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Publisher's version / Version de l'éditeur:

Canadian Geotechnical Journal, 16, 3, pp. 604-609, 1979-08

National Research Council Canada
Conseil national de recherches Canada

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Reprinted from
Canadian Geotechnical Journal
Vol. 16, No. 3, August 1979
p. 604–609

DBR Paper No. 845
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Rupture of an ice mound near Cape Dorset, N.W.T.

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Received October 11, 1978

Accepted March 14, 1979

An ice feature comprising ice blocks ranging from football size to 0.6 m cubes to 1.2 m × 3.6 m × 0.6 m slabs was observed on the surface of a frozen lake. Site investigations revealed the source of the blocks to be an ice mound that had formed along the shore of the lake. A model, supported by local meteorological, geological, and hydrological information, is proposed to explain the formation of the ice mound and its subsequent rupture.

Une formation de glace comprenant des blocs variant de la dimension d'un ballon de football à des cubes de 0.6 m de coté et à des dalles de 1.2 m × 3.6 m × 0.6 m a été observée à la surface d'un lac gelé. Les travaux de reconnaissances ont révélé que l'origine de ces blocs était un rempart de glace qui s'était formé sur la rive du lac. Un modèle, fondé sur les données météorologiques, géologiques et hydrologiques locales, est proposé pour expliquer la formation du rempart de glace et sa rupture subséquente.

[Traduit par la revue]

Can. Geotech. J., 16, 604–609 (1979)

Introduction

In early March of 1978 an unusual ice feature was observed on the surface of a lake about 45 km north-west of Cape Dorset, Baffin Island, N.W.T. The site was along a projection of the assumed reentry trajectory of COSMOS 954, so an investigation team

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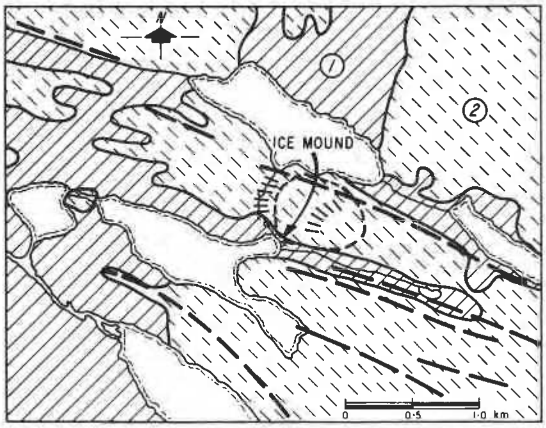

FIG. 1. Surficial geology of area surrounding ice-mound site.

comprising Canadian Armed Forces and Atomic Energy Control Board personnel was sent to the area to determine if any debris had impacted upon the lake.

Although neither radioactivity nor metal was found in the area, an explanation for the origin of this ice feature was still of interest to the investigation team. The author was requested to join the team and assist with the investigation.

This note describes the ice feature observed and puts forward an explanation for its formation. Similar features observed elsewhere in the Arctic will be briefly discussed.

Description of Ice Feature

Local Geology

The area is in the Canadian Shield and within the zone of continuous permafrost. The surficial geology of the immediate area around the site is indicated in Fig. 1 (Geological Survey of Canada, A. Dyke, personal communication, 1978). A talus veneer (zone 1) with a maximum thickness of about 1 m overlies the bedrock on the lower areas. The remainder of the area (zone 2) comprises 50% glacial-till cover less than 0.5 m thick, and 50% solid rock outcroppings. The till comprises up to 50% gravel, and in the size range of less than 2 mm the composition is more than 60% sand and less than 10% clay. Fracture and foliation lineaments in the granite–gneiss bedrock have a general northwesterly orientation. The drainage system is typical of Precambrian terrains. The section of the shoreline with the elongated ice mound is indicated by the arrow in Fig. 1. A drainage channel from another lake about 0.5 km to the north empties into the lake adjacent to the site of the ice mound. The drainage channel was covered with ice, but drilling through the ice indicated no evidence of flow.

Appearance of Ice Feature

An aerial view of the undisturbed feature is shown in Fig. 2. The ice surface of the lake on which the ice

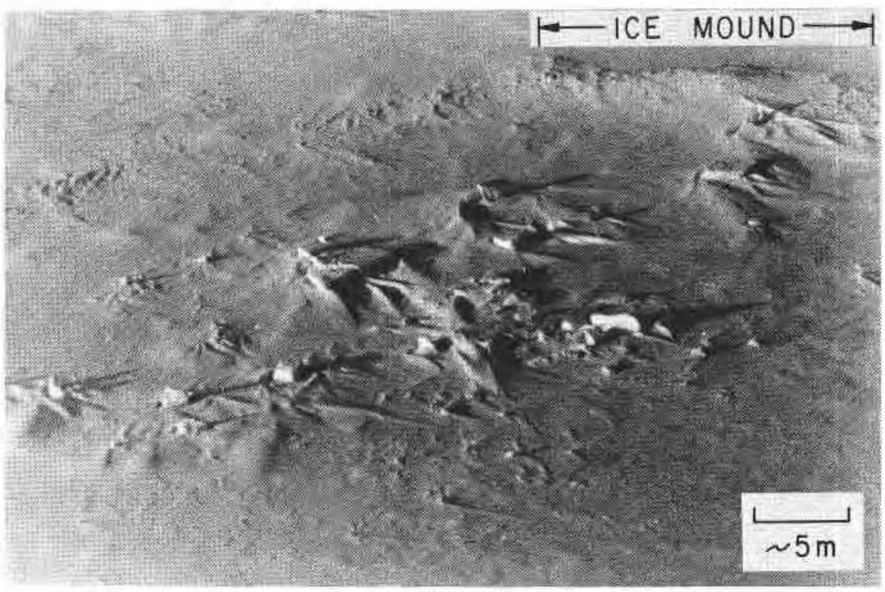

FIG. 2. Aerial view of ice feature.

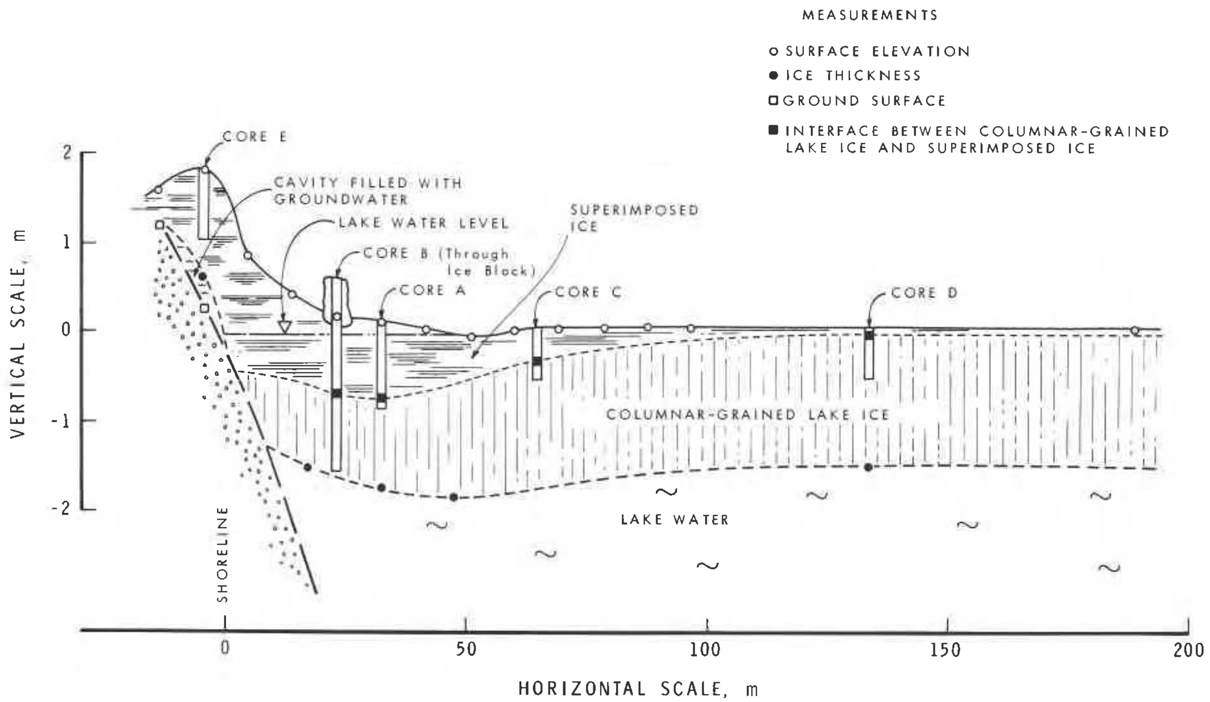

FIG. 3. Cross section of ice mound and lake ice.

blocks were resting appears in the lower two thirds of the photo. The blocks ranged from football size to 0.6 m cubes to 1.2 m × 3.6 m × 0.6 m thick slabs. They were dispersed over a 60 m × 90 m oval area adjacent to the shore. The elongated mound, which extends across the upper right-hand part of the photo, was comprised of ice. It was situated on land, about 5 m back from the shoreline, and extended about 50 m in length. The ice blocks were generally tabular in form and comprised a 0.3 m thick layer of white ice overlying about 0.3 m of black ice.

Cross Section of Ice Feature

Level-survey data, ice-thickness measurements, and ice cores taken along a common axis were used to construct the cross section illustrated in Fig. 3. The cross section extends in approximately an east–west direction. The level-survey results showed the crest of the ice mound to be almost 2 m higher than the lake ice surface. This point of maximum elevation was about 5 m back from the shore.

Four ice cores were taken through the lake ice and two from the elongated ice mound. Photo mosaics of thin sections of cores B and F are shown in Fig. 4. The thin section of each core was photographed under two different light conditions. For the left-hand side of each mosaic, a dark backing was placed behind the thin section and light reflected off it, showing voids or cavities in the ice. For the right-hand side, the thin section was between crossed polaroids with the light source beneath the bottom polaroid, illustrating the ice crystal structure.

The ice cores taken on the lake showed that the ice cover near the shore comprised layered ice superimposed over columnar-grained lake ice. The thickness of this layered ice decreased with increasing distance from the shore.

Core B (Fig. 4) was taken through an ice block about 30 m out from the shore. Core F (Fig. 4) was taken from what appeared to be an exposed ice outcropping about 5 m back from the shore. Note the similarity in the ice structure in the top 0.6 m of cores B and F.

In addition to the ice cores, several holes were augered through the ice mound. These holes showed a water-filled cavity beneath the ice mound extending for at least 25 m. In one case a small geyser of water erupted when the auger went through the bottom of the ice mound.

Explanation of Phenomenon

The review paper of Williams and van Everdingen (1973) provided a good introduction to groundwater phenomena in permafrost regions, in particular icings, pingos, and artesian pressures, and the general

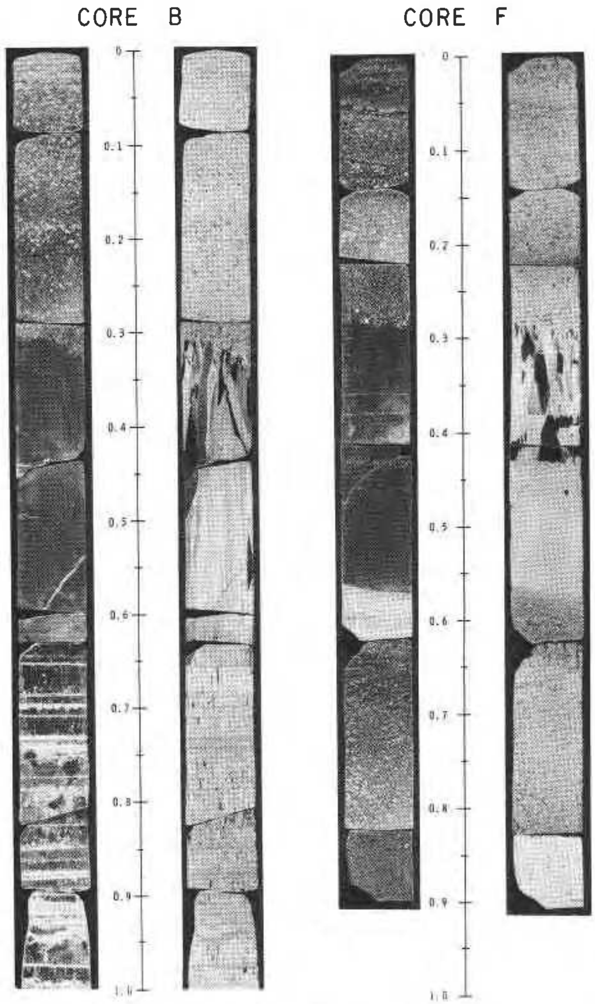

FIG. 4. Photo mosaics of thin sections of ice cores showing air bubble distributions and ice crystal structure. (NOTE: vertical scale in metres.)

requirements and conditions for their occurrence. They indicated that the understanding of these phenomena is not yet complete, and documentation of observations is necessary.

The subject of icings has received a thorough review by Carey (1973). Icings are composed of ice built up progressively on an already existing ice surface. What Carey calls an "icing mound" seems to describe most closely the phenomenon observed near Cape Dorset; he defines it as follows:

> A mound on the surface of an icing resulting from the bulging upward of the surface layer of ice. It is believed that icing mounds form when an unfrozen lens of water becomes trapped within the mass of an icing and is subjected to gradual freezing, in a process analogous to the formation of a frost mound. Icing mounds may crack explosively, casting blocks of ice considerable distances, or they may rupture quietly and bleed water to the icing surface.

Recently van Everdingen (1978) has reported on studies of several frost mounds near Fort Norman, N.W.T. He suggests a mechanism for the formation of what he calls an icing blister. It is basically similar to Carey's mechanism but he proposes that air or other gases entrained in the groundwater and trapped under the icing blister could lead to an explosive rupture.

Based on the on-site observations, the following explanation for the formation of the ice mound and its eventual rupture is suggested. Various stages in the evolution of the ice mound are illustrated schematically in Fig. 5. A site of groundwater seepage is located along the shore of a lake a small distance above the waterline (Fig. 5*a*). When the mean air temperature drops below freezing, in late October, an icing begins to form just above the shoreline as well as on the ice cover of the lake. Significant snowfall occurs during November, insulating the ground surface. The permafrost table begins to rise perhaps up into the gravel till at the shoreline, which would be the point of maximum heat loss. This stage is shown in Fig. 5*b*.

With increasingly lower temperatures the permafrost table rises and comes into contact with the icing and lake ice, cutting off flow through the gravel till towards the lake. The seeping groundwater is diverted and driven up into the snow and, drawn further by capillary action, completely saturates it (Fig. 5*c*). This water-saturated snow layer freezes from the top down, producing a homogeneous layer of granular snow ice. Once the snow ice is frozen through, continued ice growth will have a columnar-grained crystal structure. This is illustrated in core F in Fig. 4, which shows a layer of snow ice about 0.3 m thick overlying columnar-grained ice. An ice cap is effectively formed, which allows the hydrostatic head of the groundwater to exert a pressure on the ice. Under the action of the hydrostatic pressure, plus pressure developed from the volume expansion associated with freezing, the ice cap is deformed upwards into a mound-like formation while maintaining a water-filled cavity under it (Fig. 5*d*). Periodically, cracks develop in this ice mound allowing the water to seep out of the cavity.

At some time the ice mound ruptures abruptly, washing the ice blocks out on to the surface of the lake (Fig. 5*e*). The most likely triggering mechanism for abrupt rupture is a rapid temperature drop, which leads to tensile thermal stresses on the top surface of the mound as well as an increase in pressure caused by an acceleration in ice growth.

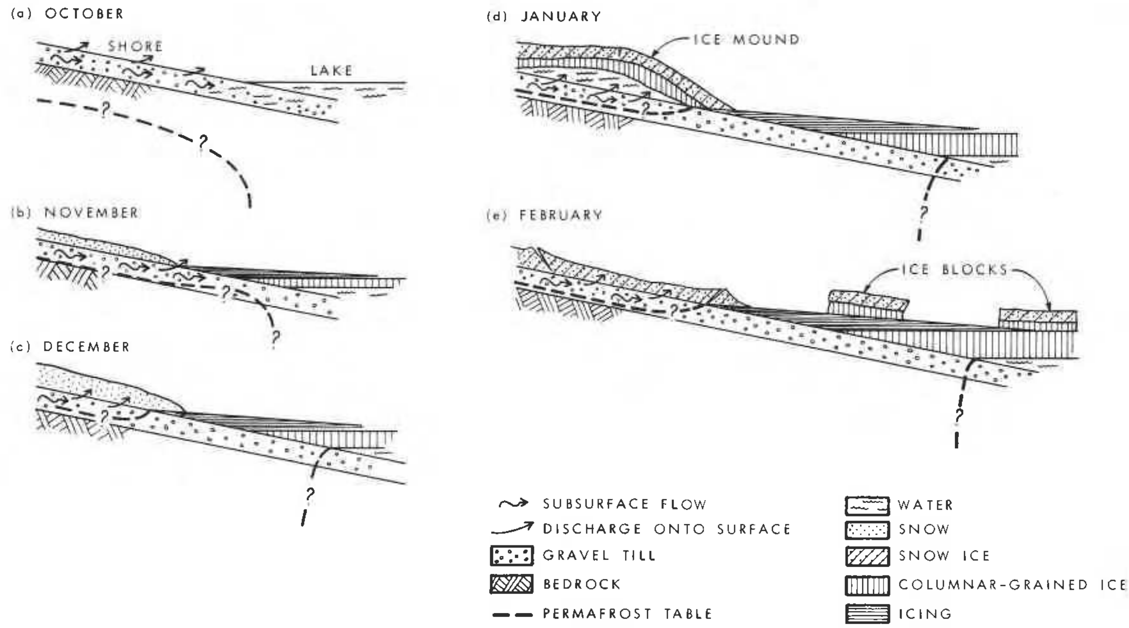

FIG. 5. Schematic of sequence of events in formation and rupture of an ice mound.

Discussion and Conclusion

The proposed model requires: (i) a source of groundwater; (ii) confinement to produce an ice mound; and (iii) some event to rupture the ice mound.

Figure 1 shows three possible sources of groundwater. One is the lake to the north, with water coming via a buried drainage channel. A second is water from the small catchment basin to the northeast of the site, and the third is along the zone of fracture lineaments extending to the east of the site. The second is the most likely source because of an unusual combination of meteorological conditions. The winter of 1977–1978 was characterized by an early and heavy snowfall and relatively mild temperatures. Another unusual feature of the weather was a mild spell at the end of October and a 1 cm rainfall on 1 November, followed immediately by a 7.5 cm snowfall. This combination of events could have resulted in an ample supply of groundwater and the persistence of an unfrozen groundwater-transmitting layer.

The second requirement is confinement. The combination of the bedrock and permafrost table underneath, the freezing through of the gravel till at the lake waterline, and the formation of the snow ice cap, effectively confine the groundwater.

The third requirement is some event to trigger the rupture of the ice mound. A temperature drop has been proposed and an examination of the daily temperature record at Cape Dorset during January 1978 showed a period at mid-month when the temperature cycled between −15 and −30°C for 2 days and then remained in the −30 to −35°C range for several more days.

Once the mound has burst, the broken fragments must still be carried up to 100 m away from their original site. The proposed model shows an icing that slopes down towards the lake ice surface. This slope also showed up in the level survey, Fig. 3. Bowden and Hughes (1939) found that the coefficient of friction of ice on ice close to the melting point is 0.02. The slope of the ice surface at the shoreline is about 0.10, and 25 m out onto the lake it is still about 0.03. Given the low friction coefficient of ice on ice and the slope of the ice surface, it is possible for the ice mound fragments to slide a considerable distance because of gravity forces alone.

The ice structure of the top 0.6 m of core B (taken through an ice block approximately 25 m out onto the lake) shows a remarkable similarity to core F (taken through a margin of the ice mound), which supports the assumption that the ice blocks on the lake ice surface came from the ice mound.

The Inuktitut word for ice mounds is 'Karniq.' One of the village elders in Cape Dorset reported that occasionally Karniq explode. Therefore, it is reasonable to assume that the occurrence of ice mounds is normal.

The impact of icings on engineering works has been discussed by Carey (1973) and the problems they cause for roads are well-documented. Wherever icings occur, formation of ice mounds is possible. Their subsequent rupture, however, is a relatively rare occurrence. The moving ice fragments from a ruptured ice mound are an obvious hazard for structures. Once they freeze into place, they are an effective barrier to transportation. It appears that while the formation of an icing may be a perennial event, the formation of an ice mound and its rupture depend upon a special set of environmental circumstances. An engineering work itself may alter these circumstances to make the occurrence either more or less likely. Therefore, in locating any engineering work in the Arctic, be it road, pipeline, wharf, airstrip, community, etc., attention should be paid to the possible occurrence of icings and the subsequent implications.

Acknowledgements

The assistance and support of the Atomic Energy Control Board of Canada and the Canadian Armed Forces are gratefully acknowledged. In particular, the assistance of Capt. G. L. Barr, Construction Engineering Section, CFB Edmonton, in carrying out part of the site investigation is appreciated. Discussions, suggestions, and assistance from my colleagues in the Geotechnical Section, particularly T. H. W. Baker and M. Nakawo in preparing this paper, are acknowledged.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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