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Deep ground temperatures

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Abstract: Some 60 holes drilled for hydrocarbon exploration in the Mackenzie valley afford the opportunity to obtain precise measurements of deep permafrost thicknesses (depth to 0°C) and ground temperatures, and are presented here on maps and graphs. Permafrost thickness is less than 100 m in the Mackenzie Delta, and up to 663 m in the adjoining Tuktoyaktuk coastlands. Permafrost varies from 35 m to 143 m in the Norman Wells area, but is thin or absent in the Fort Simpson and Yellowknife areas. Variations in ground temperatures with depth reflect differing thermal properties of soil and rock, proximity to lakes or rivers, and residual thermal disturbance due to drilling. In some cases, subsurface temperatures show features that are relict from several thousand years ago when the local site environment was different from today, due for example, to more widespread lakes, changing shorelines, or river channels.

Résumé : Grâce aux quelque 60 trous forés à des fins d'exploration des hydrocarbures dans la vallée du Mackenzie, on a pu mesurer avec précision l'épaisseur du pergélisol en profondeur (profondeur où est atteinte la température de 0 °C) et les températures du sol, et on a reporté les données sur des cartes et des graphiques. L'épaisseur du pergélisol n'atteint pas 100 m dans le delta du Mackenzie mais elle peut atteindre 663 m dans la région littorale de la péninsule de Tuktoyaktuk. Le pergélisol varie en épaisseur de 35 à 143 m dans la région de Norman Wells, mais il est mince ou absent dans les régions de Fort Simpson et de Yellowknife. Les variations de la température du sol en fonction de la profondeur peuvent être attribuables aux propriétés thermiques des sols et des roches, à la proximité de lacs ou de cours d'eau et à la perturbation thermique résiduelle causée par les forages. Dans certains cas, les températures souterraines indiquent un pergélisol relique datant de plusieurs milliers d'années, formé alors que les conditions environnementales locales étaient différentes de celles d'aujourd'hui à cause. Ces changements peuvent être liés, entre autres, à un plus grand nombre de lacs plus vastes, à l'évolution des berges ou à la migration des chenaux fluviaux.

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Pioneering measurements of deep ground temperatures and permafrost conditions were made in the Norman Wells area by R.A. Hemstock (unpub. company report, Imperial Oil Limited, Calgary, Alberta, 1949), and Garland and Lennox (1962), and in the Mackenzie valley by Mackay (1967). Over the past thirty years, subsurface temperature measurements to depths greater than 125 m have been obtained by the Geological Survey of Canada from numerous, specially adapted resourceexploration holes: some 60 such wells are located in the Mackenzie valley, 40 of which are in the Mackenzie Delta–Tuktoyaktuk coastlands area (Judge, 1973a, b; Taylor et al., 1982). This unique data set provided industry and government with the first precise measurements of permafrost thickness (depth to 0°C) and temperature of permafrost. More recently, analysis of geophysical well logs has provided, at less precision, estimates of the depth to the base of permafrost ice-bonding at many more wells (Judge et al., 1987).

Figure 1 shows typical temperature data taken periodically over eight years at a Mackenzie Delta well. The thermal disturbance due to drilling through porous, frozen rock is apparent, and tens of years may be required to refreeze and cool to undisturbed conditions (Lachenbruch and Brewer, 1959); however, such a series of measurements is used to mathematically extrapolate the estimated equilibrium (or undisturbed) temperatures T_{EQ} that are shown in this paper.

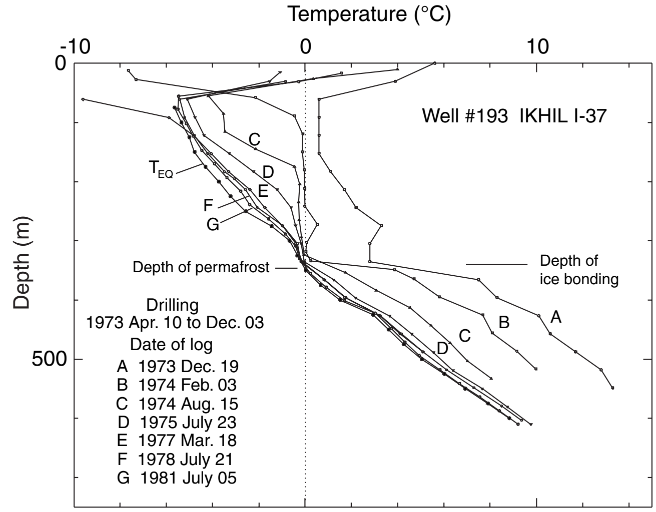

Figure 1. *Precision temperatures measured with a lightweight logging system over several years following drilling of a typical well. As the well cools from the thermal effects of drilling, temperatures 'hang' at the formation freezing point while refreezing takes place, before cooling further towards estimated undisturbed values, T_{EQ}. The depth of the intersection of the equilibrium profile T_{EQ} with 0°C is the depth of permafrost (347 m); the depth of the jump in temperatures in log A taken shortly after drilling is interpreted as the depth of ice bonding (341 ± 8 m). For location, see well #193, Figure 2b.*

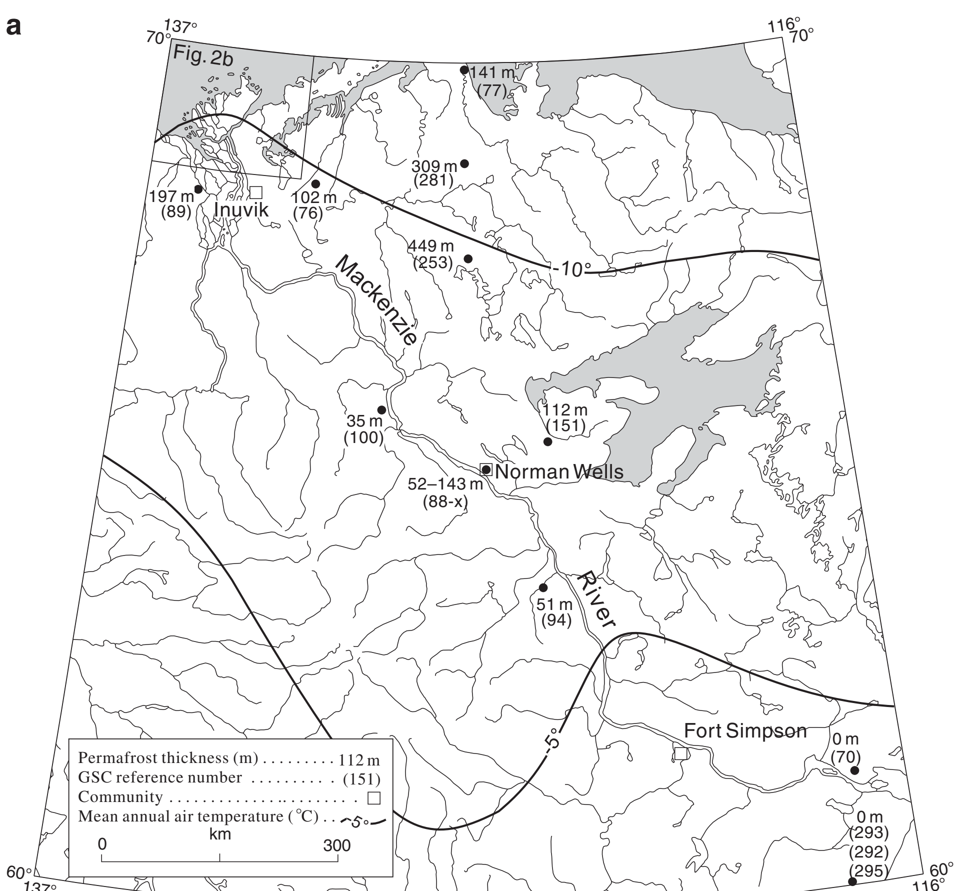

Figure 2.

Locations of wells where deep ground temperatures have been measured and permafrost thicknesses (m) have been determined. The numerals in brackets are reference numbers for identifying profiles in Figure 3. ***a****) Mackenzie valley,* ***b****) Mackenzie Delta and Tuktoyaktuk coastlands.*

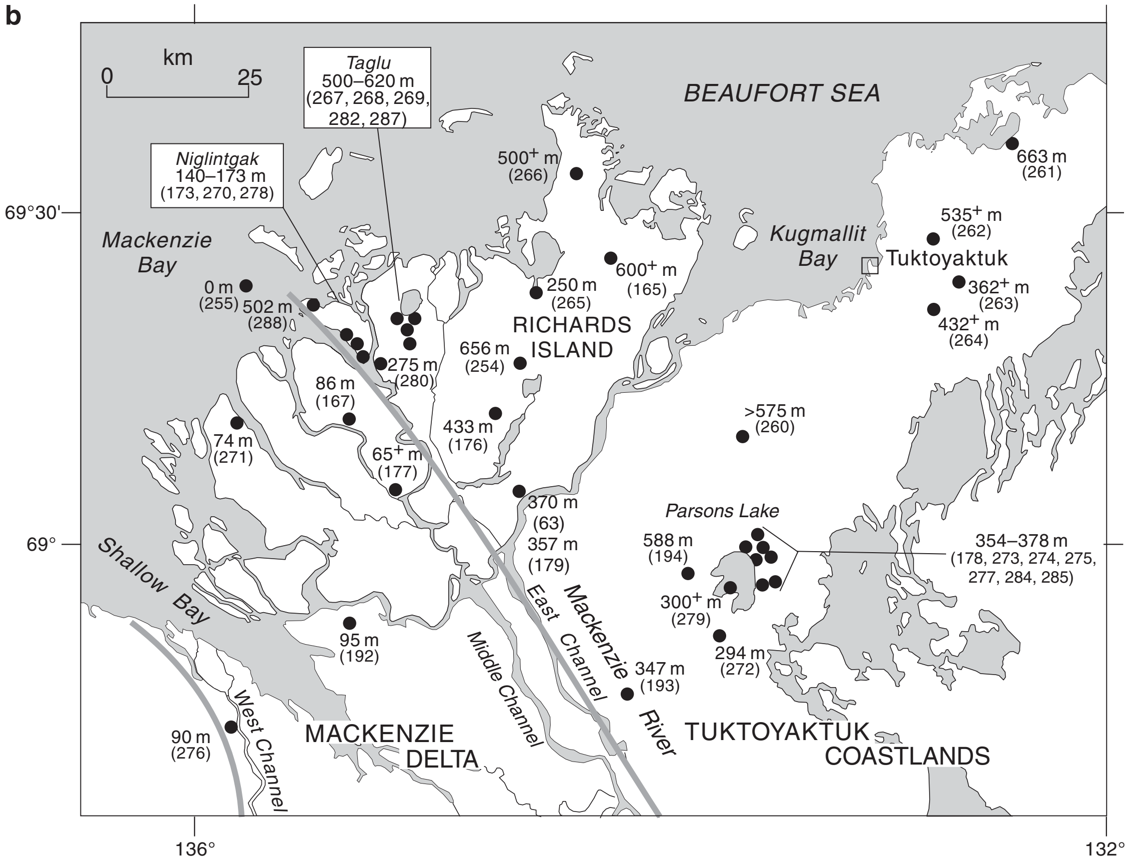

Figure 2. *(cont.)*

Figure 2a is a map of the depth to the base of permafrost determined at these wells. Permafrost is absent or thin in the extreme upper valley near 60°N, varies from 35 m to 143 m in the mid-valley around Norman Wells, and from 65 m to 663 m in the lower valley and Mackenzie Delta.

Permafrost thickness is a function of surface (air) temperatures for the past hundreds to tens of thousands of years, and of ground thermal properties. Permafrost is less than 100 m thick in the modern Mackenzie Delta (Fig. 2b), which was a deep marine trough prior to the formation of the delta in the past several thousand years; modelling suggests that about 3000 years of exposure to arctic air temperatures were required to grow the 86 m of permafrost observed at well #167 (Taylor et al., 1996). In contrast, immediately to the east, permafrost is up to 663 m thick in the Tuktoyaktuk coastlands, which was land exposed to severe temperatures for most of the past 100 000 years. In a small region, permafrost may be twice as thick in sands or sandstone as in clays or shale, because the thermal conductivity of sands and sandstone are typically twice that of clays or shale: heat loss under severe arctic conditions is greater in the higher conductivity environment.

A set of graphs, illustrates the variety of permafrost temperatures observed in the Mackenzie valley (Fig. 3). Thermal conductivity accounts for most of the variation in temperature with depth, as discussed above. The increase of temperature with depth is greater in the shale and limestone of the Mackenzie fold belt (Fig. 3b, c) than in deltaic sands and gravels of the Tuktoyaktuk coastlands (Fig. 3e). Other variations may be attributed to proximity to lakes or rivers, and to past changes in surface temperature. For instance, in the Taglu area, widespread lake or sea encroachment for a period of a few thousand years during the Holocene occurred at sites that are now on land, and temperatures remain close to the freezing point over a large depth interval because of this (Fig. 3h; Taylor et al., 1996).

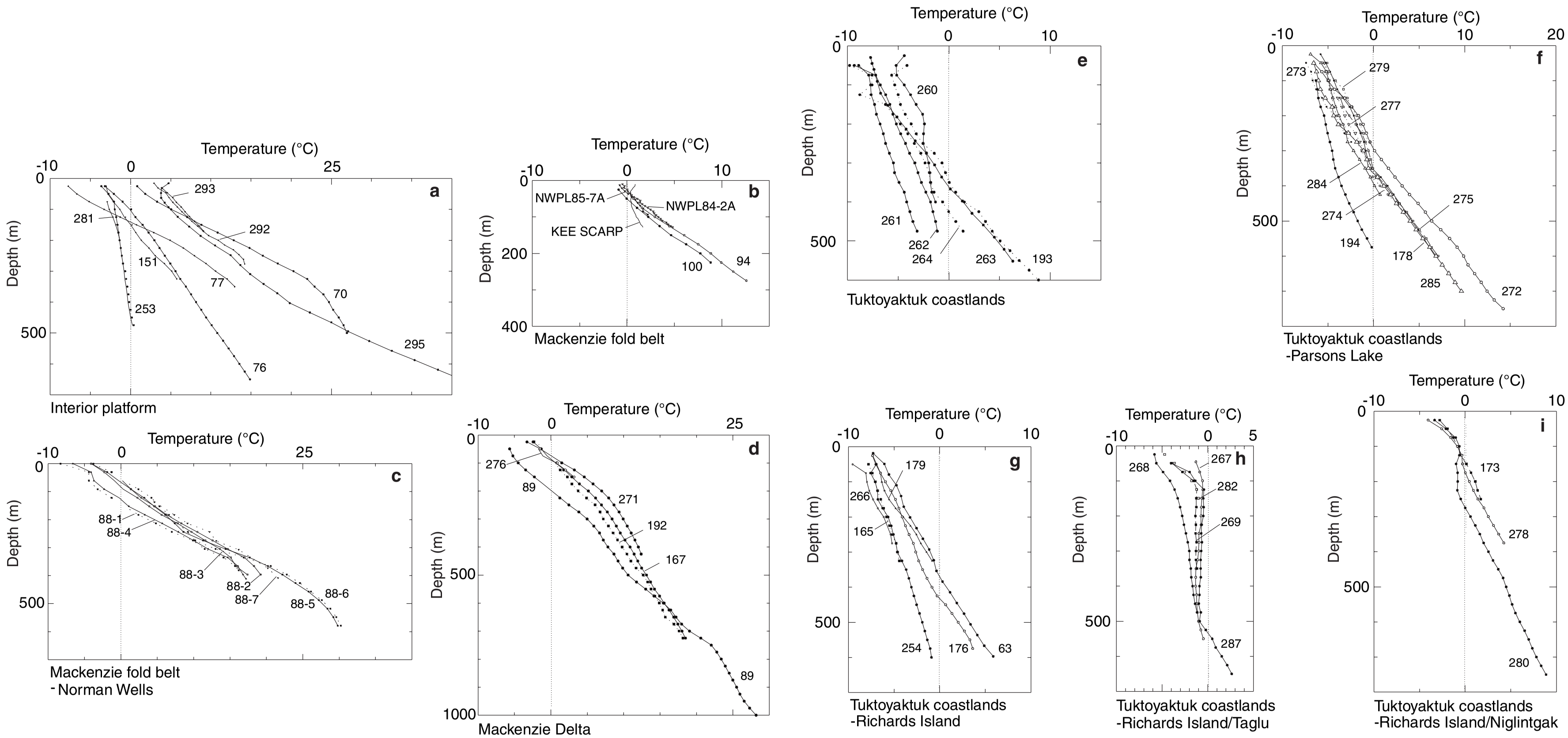

Figure 3. *Profiles of calculated equilibrium temperatures versus depth, grouped by convenient physiographic area; Niglintgak and Taglu are hydrocarbon exploration fields on western Richards Island (Fig. 2b). Numbers beside each profile provide cross-reference to Figure 2. The original data and further details are available in Taylor et al. (1982).*

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REFERENCES

Garland, G.D. and Lennox, D.H.
1962: Heat flow in Western Canada; Geophysical Journal, v. 6, p. 245–262.

Judge, A.S.
1973a: Deep temperature observations in the Canadian north; *in* Permafrost, the North American Contribution to the Second International Conference; National Academy of Sciences, Washington, D.C., p. 35–40.

Judge, A.S. (cont.)
1973b: The prediction of permafrost thickness; Canadian Geo-technical Journal, v. 10, p. 1–11.

Judge, A.S., Pelletier, B.R., and Norquay, I.
1987: Permafrost base and distribution of gas hydrates; *in* Marine Science Atlas of the Beaufort Sea — Geology and Geophysics (ed.) B.R. Pelletier; Geological Survey of Canada, Miscellaneous Report 40, p. 39.

Lachenbruch, A.H. and Brewer, M.C.
1959: Dissipation of the temperature effect in drilling a well in arctic Alaska; United States Geological Survey, Bulletin 1083-C, p. 73–109.

Mackay, J.R.
1967: Permafrost depths, lower Mackenzie Valley, N.W.T.; Arctic, v. 20, p. 21–26.

Taylor, A.E., Burgess, M.M., Judge, A.S., and Allen, V.S.
1982: Canadian geothermal data collection - northern wells 1981; Geothermal Series 13, Earth Physics Branch, Energy, Mines and Resources Canada, 153 p.

Taylor, A.E., Dallimore, S.R., and Judge, A.S.
1996: Late Quaternary history of the Mackenzie-Beaufort region, Arctic Canada, from modelling of permafrost temperatures: 2. The Mackenzie Delta-Tuktoyaktuk Coast-lands; Canadian Journal of Earth Sciences, v. 33, p. 62–71.