und zwei Entwässerungs Verhältnissen, die einem Felskessel und senkrechten, gut drainierten Oberflächen entsprechen. Diese Varianten wurden gewählt, weil sie die örtlichen Umweltverhältnisse nachahmen, die man zwischen den Felsspitzen und der Ebbelinie an der Gaspé Küste finded. Die Tonschiefer waren am meisten von der Frostsprengung beeinflusst. Der Ordnung nach folgten, Argilite, Kalcisiltite, und dolomitische siltische Argillite und grau wacken. Die grösste Zersetzung wurde bei Seewassersolutionen von halb normaler Stärke beobachtet. Die Daten zeigen, dass der Verfall in der unteren Hälfte des Kliffs am grössten ist. Die Frosstsprengung könnte auch die flachen Becken hervorrufen, die man oft hinter der Küstenplattform finded. Wärend Frostsprengung ohne Zweifel die Wellenerosion der Küstenplattform und des Kliffs erleichtert, besteht jedoch kein Beweis, dass sie der Küstenplattform einen subhorizontalen Winkel gibt.

INTRODUCTION

Most shore platform literature written in the early part of this century was concerned with the origin of subhorizontal Australasian features. The elevation of these platforms relative to tidal levels, and their degree of exposure to vigorous wave action, were considered to be fundamental genetical criteria (TRENHAILE, 1980). Although BARTRUM (1916, 1924) believed that most horizontal platforms are wave cut, he developed the theory that in warm, wet areas, which are sheltered from strong wave activity, platforms may be produced by chemical weathering of the cliff, and removal of the debris by weak wave action. Horizontal shore platforms occur in Gaspé, despite the fact that the climate is not conducive to efficient chemical weathering. It has been argued that the shore platforms of Gaspé are primarily the product of mechanical wave erosion in a mesotidal environment (TRENHAILE, 1978; TRENHAILE and LAYZELL, 1980), but the contribution which freeze-thaw activity makes to the development of these features has not been assessed. Two questions need to be answered: a) Is mechanical weathering a major process of rock destruction in cool coastal regions; and more crucially, if the answer to a) is yes, b) Does mechanical weathering produce horizontal platform surfaces, or indeed, platforms with any characteristic morphology.

THE MECHANISMS

The approximately nine percent expansion, which is attendant to the change in phase from water to ice, is capable of generating considerable pressures under ideal conditions. Maximum pressures of 214 MPa at −22°C far exceed the tensile strength of even the most resistant rocks (RZHEVSKY and NOVIK, 1971; WINKLER, 1973). These pressures, however, are probably unobtainable in the field (GRAWE, 1936). Although many types of rock are severely damaged by their exposure to temperature fluctuations about the freezing point, the responsible mechanisms are still the subject of considerable debate. The disintegration of porous materials has been attributed to the segregation of ice into layers (COLLINS, 1944), the pressures exerted by growing ice crystals in capillaries (POWERS, 1955), the generation of hydraulic pressures (POWERS, 1955), and the expulsion of water into cracks and other crevices (LITVAN, 1976). These processes require the formation of ice, but there is considerable evidence to suggest that the disintegration of fine grained argillaceous rocks is the result of temperature dependent wetting and drying, associated with the adsorption of water molecules onto internal clay surfaces (DUNN and HUDEC, 1972; HUDEC, 1973). For convenience, the traditional terms "frost action" and "freeze-thaw" are used to refer to the work of these processes, although it should not be assumed that ice necessarily forms on the interior surfaces of the rock. It is not the purpose of this paper to identify the mechanisms responsible for rock disintegration, but one must be aware of these processes to deduce the possible role of frost action in the coastal zone.

If an interconnected void system is less than about 91.7% saturated, assuming a uniform distribution of water, ice may form in a rock without generating damaging pressures (POWERS, 1955). Although the critical saturation level may be considerably less in some porous materials (FAGERLUND, 1975), it may be very difficult to attain under natural circumstances. The behaviour of rocks exposed to freeze-thaw depends primarily upon the pore structure, particularly their size and continuity, permeability, and the degree of saturation (LEWIS *et al.*, 1953; WALKER *et al.*, 1969). DUNN and HUDEC (1972) found that resistant carbonate specimens were unable to absorb or retain much water. Frost action may be facilitated in coastal environments where they are kept moist by spray or tidal action (TABER, 1950; MACKAY, 1963). Coastal engineers have long recognized the severity of cool coastal environments on concrete structures (COOK, 1952; SEKI, 1975; ACI, 1980).

Although salts lower the freezing point and probably reduce the number of freeze-thaw cycles which can occur in a given period, it is well known that rocks break down more readily in saline solutions than in fresh water. This may be because of greater osmotic pressures, or because of the higher levels of saturation which may be maintained during freezing (POWERS, 1975; MacINNES and WHITING, 1979). Several studies, however, have shown that the greatest disintegration occurs in solutions ranging from about one half to one and a half times the normal salinity of sea water (VERBECK and KLIEGER, 1957; LITVAN, 1976; MacINNES and WHITING, 1979).

COASTAL FROST ACTION

In a coastal environment, the saturation level of a rock is determined by its pore structure, and by its position in the supra- or intertidal zones. The salinity of the water in contact with that rock may at different times range from concentrated brines to fresh water. Fresh water may be provided by melting icefoots composed of frozen meltwater, snowdrifts, precipitation, or snowmelt running down the cliff face. Effective frost action in the coastal zone requires enough wave action to remove the weathered debris. In Spitsbergen, rapid cliff retreat results from intense frost shattering in spring, and debris removal by the sea in summer (MOIGN, 1974, p. 680-688; GUILCHER, 1974). Unless wave action is vigorous, however, weathered debris accumulates and progressively buries the cliff (BIRD, 1967; HOWARTH and BONES, 1972).

Even though frost action may be effective in the retreat of coastal cliffs in some areas, it remains to be answered whether this work produces shore platforms. Several workers have suggested that it does. A number of early workers emphasised the role of frost to explain the formation of platforms in polar areas where fetch is limited. NANSEN (1922) partly attributed the development of the Norwegian strandflat to frost action, and ZENKOVITCH (1967) suggested that benches may result from frost action undercutting the cliff in the frequently wetted spray zone, above the level of the high spring tides. Extensive limestone platforms on the southern coast of Anticosti Island have been ascribed to a combination of solution and frost action at the cliff base, with the removal of the debris by the icefoot (CORBEL, 1958). In western Scotland, intense frost shattering in the intertidal zone may have produced shore platforms, formed in hard rocks in sheltered areas (SISSONS, 1074). SOLLID *et al.* (1973), ANDERSEN (1968). MOIGN (1974), and DAWSON (1980), have arrived at similar conclusions.

EXPERIMENTAL WORK

Most experimental investigations have been carried out to determine the durability of rocks as building materials. Little geomorphological work was conducted until the 1950's. Subsequently, TRICART (1956), MASSEPORT (1959), and GUILLIEN and LAUTRIDOU (1970) investigated the effect of frost action on calcareous rocks, LAUTRIDOU and COUTARD (1971) considered shales, and WIMAN (1963) and MARTINI (1967) examined its effect on more resistant rocks, such as granite, conglomerate, and gneiss. POTTS (1970) used specimens of igneous, sandstone, mudstone, and shale rocks, and found that shales break down most readily. An examination of the results of these and many other studies has shown that, despite some contradiction, most workers have found that the least durable rocks are generally fine grained, and of low tensile strength. They include well foliated metamorphic rocks such as slates, phyllites, and argillites, friable chalks, and fissile shales, siltstones, claystones, and other sedimentary rock containing mica or illite clays. Resistant lithologies include medium and coarse grained quartzites, lithographic limestones, and igneous rocks such as basalts, coarse grained granites, peridotites, and pyroxenites. An important experimental consideration is the degree of saturation of the rock specimens when they are frozen. Generally, the greater the amount of water which is made available to the rock, the greater is the degree of disintegration (GUILLIEN and LAUTRIDOU, 1970; POTTS, 1970; DOUGLAS, 1970; see EMBLETON and KING, 1975, p. 9). The duration and the temperature range of the freeze-thaw cycles are also of great importance, since the bulk freezing strain of a rock may increase with the freezing rate, as well as with the water content (MELLOR, 1970). Experimental results and field evidence, however, are contradictory. A number of workers consider that fast rates of freezing or 'Icelandic' cycles with high frequency, are most conducive to frost shattering (THOMAS, 1938; BATTLE, 1960; WIMAN, 1963; ARNI, 1966; POTTS, 1970; LAUTRIDOU, 1978). Others, however, have found that the most rapid disintegration is associated with slow freezing, or with 'Siberian' cycles of low frequency (TABER, 1950; TRICART, 1956). This contradiction may arise because some mechanisms, such as the generation of damaging hydraulic pressures, require fast freezing rates, whereas others, such as crystal growth and the segregation of ice into layers, are facilitated by slow freezing.

THE STUDY AREA

Shore platforms occupy most of the northern Gaspesian coast, between Rivière-à-Claude and Rivière-au-Renard (Fig. 1). They have formed in the steeply dipping middle Ordovician Chloridorme Formation, consisting of: dark grey shales and argillites, which constitute about sixty percent of the formation; interbedded coarse graywackes which comprise about fifteen percent; calcisiltites twenty percent; calcareouswackes three percent; and dolostones, limestones, volcanic ash, and silty dolomitic argillite which make up about two percent (ENOS, 1969). The platforms are quasi-horizontal and often terminate abruptly seawards in a low tide cliff or ramp. Their morphology has been attributed to wave erosion operating within a tidal range of only between 2.25 and 3.4 m, but freeze-thaw appears to be an important secondary process (TRENHAILE, 1978).

Gaspé is situated between the temperate low pressure and the polar high pressure systems. In winter, polar continental air dominates the area, but in summer, weakening of this system permits the intrusion of warmer air. Gaspé is in a wet, cool temperate climatic zone, with a mean annual air temperature of about 2.5°C, and mean daily maximum temperatures less than −10°C in January, and 20°C in July (Fig. 2). In the five year period 1971-75, an average of forty-one freeze-thaw days (temperatures ranging from 1.1°C or higher, to −2.2°C or lower in twenty-four hours), occurred each year at Mont-Louis, and sixty-one at Grande-Vallée. The greatest number occurs in March and April, although November is also a period of considerable frost activity. About forty percent of the 90 to 100 cm of annual precipitation falls as snow. On this shaded northward facing coast, the intertidal zone is ice covered from about mid-December to late March or early April (OWENS, 1974), and may persist into late May.

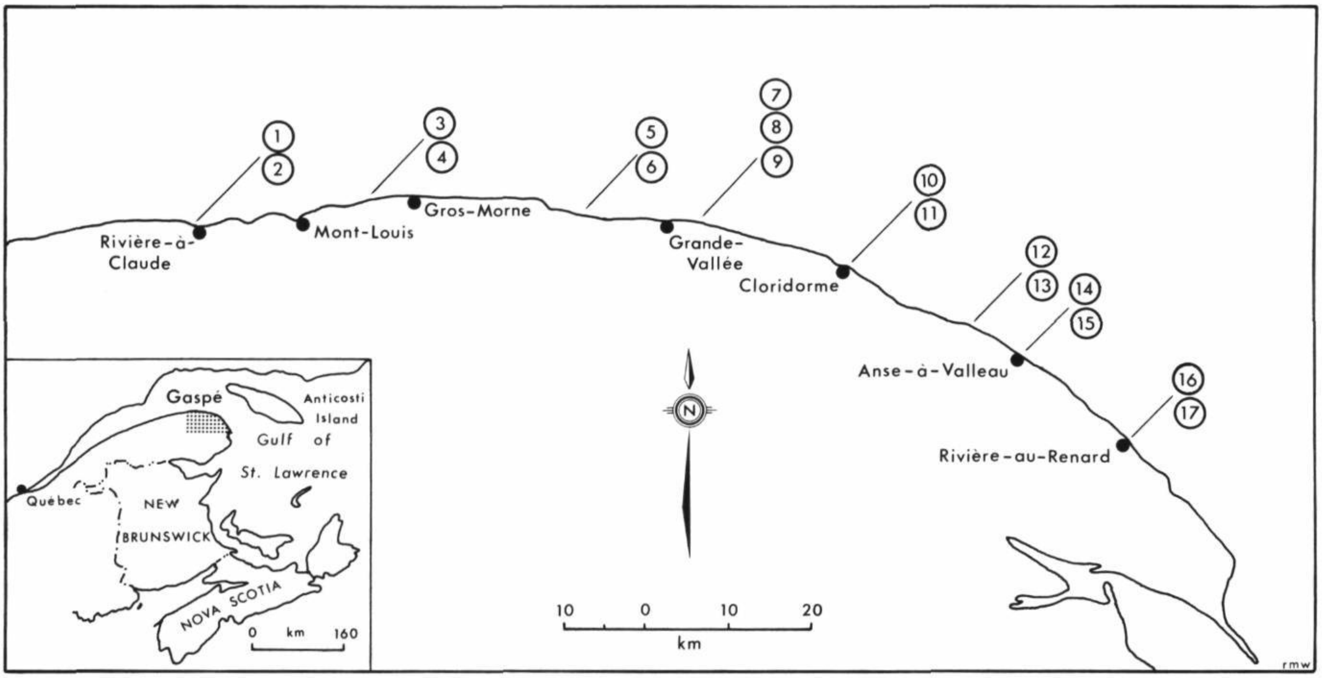

FIGURE 1. The study area, showing where each rock specimen was obtained (see tables for lithologies).

Carte de localisation de la région étudiée et emplacement des échantillons (voir les tableaux pour les données lithologiques).

EXPERIMENTAL METHOD

The resistance of seventeen Gaspesian rock samples to freeze-thaw activity was investigated (Fig. 1). The graywackes largely consist of quartz with a matrix of illite, with some chlorite and carbonaceous material. The shales and argillites contain a greater proportion of mica and clay minerals, and a lower proportion of quartz. Flakes of chlorite and muscovite lie between the bedding planes of the argillites and shales. The argillites mostly consist of chlorite and illite, whereas the dolomitic silty argillite is largely illite with small amounts of quartz, carbonaceous fragments, and muscovite flakes. The clastic carbonates and calcisiltites have small amounts of quartz in a matrix which is largely composed of chlorite with some carbonaceous material. Pyrite occurs in small lenses intermittently throughout the calcisiltite.

A total of twenty-four cores were extracted from each rock sample, using a 25 mm diameter diamond drill. Each core was cut to a length of 25 mm, using a diamond bladed circular saw. The use of cores eliminated the effect of variable rock size and shape on the rate of breakdown. The remaining portions of the rock samples were crushed and sieved, the fraction between 10 and 13 mm being retained and stored in 0.1 kg units.

Separate core and crushed rock samples were used to determine the bulk specific gravity and absorption capacity (%) of the rock samples, according to the techniques described by WINKLER (1973). The samples were then placed into a freezing chamber equipped with a temperature cycling device. Three variables besides rock type were used to try to simulate spatial and temporal variations in the coastal environment of Gaspé.

Artificial sea water was prepared using Kalle's data (see RILEY and SKIRROW, 1975). Four salinity levels were used: distilled water; sea water (35‰); and one half (17‰) and one and a half times (52‰) the salinity of 'normal' surface sea water. The salinity levels were selected with reference to values found in the field in Gaspé, and reports from other areas (*eg.* TRITES and WALTON, 1975; EL-SABH, 1975; SCHNEIDER, 1976; TRUDGILL, 1976). Although constant values had to be assigned to specific environments, it should be re-emphasised that the salinity of rock pools may vary greatly at different times. In one series of experiments, sufficient water was used to completely inundate the rock cores and fragments, whereas in another, only enough water was used to cover the lower half of the samples. In both experiments, the quantity of water available to the rock specimens was carefully measured. The third variable concerns the characteristics of the freeze-thaw cycles used in the experiments. Two cycles were used, based upon the daily weather records available for this coast. The first cycle was of twelve hours duration, of which two-thirds consisted of temperatures

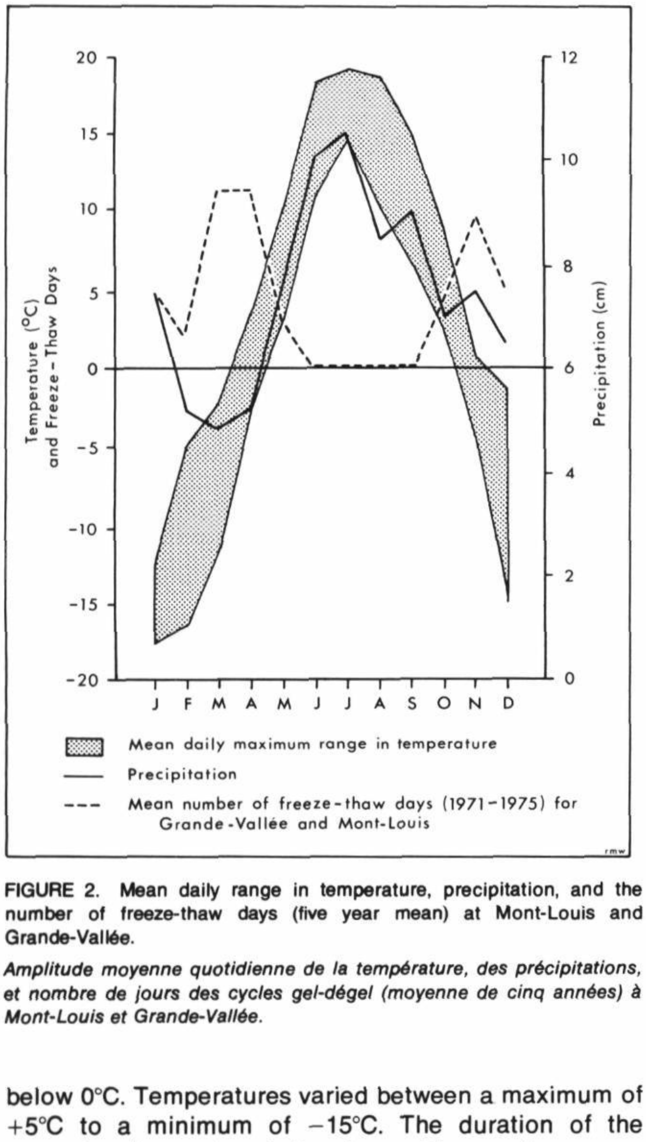

FIGURE 2. **Mean daily range in temperature, precipitation, and the number of freeze-thaw days (five year mean) at Mont-Louis and Grande-Vallée.**

Amplitude moyenne quotidienne de la température, des précipitations, et nombre de jours des cycles gel-dégel (moyenne de cinq années) à Mont-Louis et Grande-Vallée.

below 0°C. Temperatures varied between a maximum of +5°C to a minimum of −15°C. The duration of the second cycle was twenty-four hours. Temperatures were above freezing for eight hours, reaching a maximum of +5°C, and below freezing for sixteen hours, reaching a minimum of −10°C after eight hours of freezing. The first cycle was chosen to represent changing temperatures in the intertidal zone, induced by a combination of fluctuating air temperatures and tidal levels. In the intertidal zone, rocks may freeze during low tide while exposed, but rapidly thaw at high tide when inundated. The cycle represents an average drop in temperature of 1° in 1.08 ks and one of 1° in 0.96 ks for the subzero portion. The cycle is similar to that recorded in the intertidal zone of Maine (COOK, 1952). The second cycle was chosen to approximate the range of maximum and minimum average daily temperatures above high tide level during the months in which there are freeze-thaw days at Mont-Louis and Grande-Vallée. Average temperature drops at a rate of 1°C in 2.88 ks, which is the same as that in the subzero portion of the curve.

The cores and the crushed rock samples were oven dried for twenty-four hours at 65°C, then dried in a dessicator, cooled, and weighed. Each specimen was then placed in a container with the required amount of water of known salinity, and placed in the freezing chamber which was set to reproduce one of the specified temperature cycles. Each experiment was run for twenty-five days, subjecting the rocks to either fifty or twenty-five freeze-thaw cycles, depending upon the cycle in use. The experiments were duplicated using two specimens from each rock sample. During each experiment, the samples were periodically examined to ensure that the required water levels were being maintained, the levels being topped up with water of the same temperature and salinity when necessary. Weight loss by the cores was measured during and after completion of each experiment by washing with distilled water to remove the salt, then by drying for twenty-four hours at 65°C, to avoid extreme dessication. Weight loss for the crushed samples was obtained by first filtering out the water, washing with distilled water, and drying for twenty-four hours. The samples were then resieved on a 10 mm screen, and the fraction remaining weighed. An error value, emanating from weight loss caused by alternate wetting and drying and from sieving itself, was previously determined in a separate experiment; this was then used as a correction factor to determine the weight loss owing to freeze-thaw alone.

RESULTS

Rock cores generally experienced far less disintegration than the crushed rock samples. Disintegration of the cores tended to occur along planes of weakness. Most disintegration of the cores occurred in the shale specimens, in which numerous S-planes (WIMAN, 1963) provided access to growing ice. The rock samples which disintegrated most readily were those which were able to absorb the greatest amounts of water. Using the average percentage breakdown of crushed rock samples for all salinity and drainage conditions, provided a significant correlation value of 0.71 between the amount disintegrated and the absorption weight of each specimen using the twenty-four hour cycle, and one of 0.52 for the twelve hour cycle. These correlations are high, considering that it is not the total amount of water which is absorbed, but the proportion contained in small capillaries that is important (HUDEC, 1977). SWEET (1948), for example, found no relationship between absorption and frost susceptibility. The mean value of the absorption weight of the shale samples was 2.57 percent, compared with 0.85 for the argillites, 0.41 for the graywackes, 0.40 for the dolomitic silty argillites, and 0.32 for the calcisiltites. These values approximate, in a general way, the relative susceptibility of each rock type to freeze-thaw activity. The correlations between the amount of disintegration and bulk specific gravity were found to be insignificant.

The disintegration of the argillites and shales produced flat tabula flakes, varying in size from 0.5 to 5.0 mm from the cores, and from 0.5 to 3.0 mm from the crushed rock. Very little breakdown of the graywacke cores occurred, but what did, produced very small fragments between 0.5 and 0.2 mm in size. Graywacke crushed rock samples produced slightly larger fragments between 2.0 and 4.0 mm in diameter. Calcisiltite cores produced small elongated, rod-like fragments about 0.5 mm in size, whereas the crushed rock fragments ranged from 1.0 to 7.0 mm.

Only 12 of 408 rock cores experienced disintegration amounting to more than one percent of their original mass, most of these being shale or argillite samples (Table I). Lack of disintegration prevented statistical analysis of these core data, but prompted some general observations:

a) the greatest disintegration is associated with total rather than partial inundation of the cores;

b) very saline environments are not suitable for rapid disintegration of rock cores, relative to normal sea water, or more especially to solutions of one half the salinity of sea water;

c) the presence of a fairly low amount of salt appears to facilitate rock disintegration in comparison with that which is possible in fresh water; and

d) disintegration is greater when the twelve hour freeze-thaw cycle is used.

The crushed rock samples experienced much greater variation in the rates of disintegration according to the environmental conditions (Table II). All lithologies again disintegrated most readily when the twelve hour freeze-thaw cycle was used. To determine whether rock breakdown varies according to rock type, salinity, the availability of water, and the characteristics of the freeze-thaw cycle, a multivariate analysis of variance test was employed (LINDQUIST, 1956). All variables were found to make a significant contribution to the variation in the rate of disintegration, accounting in sum for seventy-four percent of the total variation. Rock type and the type of cycle were the most significant, followed by the availability of water and its salinity, although the latter factor was only of minor importance. The F-ratios indicated that the type of cycle was probably the most important factor, although the experimental design does not enable one to determine whether it is the lower freezing temperatures, the more rapid freezing rates, or the greater frequency of freezing which makes the twelve hour cycle more potent in the disintegration of the rock samples than the twenty-four hour cycle. Significant although minor interaction effects between

TABLE I

Disintegration of rock cores (%)

No.	Lithology	— Partial Immersion —			— Full Immersion —		
		Salinity			Salinity		
		0.0‰	17‰	35‰	17‰	35‰	52‰
1	Shale	0.14/0.24	0.21/0.33	0.11/0.21	0.42/0.52	0.31/0.18	0.25/0.48
2	Graywacke	–	–	–	–	–	–
3	Shale	0.10/1.10	0.63/0.87	0.21/0.56	1.22/3.26	1.53/0.13	1.31/1.68
4	Graywacke	0.12	– /0.36	–	–	–	–
5	Graywacke	–	–	–	–	–	–
6	D.S. Argillite	0.11	0.12/0.13	–	–	–	–
7	Graywacke	0.10	–	–	–	–	–
8	Calcisiltite	–	–	–	–	–	–
9	Calcisiltite	–	–	–	– /1.27	– /0.12	–
10	Calcisiltite	–	–	–	–	–	–
11	Shale	– /0.17	– /0.12	0.25/0.56	0.12/0.61	0.24/1.02	0.10/0.49
12	Argillite	0.14/0.10	0.23/0.26	0.10/0.10	0.88/0.45	– /0.29	0.17
13	Argillite	– /0.10	–	0.38	–	–	–
14	Calcisiltite	–	–	–	–	–	–
15	Calcisiltite	–	–	–	–	–	–
16	Calcisiltite	0.10/0.11	– /0.38	–	– /0.44	0.44	–
17	Calcisiltite	– /0.65	–	–	0.17	–	–

Only values > 0.1% are shown. The first value represents the breakdown recorded when the twenty-four hour cycle was used, the second, the breadown with the twelve hour cycle. Each value is the mean breakdown of two rock cores.

TABLE II

Disintegration of rock fragments (%)

No.	Lithology	— Partial Immersion —			— Full Immersion —			Mean	Standard Deviation
		0.0‰	17‰	35‰	17‰	35‰	52‰		
1	Shale	5.08/ 7.99	4.04/10.40	3.07/6.14	1.89/5.36	5.29/6.65	4.78/4.63	4.03/6.86	1.32/2.08
2	Graywacke	0.65/ 1.09	0.38/ 2.38	0.18/0.95	0.58/1.22	0.97/1.87	0.15/0.73	0.49/1.37	0.31/0.63
3	Shale	1.24/ 4.61	2.23/ 5.32	2.65/6.40	3.06/5.04	2.05/2.27	2.88/4.14	2.35/4.63	0.67/1.38
4	Graywacke	0.78/ 2.04	0.55/ 2.43	1.57/1.92	0.40/0.46	1.61/2.39	0.17/1.33	0.85/1.76	0.61/0.75
5	Graywacke	0.27/ 0.85	0.62/ 1.98	0.68/0.93	0.37/1.01	1.04/1.26	0.10/1.79	0.51/1.30	0.54/0.47
6	D.S. Argillite	1.34/ 1.52	2.02/ 6.19	1.01/2.33	1.76/3.26	0.85/0.84	0.49/1.07	1.25/2.54	0.58/2.00
7	Graywacke	1.60/ 2.83	0.66/ 1.15	0.47/3.91	0.79/1.88	1.08/8.81	0.13/1.15	0.79/3.29	0.51/2.91
8	Calcisiltite	0.26/ 2.65	0.34/ 3.19	0.58/1.69	0.32/2.68	0.49/1.06	0.86/4.70	0.48/2.66	0.22/1.26
9	Calcisiltite	0.56/ 2.10	2.44/ 3.01	1.29/1.51	1.40/1.73	0.71/6.59	1.93/1.89	1.39/2.81	0.71/1.93
10	Calcisiltite	0.66/ 1.01	1.61/ 3.82	1.18/1.47	0.34/2.45	0.61/1.94	0.12/3.99	0.75/2.45	0.55/1.23
11	Shale	3.56/ 4.24	3.38/ 4.19	2.23/2.29	1.68/2.22	0.96/1.16	0.77/2.08	2.10/2.70	1.19/1.24
12	Argillite	0.35/ 6.31	6.44/ 7.33	2.41/5.41	1.95/1.98	0.96/2.54	1.23/2.01	2.22/4.26	2.19/2.37
13	Argillite	1.95/ 2.17	0.87/ 2.39	0.41/1.54	1.26/1.30	0.29/2.54	0.79/1.34	0.93/1.88	0.61/0.55
14	Calcisiltite	0.92/ 1.68	0.96/ 2.51	0.70/2.85	0.73/4.40	0.51/0.64	1.01/1.18	0.81/2.21	0.19/1.35
15	Calcisiltite	1.49/10.09	1.22/ 4.66	1.40/2.98	2.00/3.83	0.45/1.01	0.47/1.65	1.17/4.04	0.61/3.26
16	Calcisiltite	1.67/ 2.36	0.68/ 8.46	0.89/2.06	2.93/5.32	0.63/1.68	0.67/2.95	1.25/3.81	0.91/2.62
17	Calcisiltite	0.56/ 2.68	1.69/ 5.42	0.84/2.13	0.75/2.36	0.40/0.68	0.74/1.41	0.83/2.45	0.45/1.62
Mean		1.35/ 3.31	1.77/ 4.40	1.27/2.74	1.31/2.74	1.11/2.58	1.02/2.34		
Standard Deviation		1.26/ 2.60	1.61/ 2.52	0.85/1.72	1.02/1.55	0.88/2.40	1.17/1.32		

the type of rock and the number of cycles indicated that different lithologies respond at different rates to the stresses imposed. Weak interaction between rock type and salinity also indicates that the response of rocks to freeze-thaw varies according to the salinity of the solutions. In contrast to the rock cores, and to previous reports, the greatest disintegration occurred when the rock fragments were only partially rather than fully inundated in the solutions, but the differences were generally slight. A weak but significant interaction occurred between the salinity and moisture availability effects on rock disintegration, as suggested by DUNN and HUDEC (1972). The effect of salinity variations on rock disintegration was significant but weak. Maximum disintegration tended to be associated with salinity levels which are approximately half that of normal sea water.

A battery of t-tests was used to assess the effect of individual variables on rock disintegration. Firstly, tests were run between combinations of water availability and salinity for the same rock types. Secondly, rock disintegration was compared between the different rock types, and this was followed by tests of the differences between the two freeze-thaw cycles with the other variables held constant. Finally, the effect of differences in the availability of moisture was evaluated. Because of the small number of dolomitic silty argillite samples, tests were not run for this rock type. With the exception of totally inundated graywackes in a 52‰ saline solution, subject to the twenty-four hour cycle, no significant differences (at the 0.05 level) were found between rock disintegration in fresh and saline environments. A few differences between the disintegration of calcisiltites and graywackes in solutions of different salinity were significant, but none for the shales and argillites. With the exception of the argillites and calcisilities, the disintegration of all rock types was significantly different, whichever freeze-thaw cycle was used. Similarly, the effect of the different cycles was significantly different for all rock types. With the exception of calcisilities in 35‰ salt solutions, the availability of moisture was not significant in determining rates of disintegration.

The disintegration of the crushed rock samples was greater for the shorter duration cycle, as it was for the rock cores. The fastest disintegration of the crushed specimens generally occurred within the first five days of each experiment.

The results for the crushed rock samples may be summarised as follows:

a) The disintegration of the samples was largely determined by the type of freeze-thaw cycle and by the type of rock. The greatest disintegration occurred when the twelve hour cycle was used. Shales were the least durable rock type, followed in increasing order of durability by argillites, calcisiltites, and graywackes;

b) Although the amount of disintegration was slightly greater if the specimens were partially rather than completely inundated, this surprising relationship was not statistically significant;

c) Similarly, whereas the greatest breakdown occurred in solutions of about half normal sea water salinity, differences were not significant over the rather narrow range of salinities which were considered.

DISCUSSION

The question arises with all experimental work of a geomorphological nature, whether the results are applicable to the real world. All that can be said with confidence is that rock cores and fragments disintegrate at various rates in the laboratory under certain environmental conditions. The variables used in this study were selected in an attempt to simulate environmental conditions along the Gaspé coast, but considerable measurement needs to be made in the field before they can be accepted with confidence. This is particularly true of the temperature cycles used in this study. Although they were selected with reference to the climatic record, because these data refer to air temperatures, rather than to the temperatures at the rock surface, the cycles are essentially arbitrary. The experimental results discussed in this paper therefore, should be considered only as a rough guide to the effect of environmental factors on rock disintegration. Rates of disintegration may be considered to be indicative of the relative susceptibility of various rocks in various environments to frost action, but not as a true indication of the erosion rate *per se.*

Using the data provided by the crushed rock samples, and to a lesser extent by the cores, it is tempting to speculate on the relative importance of frost action on the coastal profile. In the intertidal zone, it is probable that low temperatures beneath the ice prevent effective freeze-thaw activity between mid-December and the end of March, so that it is largely restricted on the platform to the months of April, May, November, and early December. On the cliff, however, freeze-thaw may be active from October to May, nurtured by fresh rain, ground water, and snowmelt, together with saline sea spray when the nearshore zone is ice free. The salinity of tidal pools varies according to tides, precipitation, and evaporation; ice formation may increase the salinity of pools and nearshore waters. Fresh water may be abundant on the platform and it may lower the salinity of pools near the cliff base in late April and early May, as the icefoot melts. Evaporation and rainfall are greatest during the summer months when there are no freeze-thaw cycles, but they also affect salinity levels to a lesser degree at other times.

A relative value for the rock disintegration caused by freeze-thaw was calculated, in which:

$$I_f = \Sigma (E/C) F_d$$

where I_f is the freeze-thaw disintegration index; E is the percentage disintegration of a rock under the specified environmental conditions; C is the number of days over which each experiment was run (25); and F_d is the average number of days of freeze-thaw in the required month. I_f is obtained by summing the values for each month. For the platform, the value of E was obtained using the results of the experiments with the twelve hour "intertidal" freeze-thaw cycle, whereas the twenty-four hour cycle was used for the cliff. Each combination of variables is assumed to represent a natural environment in the coastal zone. The upper portion of the cliff, above the level of abundant sea spray, is dominated by fresh rain water or snowmelt, whereas at lower levels, sea spray and salts, possibly accumulated by evaporation, provide a more saline environment. On both the upper and lower portions of the cliff, steep gradients prevent sufficient accumulation of water to inundate the rock. On the platform, freezing takes place while it is exposed to air temperatures, since water temperatures are above freezing for the months in which freeze-thaw is active (EL-SABH, 1975). On the platform therefore, freeze-thaw must take place on rocks which are not inundated, and in environments in which water is not abundant. In tidal pools, however, rocks are inundated for long periods in solutions which vary greatly in salinity. Each of these environments is represented by an experimental run. The results suggest that rapid disintegration of shales by frost action in the upper and lower portions of the cliff may facilitate platform development (Table III). The most active environment is the lower cliff, where the argillites are also very susceptible to disintegration. This conclusion is compatible with the occurrence of a shale and argillite scree which covers the cliff base in mid-May, near the end of the spring freeze-thaw period. The experimental data of this and other studies suggest that if the salinity of the solution was increased to that of sea water, as when high onshore winds drive spray on to the lower cliff, the rate of disintegration would decrease. A supply of fresh water therefore, is a favourable, although not essential factor, for the destruction of marine cliffs by freeze-thaw.

On the platform, rapid disintegration may be accomplished on argillites and shales during periods of low tide, and in pools of mixed seawater and freshwater. In the pools, there is an indirect relationship between the rate of destruction and the presence of salts.

The results may explain, in part, the occurrence of pools associated with shale outcrops in Gaspé and in similar rocks elsewhere, such as in western Newfoundland. These pools are generally most pronounced near the back of the platforms. This may be because this area is exposed to freezing air temperatures most fre-

TABLE III

Disintegration indexes for Gaspé

	Partial Immersion Salinity			Full Immersion Salinity		
	0.0‰	17‰	35‰	17‰	35‰	52‰
Shale	7.01	6.91	6.33	5.39	4.30	4.65
Argillite	2.45	5.60	4.44	2.10	3.25	2.07
Graywacke	1.73	1.35	2.47	2.93	4.58	1.61
Calcisiltite	1.85	2.34	2.68	4.17	2.49	3.25
D.S. Argillite	2.85	3.72	2.98	4.17	1.07	1.37
Environment	upper cliff and back of platform	lower cliff	platform surface	— platform pools —		

quently, and for the greatest period of time. Alternatively, however, it is also the area where snowmelt from the icefoot accumulates in April and May, and the only area where rainfall may remain for some time before being replaced by seawater. The data suggest that the presence of freshwater may be an important factor in explaining the destruction of shales.

The question remains, however, whether frost action can produce horizontal platforms. Let us assume that a smooth horizontal surface has developed in the steeply dipping rocks of Gaspé. The data suggest that pools will develop on the shale outcrops, and less rapidly on the argillites. Inundation of the shales and argillites retards further deepening of the pools, particularly if they have developed in argillites, whatever the salinity of the pool waters. Nevertheless, because of the much slower disintegration of the surrounding graywackes and calcisiltites, pool deepening will continue, thereby accentuating the irregularity of the platform surface. Similarly, if mechanical wave erosion initially provides a sloping wave cut ramp, the role of freeze-thaw will be largely restricted to emphasising its irregularity, rather than to lowering its gradient. Slight flattening at the cliff foot may be associated with shale outcrops and a supply of fresh water, but it is locally restricted and, in any case, can hardly explain the general occurrence of linear subhorizontal platform profiles throughout Gaspé.

CONCLUSIONS

These preliminary results suggest that freeze-thaw plays an important role in the development of cool coastal regions. The data and field observations suggest that shales, argillites, and other fine grained argillaceous rocks often rapidly disintegrate in coastal cliffs. To this extent therefore, frost action may facilitate, and in some cases be a necessary precursor to, the formation of shore platforms in cool climates. Whether frost action is also capable of producing subhorizontal platforms, however, is less clear. The experimental data provided by this and numerous other studies has demonstrated that there is a considerable difference in the susceptibilities of various rock types to temperature fluctuations about the freezing point. Unlike mechanical wave action, in which various negative feedback mechanisms operate to arrest the continued deepening of pools cut in the weaker strata, it appears that shales and other particularly susceptible lithologies would continue to be deepened by frost action after they become the sites of rock pools. The work of frost, therefore, appears to be to emphasize rather than to eliminate platform irregularities. It is difficult to understand how fairly smooth, subhorizontal platforms could be formed by freeze-thaw processes across a variety of rock types. It should also be noted, although a full explanation will be published elsewhere, that the most frequent fluctuations in air temperatures about the freezing point, and the freezing of rocks in air and thawing in water, occur in the midlatitude storm wave environments, where wave action is also most vigorous, rather than in polar low wave energy environments. Those rocks, which have been found to be most susceptible to physical weathering, are also particularly vulnerable to mechanical wave erosion. Vigorous wave erosion of weak rock formations may therefore prevent efficient frost weathering in many areas. Where the coast is sheltered from wave action, weathering may assume a more dominant role, but without sufficient wave action to remove the debris, the process cannot operate efficiently. Weathering may be an important agent of cliff erosion in some areas, and may be capable of producing narrow, rugged platform surfaces, particularly if the rock is fairly homogeneous. It is difficult, however, to attribute the formation of smooth, subhorizontal platforms to physical weathering, where they truncate a variety of rock types. Nevertheless, much more needs to be done in the laboratory and in the field, if we are to confidently assess the role of frost and related processes in coastal environments.

ACKNOWLEDGMENT

This work was made possible by a grant from the NSERC of Canada.

REFERENCES

ACI (1980): *Performance of Concrete in Marine Environment*, (Am. Concrete Inst., Detroit), Paper SP 65, 627 p.

ANDERSEN, B.C. (1968): Glacial geology of western Troms, north Norway, *Norges Geol. Unders.*, vol. 256, p. 1-160.

ARNI, T.H. (1966): Resistance to weathering, *Amer. Soc. Testing Mater.*, Stand. Spec. Tech. Publ., Vol. 169A, p. 261-274.

BARTRUM, J.A. (1916): High water rock platforms: a phase of shoreline erosion, *Trans. N.Z. Inst.*, Vol. 48, p. 132-134.

——— (1924): The shore platform of the west coast near Auckland: its storm wave origin, *Rept. Austr. Assoc. Adv. Sci.*, Vol. 16, p. 493-495.

BATTLE, W.R.B. (1960): Temperature observations in bergschrunds and their relationship to frost shattering, *Roy. Geogr. Soc. Res. Series*, Vol. 4, p. 83-95.

BIRD, J.B. (1967): *The Physiography of Arctic Canada*, Baltimore, John Hopkins, 336 p.

COLLINS, A.R. (1944): The destruction of concrete by frost, *Inst. Civil Eng. J.*, Vol. 23, p. 29-41.

COOK, H.K. (1952): Experimental exposure of concrete to natural weathering in marine locations, *Amer. Soc. Testing Mater.*, Vol. 52, p. 1169-1180.

CORBEL, J. (1958): Les karsts de l'Est canadien, *Cah. Géogr. Qué.*, Vol. 2, No. 4, p. 193-216.

DAWSON, A.G. (1980): Shore erosion by frost: an example from the Scottish lateglacial, *in Studies in the Lateglacial of North-west Europe*, LOWE, J.J., GRAY, J.M., and ROBINSON, J.E. (eds.), Oxford, Pergamon, p. 45-53.

DUNN, J.R. and HUDEC, P.P. (1972): Frost and sorption effects in argillaceous rocks, *Highways Res. Board,* No. 393, p. 65-78.

EL-SABH, M.I. (1975): *Transport and currents in the Gulf of St. Lawrence*, Bedford Inst. Ocean. Rept. Ser., No. BI-R-75-9, 180 p.

EMBLETON, C. and KING, C.A.M. (1975): *Periglacial Geomorphology*, London, Edward Arnold, 203 p.

ENOS, P. (1969): *Chloridorme formation, middle Ordovician flysch, northern Gaspé peninsula, Québec*, Geol. Soc. Amer. Spec. Pap., No. 117, 66 p.

FAGERLUND, G. (1975): The significance of critical degrees of saturation at freezing of porous and brittle materials, *in Durability of Concrete* (Am. Concrete Inst., Detroit), Pap. SP 47-2, p. 13-65.

GRAWE, O.R. (1936): Ice as an agent of rock weathering: a discussion, *J. Geol.,* Vol. 44, p. 173-182.

GUILCHER, A. (1974): Les rasas: un problème de morphologie littorale générale, *Ann. Géogr.,* Vol. 83, p. 1-33.

GUILLIEN, Y. and LAUTRIDOU, J.-P. (1970): *Recherches de gélifraction expérimentale du centre de géomorphologie — 1. Calcaires des Charentes*, Bull. Centre de Géomorphologie de Caen, Vol. 5, 45 p.

HOWARTH, P.J. and BONES, J.G. (1972): Relationships between process and geometrical form on high Arctic debris slopes, south-west Devon Island, Canada, *in Polar Geomorphology*, PRICE, R.J. and SUGDEN, D.E. (eds.), Inst. Brit. Geog. Spec. Publ. No. 4, p. 139-153.

HUDEC, P.P. (1973): Weathering of rocks in arctic and subarctic environment, *in Canadian Arctic Geology*, AITKEN, J.D. and GLASS, D.J. (eds.), Geol. Soc. Assoc. Can. — Can. Soc. Petroleum Geol. Symp. (Saskatoon, Sask.), p. 313-335.

——— (1977): Deterioration and dimensional changes on wetting of carbonate rocks as a function of adsorbed water content, *in Proc. 2nd Int. Symp. on water-rock interaction* (Strasbourg, France), Vol. 4, p. 38-45.

LAUTRIDOU, J.-P. (1978): Principaux résultats des expériences de gélifraction expérimentale effectuées au centre de géomorphologie, *Inter-Nord*, Vol. 15, p. 5-13.

LAUTRIDOU, J.-P. and COUTARD, J.-P. (1971): *Recherches de gélifraction expérimentale du centre de géomorphologie. Schistes, grès et roches métamorphiques de Basse-Normandie. Conclusions générales*, Bull. Centre de Géomorphologie de Caen, Vol. 10, 84 p.

LEWIS, D.W., DOLCH, W.L. and WOODS, K.P. (1953): Porosity determinations and the significance of pore characteristics of aggregates, *Amer. Soc. Testing Mater. Proc.*, Vol. 53, p. 949-958.

LINDQUIST, E.F. (1956): *Design and Analysis of Experiments in Psychology and Education*, Boston, Houghton Mifflin, 393 p.

LITVAN, G.G. (1976): Frost action in cement in the presence of de-icers, *Cement and Concrete Res.*, Vol. 6, p. 351-356.

MacINNES, C. and WHITING, J.D. (1979): The frost resistance of concrete subjected to a deicing agent, *Cement and Concrete Res.*, Vol. 9, p. 325-336.

MACKAY, J.R. (1963): *The Mackenzie Delta area, N.W.T.*, Can. Mines and Tech. Surv., Geogr. Branch, Mem., No. 8, 202 p.

MARTINI, A. (1967): Preliminary experimental studies on frost weathering of certain rock types from the West Sudetes, *Biul. Peryglac.*, Vol. 16, p. 147-194.

MASSEPORT, J. (1959): Premiers résultats d'expériences de laboratoire sur les roches, *Rev. Géogr. alp.*, Vol. 47, p. 531-537.

MELLOR, M. (1970): *Phase composition of pore water in cold rocks*, CRREL Res. Rept. (U.S. Army Corps Eng.), No. 294, 61 p.

MOIGN, A. (1974): *Strandflats immergés et émergés du Spitsberg central et nord-occidental,* Thèse de doct., Brest, publ. Lille III, 692 p.

NANSEN, F. (1922): *The Strandflat and Isostacy*, Kristiania, Vidensk. Skr., Math. Natur. Kl., No. 11, 313 p.

OWENS, E.H. (1974): A framework for the definition of coastal environments in the southern Gulf of St. Lawrence, *in Offshore Geology of Eastern Canada*, PELLETIER, B.R. (ed.), Ottawa, Geol. Surv. Can., Pap. 74-30, p. 47-76.

POTTS, A.S. (1970): Frost action in rocks: some experimental data, *Trans. Inst. Brit. Geog.*, Vol. 49, p. 109-123.

POWERS, T.C. (1955): Basic considerations pertaining to freezing and thawing tests, *Amer. Soc. Testing Mater. Proc.*, Vol. 55, p. 1132-1155.

—— (1975): Freezing effects in concrete, *in Durability of Concrete* (Am. Concrete Inst., Detroit), Pap. SP 47-1, p. 1-11.

RILEY, J.P. and SKIRROW, G. (1975): *Chemical Oceanography,* London, Academic Press, Vol. 1 (2nd ed.), 606 p.

RZHEVSKY, V. and NOVIK, G. (1971): *The Physics of Rocks,* Moscow, Mir Publ., 320 p.

SCHNEIDER, J. (1976): Biological and inorganic factors in the destruction of limestone coasts, *Contr. Sedim.*, Vol. 6, p. 1-112.

SEKI, H. (1975): Deterioration of concrete of coastal structures in Japan, *in Durability of Concrete* (Am. Concrete Inst., Detroit), Pap. SP 47-13, p. 293-303.

SISSONS, J.B. (1974): Late-glacial marine erosion in Scotland, *Boreas*, Vol. 3, p. 41-48.

SOLLID, J.L., ANDERSEN, S., HARME, N., KJELDSEN, O., SALVIGSEN, O., STURD, S., TVEITA, T., and WILHELMSEN, A. (1973): Deglaciation of Finmark, north Norway, *Norsk. Geogr. Tidssk.*, Vol. 27, p. 233-325.

SWEET, H.S. (1948): Research on concrete durability as affected by coarse aggregates, *Amer. Soc. Testing Mater. Proc.*, Vol. 48, p. 988-1016.

TABER, S. (1950): Intensive frost action along lake shores, *Amer. J. Sci.*, Vol. 248, p. 784-793.

THOMAS, W.N. (1938): *Experiments on the freezing of certain building materials*, Great Britain Dept. Sci. and Ind. Res., *Building Res. Stat. Tech. Pap.*, No. 197, 146 p.

TRENHAILE, A.S. (1978): The shore platforms of Gaspé, Québec, *Ann., Assoc. Amer. Geogr.*, Vol. 68, p. 95-114.

—— (1980): Shore platforms: a neglected coastal feature, *Prog. Phys. Geog.*, Vol. 4, p. 1-23.

TRENHAILE, A.S. and LAYZELL, M.G.J. (1980): Shore platform morphology and tidal duration distributions in storm wave environments, *in The Coastlines of Canada*, McCANN, S.B., (ed.), Ottawa, Geol. Surv. Can., ap 80-10, p. 207-214.

TRICART, J. (1956): Étude expérimentale du problème de la gélivation, *Biul. Peryglac.*, Vol. 4, p. 285-318.

TRITES, R.W. and WALTON, A. (1975): *A Canadian coastal sea*, Bedford Inst. Ocean. Rept. Series, No. B1-R-75-15, 29 p.

TRUDGILL, S.T. (1976): The marine erosion of limestone on Aldabra Atoll, Indian Ocean, *Zeitsch. Geomorph.*, Suppl. Bd. 26, p. 164-200.

VERBECK, G.J. and KLIEGER, P. (1957): Studies of salt scaling of concrete, *Highway Res. Board Bull.*, Vol. 150, p. 1-13.

WALKER, R.D., PENCE, H.J., HAZLETT, W.H. and ONG, W.J. (1969): One cycle slow freeze test for evaluating aggregate performance in frozen concrete, *Highway Res. Board Prog. Rept.*, No. 65, p. 14-21.

WIMAN, S. (1963): A preliminary study of experimental frost weathering, *Geogr. Ann.*, Vol. 45, p. 113-121.

WINKLER, E.M. (1973): *Stone: Properties, Durability in Man's Environment,* New York, Springer-Verlag, 230 p.

ZENKOVITCH, V. P. (1967): *Processes of Coastal Development*, New York, John Wiley, 738 p.