Reports

Relic Pleistocene Permafrost, Western Arctic, Canada

Abstract. *Icy layers and interbedded frozen sediments along the Arctic Coastal Plain of northwestern Canada have been subjected to glacial deformation. Radiocarbon dates indicate that the deformation took place more than 40,000 years ago.*

Available evidence indicates that permafrost, which was originally formed during the Pleistocene, is preserved in frozen sediments along the Arctic Coastal Plain of northwestern Canada. The area involved stretches 400 km from Herschel Island on the west to Nicholson Peninsula on the east (Fig. 1). The Quaternary stratigraphy of the area shows (i) the presence of widespread Pleistocene fluvial, lacustrine, and marine sediments that originated many years before an early glaciation; (ii) deposits and landforms attributed to two or more Laurentide glaciations; (iii) varied postglacial sediments chiefly of fluvial and lacustrine origin; and (iv) a complex of surface materials emplaced by periglacial processes (*1*). The Pleistocene sediments are now frozen to a considerable depth, as permafrost probably exceeds a thickness of 400 m in some localities (*2*).

Often the sediments contain excess ice (that is, they would be supersaturated if melted) in the form of ice veins, lenses, layers, and, in some cases, nearly pure ice beds as much as 30 m thick (*3*). At many localities, the sediments, along with the ice they contain, show some degree of folding or faulting. Specifically, deformed beds occur at Herschel Island to an altitude of about 180 m; at Kay Point, King Point, and Garry Island to over 60 m; and at Nicholson Peninsula to 90 m (*4*). The deformed sites at Kay Point, King Point, Garry Island, and Nicholson Peninsula all exceed 2 km^2 in area, whereas that at Herschel Island exceeds 100 km^2. Deformed beds, below 50 m in altitude, have also been observed at Pelly Island, Hooper Island, Kendall Island, Rae Island, Richards Island, Stokes Point, and in the environs of Tuktoyaktuk.

With only minor exceptions, the icy layers parallel the bedding of both undeformed and deformed structures. This fact indicates that the icy layers were an integral part of the stratigraphic succession prior to deformation. The ice layers would not parallel the bedding if they had grown, in place, subsequent to the deformation because ice segregation takes place in response to a thermal gradient that would be normal to the ground surface. The disturbed icy sections have never undergone thawing and refreezing, because thawing would have obliterated the primary sedimentary structures, which are still preserved.

The beds are thought to have been deformed by glacier ice-thrust in a manner similar to that of glacially deformed beds in many other parts of the world (*5*). The main arguments favoring glacier ice-thrust are as follows: (i) all deformed beds have been found within the maximum limit of glaciation; (ii) available geophysical evidence suggests that the deformed beds are confined to the top several hundred meters below the ground sur-

Table 1. Carbon-14 dates, site descriptions, and references.

Sample No.	^{14}C age (years)	Location (see Fig. 1)	Material and stratigraphic details dated	Reference
GSC-1262	22,400 ± 240	Stokes Point (*A*)	Organic detritus from 1 m above base of sand and gravel overlying till	
GSC-1229	> 43,000	Phillips Bay (*B*)	Fragments of waterworn wood from near base of 3 m of sand and gravel overlying pebbly clay (till or glaciomarine sediment?)	
GSC-562	> 35,000	Garry Island (*C*)	Fresh-looking shells, many with intact periostracum, from unglaciated estuarine (?) terrace sands	(*7*)
GSC-690	> 37,000	West Richards Island (*D*)	Fresh-looking shells from unglaciated estuarine (?) terrace sands	(*8*)
GSC-1373	> 31,000	Yaya Lake (*E*)	Twigs from sand underlying 1 m of peat; sands deposited during period when lake level was high	
GSC-709	> 40,000	East Channel (*F*)	Waterworn tree trunk from 7 m below crest of 17-m glaciofluvial (?) terrace	
S-69	12,000 ± 300	Ibyuk Pingo (*G*)	Organic matter from near midpoint of 3.5 m of lake sediments, overlying mudflow deposits	(*10*)
GSC-481	17,860 ± 250	Ibyuk Pingo (*G*)	Peat, 15 cm above base of 1 m of mudflow deposit	(*9*)
GSC-512	14,130 ± 440	Ibyuk Pingo (*G*)	Organic silt, 5 cm above base of 1 m of mudflow deposit	(*9*)
GSC-485	> 42,900	Ibyuk Pingo (*G*)	Wood, about 1 m from top of sands underlying mudflow deposit	(*9*)
GSC-486	> 37,500	Ibyuk Pingo (*G*)	Wood, about 2 m from top of sands underlying mudflow deposit	(*9*)
BE-49	> 26,000	Ibyuk Pingo (*G*)	Wood, about 4 m from top of sands underlying mudflow deposit	(*11*)
L-300A	> 33,000	Ibyuk Pingo (G)	Wood, about 7 m from top of sands underlying mudflow deposit	(*10*)

face; and (iii) the orientations of the deformed structures are compatible with deformation by glacier ice moving down the lower Mackenzie Valley and then fanning out into the Beaufort Sea. This pattern of movement is suggested by the maximum limit of glaciation and topographic controls on glacial flow in the area. Subsequent glacial flow by late Wisconsin glaciers, as indicated by glacial fluting, has followed such a pattern (*6*).

The majority of the deformed structures lie in areas beyond the maximum limit of late Wisconsin glaciation (Fig. 1 and Table 1) (*7–11*). The precise limit of late Wisconsin ice is open to question, because extensive thermokarst activity in many areas has produced topography similar to that of the dead-ice moraines of late Wisconsin age. However, the broad limit is reasonably well defined on a geomorphic basis (*9, 12*) and can be supported by ^{14}C dates on materials from nonglacial sediments lying outside the inferred limits along the Yukon Coastal Plain and in the vicinity of Richards Island (Table 1). The ^{14}C dates should be considered in toto as supporting evidence, because individual samples of wood and organic detritus could possibly be reworked interglacial materials (*13*). Although dated materials at Stokes Point and the finitely dated materials at Ibyuk Pingo (Table 1) do not predate the late Wisconsin interval, they do predate the time when late Wisconsin ice was probably at its maximum in this area, between 13,500 and 14,000 years before the present (B.P.) (*14*). This fact suggests that the sites were, therefore, glaciated during an earlier glaciation. Dates from the sands underlying the mudflow at Ibyuk Pingo (Table 1) are difficult to relate to the glacial history of the site, for it is not clear whether the sands have been overridden by a glacier or whether they were deposited as outwash when the glaciers were to the south of the site.

Because cumulative radiocarbon and geomorphic evidence indicates that the Arctic Coastal Plain, where most of the glacially deformed permafrost is located, was not glaciated during the last 40,000 years, it follows that the glacially deformed beds and associated ground ice are much older than 40,000 years. Whether the permafrost was formed in the early Wisconsin or even earlier is not clear. It is evident, however, that permafrost was present prior to glacier ice-thrusting and extended at least to the original depth of ice in the undisturbed sediments.

The present mean annual ground temperature at about 15 m (this depth approximates the depth at which there is no appreciable annual temperature change) ranges from about $-7°$ to $-10°C$ in the Richards Island–Tuk-

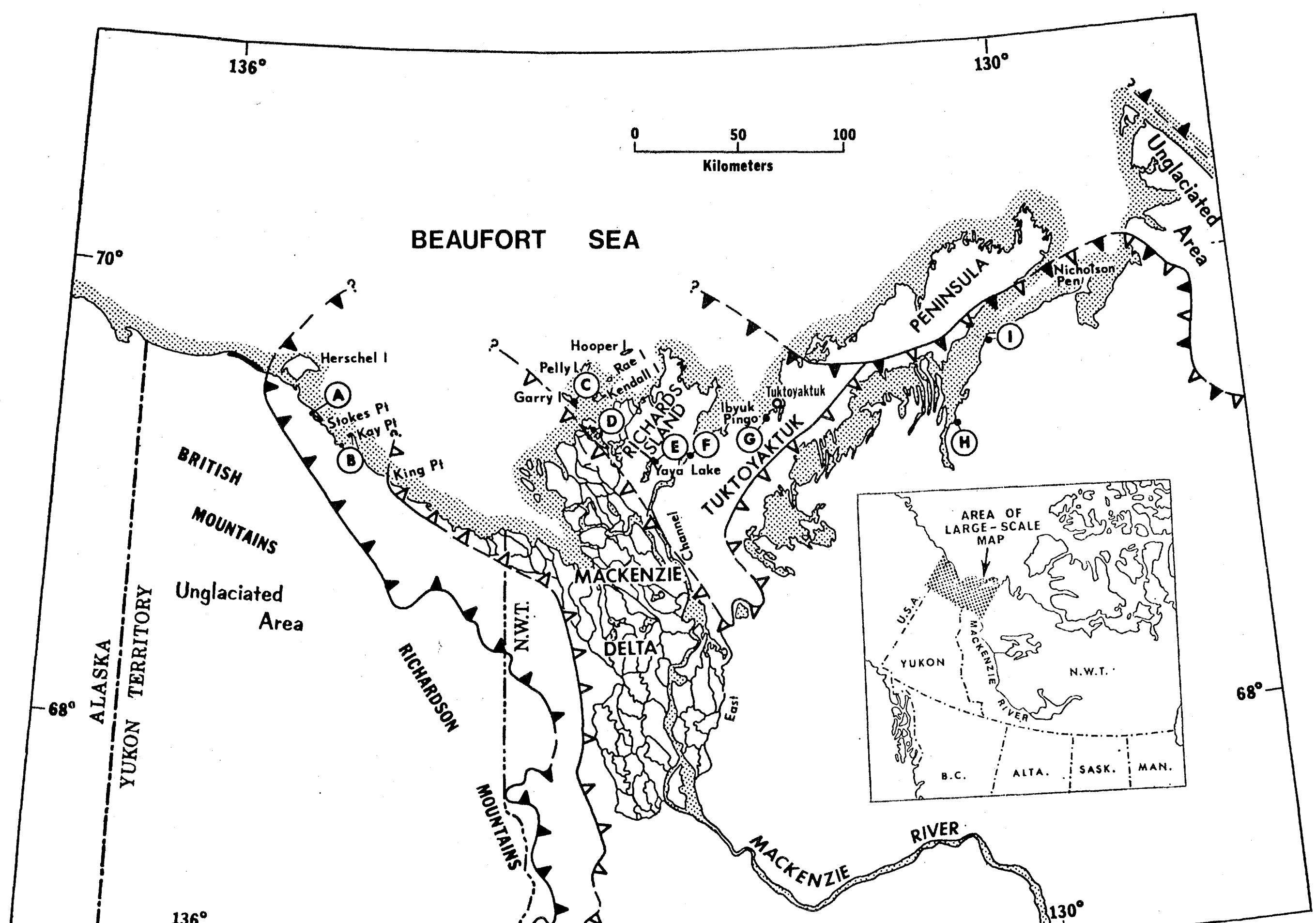

Fig. 1. Maximum and late Wisconsin limits of glaciation in the lower Mackenzie region (*9, 12*). Lines with solid triangles represent the maximum limit of glaciation; lines with open triangles represent the late Wisconsin limit of glaciation (less extended alternatives east of Mackenzie Delta for the limit of late Wisconsin ice have been omitted). Circled capital letters indicate locations of ^{14}C samples referred to in Table 1 and (*9, 12*): *A*, GSC-1262 (22,400 ± 240); *B*, GSC-1229 (> 43,000); *C*, GSC-562 (> 35,-000); *D*, GSC-690 (> 37,000); *E*, GSC-1373 (> 31,000); *F*, GSC-709 (> 40,000); *G*, S-69 (12,000 ± 300), GSC-512 (14,130 ± 440), GSC-481 (17,860 ± 250), BE-49 (> 26,000), L-300A (> 33,000), GSC-486 (> 37,500), and GSC-485 (> 42,900); *H*, I-482 (> 38,000); *I*, GSC-1281 (> 36,000).

toyaktuk Peninsula area. The temperatures of the Yukon Coastal Plain are probably also in the same temperature range. Consequently, the mean annual ground temperature has not risen, for any prolonged period, by more than 7° to 10°C above that of the present, for a period greater than 40,000 years, otherwise melting and collapse of the icy structures would have occurred.

J. ROSS MACKAY
Department of Geography, University of British Columbia, Vancouver
V. N. RAMPTON
J. G. FYLES
Geological Survey of Canada, Ottawa, Ontario

References and Notes

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7. The date was originally reported as > 42,000 years by D. E. Kerfoot [*The Geomorphology and Permafrost Conditions of Garry Island, Northwest Territories* (Univ. of British Columbia, Vancouver, 1969), p. 289]; corrected date was reported by J. A. Lowdon *et al.* (*8*).
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13. Two infinite radiocarbon dates, samples I-482 and GSC-1281 (Fig. 1), are on wood from fluvial deposits at sites where there is no absolute evidence for glaciation subsequent to the deposition of the fluvial deposits. However, these dates cannot be rectified with other ^{14}C dates and geomorphic evidence relative to the late Wisconsin limit, and they have been omitted from this discussion.
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15. We thank Dr. O. L. Hughes and J. M. Shearer for helpful comments on the manuscript. The fieldwork was supported by the Geological Survey of Canada.

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A Hydrogen Economy

The medium of energy transport from an atomic reactor to sites at which energy is required should not be electricity, but hydrogen. The term "hydrogen economy" applies to the energetic, ecological, and economic aspects of this concept.

The concept envisages atomic reactors held on platforms floating on water. They are in water sufficiently deep to make heat dissipation easy. The electricity they make would be converted on site to hydrogen and oxygen by electrolysis. The hydrogen would be piped to distribution stations and thereafter sent to factory and home. Reconversion to electricity would take place in on-site fuel cells, the only side product being pure water. Some advantages of the concept are:

1) A considerable increase in our energy supply will be needed in coming decades, and we must avoid air and heat pollution in its creation. This method avoids both. It does not imply a pollutional limit on growth. Its efficiency would be about 36 percent (if one assumes conservatively a 60 percent efficiency in both the use of energy to produce hydrogen and its reconversion at the fuel cell). Conversely, direct current would be generated. (In a transition period, alternators would consume another 1 to 2 percent of energy.)

2) The electricity supplied thus would be cheaper than that sent by overhead cables at distances greater than about 400 km from the reactor source (*1*). At 1600 km, the cost would thereby be halved.

3) The hydrogen economy would produce about 14 liters of pure fresh water per household per day, at the present level of the use of electricity. By A.D. 2000, the average household in the United States is likely (*2*) to consume ten times more electrical energy than at present. In this situation, the drinking water needed for a household would be a by-product of its electrical energy source.

4) Energy needs are cyclical; atomic reactors work continuously. Cryogenic hydrogen storage would be possible.

5) The hydrogen would run trucks, cars, ships, and trains, by means of fuel cell–battery combinations and electric motors. Transportation would be not only nonpolluting but also silent and cheaper in running costs (because of the greater efficiency of energy conversion). The performance of vehicles thus powered (without further research) would be comparable with that of present ones.

6) Aircraft could run on liquid hydrogen by using jet transducers similar to the present ones. Their range would be increased two to three times for the same weight of fuel. The emission into the atmosphere of CO_2, NO, and unsaturated hydrocarbons would be avoided. One-man jet helicopters might become feasible because the use of liquid hydrogen would give a 300 percent reduction in weight of fuel per unit of energy compared with gasoline.

7) Chemistry and metallurgy: Iron ore could be economically reduced by hydrogen directly to iron, the airborne excess product being steam. At plasma temperatures, aluminum could be produced more cheaply by thermal reduction of Al_2O_3 with H_2 than by the present method, even if cheapened electricity were used. Ammonia could be produced at about half the present price. Hydrogenation of fats would be cheaper. Those processes in chemical technology which involve continued emissions could be converted to fumeless electrochemical processes.

8) Fusion reactors will need deuterium. Deuterium is a by-product of water electrolysis.

The main difficulties which we would face in getting started toward a hydrogen economy are (i) conservatism; (ii) the absence of education or training in electrochemical engineering; and (iii) the public's fear of hydrogen. This is outmoded; railway cars containing liquid hydrogen pass casually through our cities and tunnels.

The prospect is for abundant energy and as affluent an economy (if the population growth can be limited) as we want in the future without the ecological difficulties which we now foresee in obtaining the first and maintaining and spreading the other.

J. O'M. BOCKRIS
School of Physical Sciences, Flinders University, Bedford Park, South Australia 5042, Australia

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3. I acknowledge discussion with F. T. Bacon of Energy Conversion, Cambridge CB2 5ES, England; with R. Henderson and N. Triner of the General Motors Technical Center, Warren, Mich.; with D. Gregory and D. Ng of the Institute of Gas Technology, 3424 South State Street, Chicago, Ill.; and with J. Appleby of the Centre Nationale de la Recherche Scientifique, Paris.

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