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Marine Ice-Pushed Boulder Ridge, Beaufort Sea, Alaska

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ABSTRACT. A steep-faced boulder ridge up to 4 m high by 300 m long was encountered along the arctic coast east of Prudhoe Bay, Alaska, in the summer of 1979. Marine occurrences of similar ridges are rare. Since ice-push sorts cobble- and boulder-sized material in the construction of a ridge, recent onshore excursions of ice due to wind stress on the fast ice are believed to be responsible for building the boulder ridge. Ice push is a mechanism that preferentially sorts cobble- and boulder-sized material from 1-2 m water depths and that forms boulder ridges in areas of high boulder concentrations.

Key words: marine ice-pushed boulder ridge, Beaufort Sea, Alaska

RÉSUMÉ. Une crête de poussée glacielle à parois abruptes, constituée de blocs atteignant 4 mètres de hauteur par 300 mètres de long a été observée le long du littoral arctique, à l'est de la baie de Prudhoe, Alaska, durant l'été 1979. Des phénomènes semblables, d'origine marine, sont rares. Etant donné que les poussées glacielles trient les matériaux de la taille des cailloux et des blocs lors de la construction d'un bourrelet, il est probable que la crête soit le résultat de la propulsion par le vent de radeaux de glace du pied de glace vers la rive. Une poussée glacielle est un processus que trie les matériaux de la taille des cailloux et des blocs à des profondeurs d'eau variant de 1 à 2 mètres. Elle forme des crêtes constituées de blocs dans les régions qui en contiennent une forte concentration.

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INTRODUCTION

The interaction of sea ice with the seabed and the coast is a significant factor in the coastal morphology and geology of modern and ancient arctic coasts, and in determining design criteria for artificial structures in the coastal environment.

A rigorous historical and theoretical treatment of ice pile-up and ride-up in conjunction with recent field observations was given in Kovacs and Sodhi (1980). These authors also pointed out many of the shore and coastal features resulting from ice interaction with the coast. Dionne (1979) presented a review of the erosional and depositional features along shores of arctic rivers and coasts of arctic lakes which he related to ice motion. Many of the reported features were boulder ridges.

This paper describes the character and postulated processes in an area where ice push (the bulldozing of sediments by onshore ice excursion) has erected a ridge of boulders along the arctic coast of Alaska. The formation of the boulder ridge is further related to the onshore and offshore geologic environment and to the nearshore ice environment.

Environment

The arctic coast of Alaska is characterized by bluffs 1-10 m high, and linear accretionary islands. The bluffs are composed of frozen marine and non-marine units of the Gubik Formation of Pleistocene age (O'Sullivan, 1961; Black, 1964). The islands consist of sand and gravel ridges 1-4 m high, which form barriers that protect coastal lagoons and sounds. The coastal segment we studied is typical of this environment (Fig. 1).

The seasonal sea ice growth along the arctic coast starts in October, and by May, the thickness is generally between 1.5 and 2.0 m. Ice pile-up and ridging, caused by ice motion against the coast due to onshore winds or dynamic motions within the ice field, can increase ice thickness

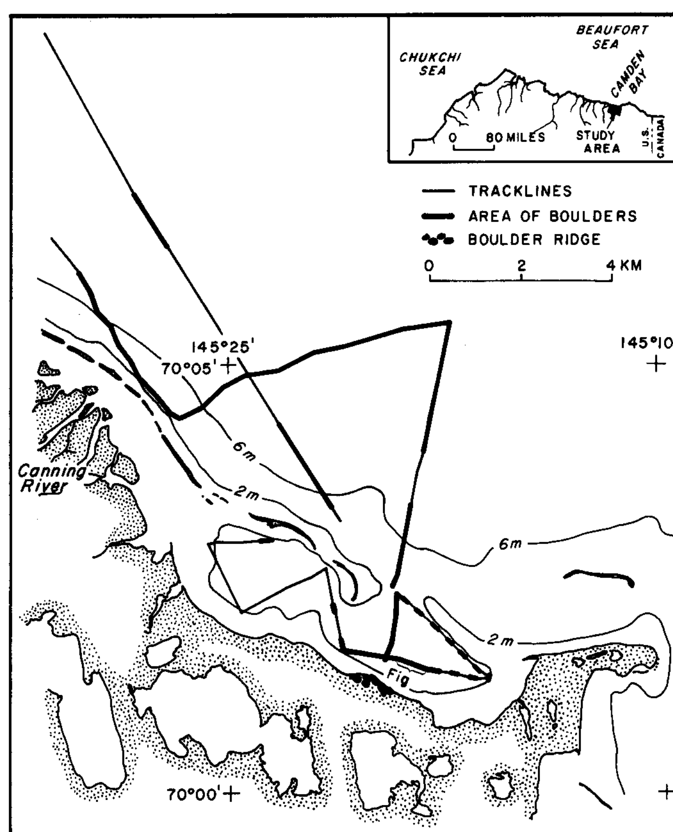

FIG. 1. Location of boulder ridge and side-scan sonar tracklines east of the Canning River. Heavy segments of the side-scan lines indicate areas where boulders were interpreted from the records as in Figure 6.

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many times at any one location. Several researchers (Taylor, 1978; Kovacs and Sodhi, 1980) noted coastal ice piles of both thick and thin ice, typically 5-10 m in height, whose plowing action may result in relief of 0.5-2 m in beach sediments.

During winter, dominant northeasterly winds are instrumental in developing ice ridges both offshore and along the coast. These ridges normally form offshore in water 15-20 m deep and create a stamukhi zone of firmly grounded ice which helps deter subsequent onshore ice-push events (Reimnitz *et al.*, 1978).

OBSERVATIONS

During the summer of 1979, we visited a boulder beach ridge on the mainland coast east of the Canning River in northern Alaska (Fig. 1). The total length of the ridge was about 300 m. Height and boulder abundance decreased laterally from the center. Boulders up to 1.4 m in diameter, lying at the angle of repose (approximately 35°), formed the ridge which extended about 10 m onshore from the water's edge. The ridge attained a height of 3.5 m and abutted a 2-m high tundra bluff (Figs. 2 and 3). Many boulders in the ridge appeared to be piled in an unstable fashion. Sand and gravel were present in patches on the tops of some of the boulders (Fig. 4 and 5) and up to 15 m onshore on the tundra.

FIG. 4. Close-up view of ridge from the ridge crest. Note lack of marine growth and the distribution of gravel patches behind and on top (arrow) of the ridge boulders. Light-coloured boulder in the foregound is about 1 m across.

FIG. 2. View of boulder ridge from eastern end with man (arrow) at water's edge for scale. Note the cleanliness and varied angularity of the clasts and steepness of seaward flank of ridge.

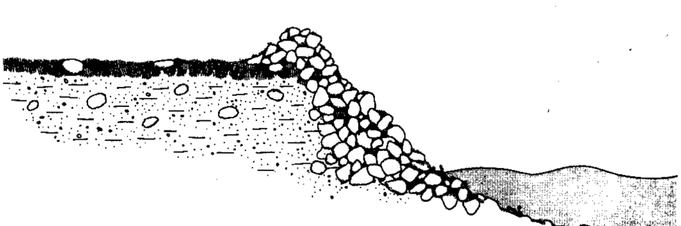

FIG. 3. Diagrammatic cross-section of the boulder ridge illustrating the presumed relationship of boulders in the tundra and offshore (not to scale).

Evidence for lateral onshore push related to the boulder ridge included folded tundra mats, bulldozed beach ridges oriented perpendicular to the shoreline (Fig. 5), and a benchmark pipe bent shoreward while embedded in the central part of the ridge. Although the boulders appeared to have been transported from offshore where marine growth is common, no remnants of attached or encrusting marine growth were observed within the boulder ridge (Figs. 2, 4 and 5). Pink granite, pink gneiss, and quartzite were conspicuous lithologies in the ridge, and boulder shapes varied from angular to rounded.

The tundra surface onshore from the boulder ridge contained scattered boulders whose top surfaces were roughly flush with the ground, similar to those on Flaxman Island (Leffingwell, 1919) (Fig. 3). However, along the shore beyond the ends of the boulder ridge, boulders were

FIG. 5. View shoreward of ice-pushed boulder. Push moraine (dashed lines) extends seaward from the sides of boulder. The boulder is about 120 cm across. Note the lack of encrusting organisms.

not observed in the tundra or on the beach. We assume that the boulders in the ridge are a reworked lag deposit from tundra that once extended offshore.

Seaward from the coastal ridge, boulders are sparse but widespread on the sea floor inside and outside the lagoon. Side-scan sonar records show small targets with distinct shadows cast by individual boulders on the seabed (Fig. 6). There were boulder reflectors over much of the central and eastern part of the lagoon and seaward more than 8 km, in water >10 m deep.

We found further evidence of seabed boulders when we anchored 300 m seaward of the coastal boulder ridge in 3 m water depth and our anchor brought up a small boulder, 30 cm in diameter, with kelp and other marine growth. Inshore, however, repeated attempts by dragging to locate boulders in water 0.5-2 m deep were unsuccessful.

DISCUSSION

Occurrences of boulder ridges in the marine environment are rare. We know of only one reference to a marine setting for boulder ridges in the Arctic, describing occasional occurrences along the coast of James Bay in Northern Canada (Martini, 1980). On the other hand, numerous non-marine boulder ridges on the shores of lakes and rivers in arctic Canada are mentioned by Dionne (1979) and have also been observed along the coast of Imuruk lake in arctic Alaska (D.M. Hopkins, pers. comm.). These ridges were formed as a result of ice push. Boulder "barricades" occur in the coastal environment of northeastern Labrador (Rosen, 1979) bounding the low-tide zone, but do not occur as steep boulder piles as do the boulder ridges in this study. Therefore, they presumably undergo different formation processes.

Method of Ridge Formation

We believe the most logical process involved in the formation of marine boulder ridges parallels the ice-push mechanism described for non-marine ridges (Dionne, 1978; 1979). Arctic coastal ice-push events in the absence of boulders have been documented by Kovacs and Sodhi (1980). The ice responsible for the formation of the boulder ridge in Camden Bay could be transmitted from offshore through the opening in the lagoon (Fig. 1) which is NE of the boulder ridge in the dominant winter wind direction. These winds provide the driving force for ice-

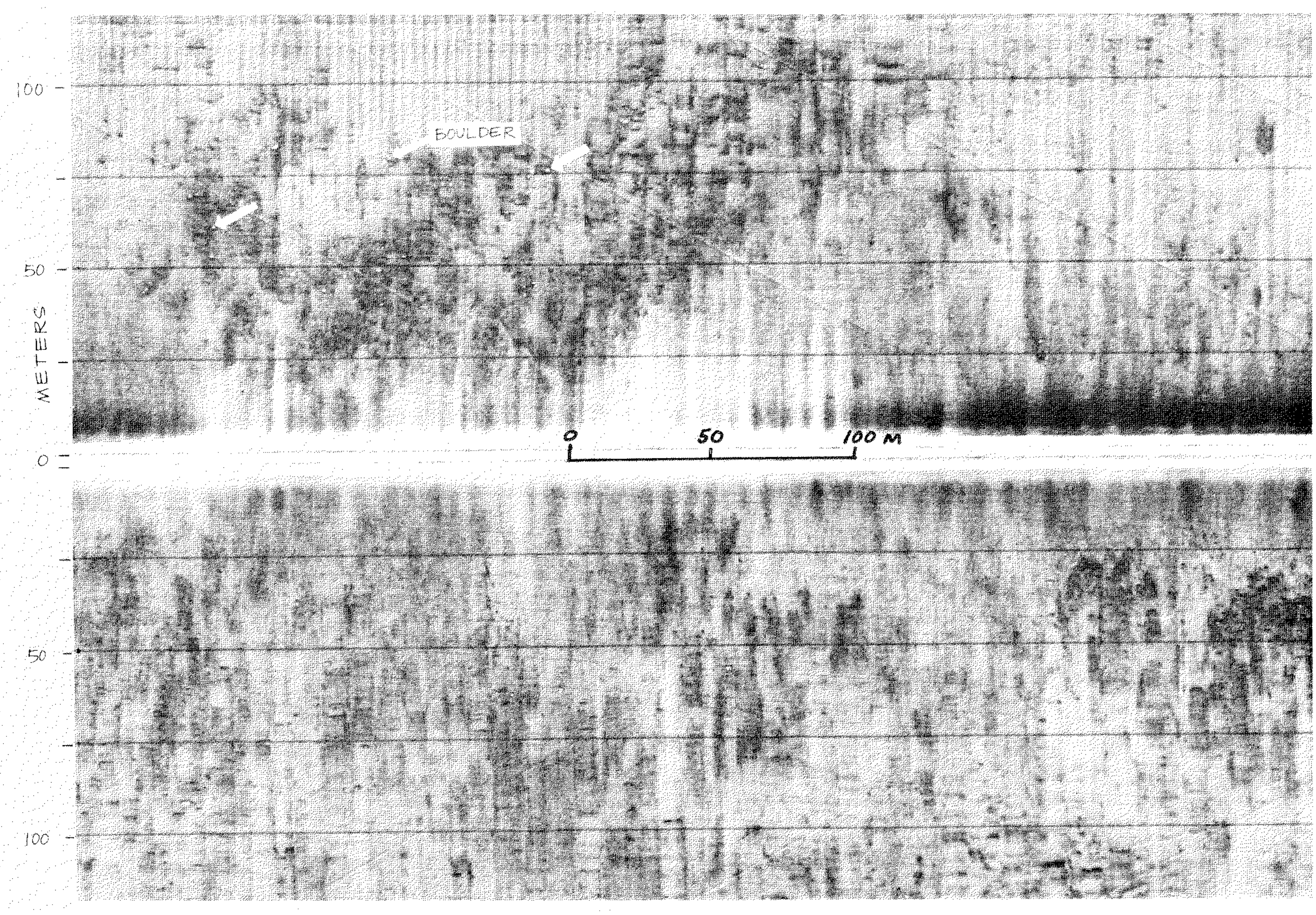

FIG. 6. Sonograph of lagoon floor seaward of the boulder ridge showing the character and distribution of boulders at 3 m depth. Note the darker reflectors associated with the boulders, which could be indicative of areas of outcrop. (See Fig. 1 for location).

push onshore. The sonar records reveal ice gouges oriented north-south in the entrance channel north of the boulder beach (Fig. 1).

The following scenario for the formation of the boulder ridge is postulated for an area where the sea bottom is strewn with a lag of boulders. Ice moving onshore would bulldoze both boulders and ice into a ridge in a form similar to the coastal ice ridges described by Kovacs and Sodhi (1980). Prior to onshore ice movement, boulders partly or wholly incorporated in the ice canopy would create a naturally weak point in the ice. As the ice sheet breaks under onshore stress, ice blocks would be formed, many with dimensions similar to those of boulders. These ice blocks would move and tumble in much the same manner as boulders. Boulders could ultimately be included in the matrix because of their similar size and their protrusion from the seabed. Other boulders on the sea floor could be readily pushed or brushed onshore by overriding ice sheets (Fig. 7). As the cross sections of ice-block ridges (Kovacs and Sodhi, 1980) and boulder ridges (Fig. 3) are strikingly similar, ice blocks may have initiated the ridging process.

In the above scenario, gravel, sand and silt would be mostly excluded because of their small size relative to the ice blocks. When included, they would constitute only a small portion of the mass. Both rock and ice blocks would form a jumbled ridge, with rock boulders remaining at the base of the pile due to their seabed source and higher density.

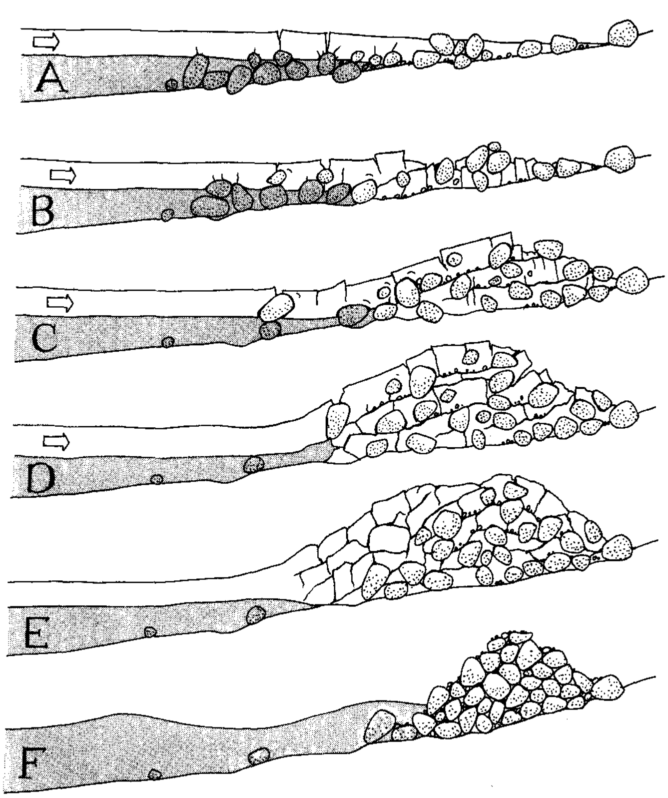

FIG. 7. Diagrammatic sequence of events of boulder-ridge formation. Ice thickness is about 1 m.

Observations just seaward of the boulder ridge and at other boulder-rich coastal sites suggest a mechanism that preferentially removes boulders from the seabed between the 1 and 2 m depth contours, though the mechanism only rarely results in ridge formation. The ice growth which occurs inshore of 2 m during winter would include large objects such as boulders. Even if the movement of the ice canopy is slight, the boulders included in the ice or brushed by the ice would move either onshore, along the shore, or offshore. The process would, in time, preferentially remove boulders from water 1-2 m deep and eventually the boulders would be in water too shallow or too deep to permit movement by normal ice motions. Ice and boulder movement inshore of about 1 m would be restricted by ice bonding to the seafloor in winter. Boulder movement would be restricted by rapid melting prior to ice motion, and by the limited forces available from small ice blocks during spring and summer. The building of a boulder ridge is a unique occurrence when significant onshore ice motion and an abundant number of boulders are present.

Age of the Boulder Ridge

Several persons familiar with this segment of the coastline could not recall seeing the ridge prior to 1978. The presence of sand and gravel lag on the upper surfaces of many boulders (Fig. 4) would not have survived many summers of rain and wave spray, or winters with high winds. Similarly, the gravel-push ridge that extends from one boulder (Fig. 5) to the swash zone would not have survived many summers with major storms. After repeated visits to the Camden Bay boulder ridge, we concluded that the ridge formed (or re-formed) two or three years prior to our initial observations.

Implications

The above discussion suggests that boulders used as rip-rap to protect natural and artificial islands from wave and current erosion might be readily ridged during ice movements, because of their comparatively large grain size. The seaward face of the boulder ridge, which is at the angle of repose, may represent the most stable configuration for a boulder beach face under lateral pressure from ice.

CONCLUSIONS

1. A boulder ridge as high as 3.5 m formed on the coast east of the Canning River in the past few years. This ridge is strikingly similar to ridges described for lakes and rivers, but has been rarely reported from the arctic marine environment.

2. The ridge formed along a section of coast from a boulder-rich segment of the Gubik Formation and is a lag from that formation.

3. The method of formation of the boulder ridge is linked to ice-push from offshore, probably from a wind-induced ice-movement event.

4. The formational mechanism preferentially sorts boulders from finer sediment sizes and may explain the apparent lack of boulders in water depths of 1-2 m in the Alaskan Arctic.

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