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PERMAFROST STUDIES IN NORTHERN QUÉBEC*

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ABSTRACT In cooperation with mining companies, temperature data are being acquired at several sites in the Cape Smith — Wakeham Bay Belt of Northern Québec. Cables, containing up to twenty thermistors, are lowered into exploratory diamond-drill holes upon completion, and allowed to freeze in place. Three temperature profiles at Asbestos Hill yield low geothermal gradients; thermal conductivities of core are moderate to low and hence low values of the terrestrial heat flow are observed. Extrapolating temperature profiles to greater depths gives a permafrost thickness of at least 540 m. The uncorrected terrestrial heat fluxes calculated for the shallow holes are about 2/3 that of the lower section of the deeper hole. Such contrast in heat flow is used to develop a simple model of surface temperature history for the area for the past 85 000 years. Using this geothermal data, engineering estimates may be made of such parameters as maximum active layer thickness and thaw penetration of both open pit walls and underground drifts.

RÉSUMÉ *Les études sur le pergélisol dans le nord québécois.* Depuis plusieurs années, le Service d'études géothermiques, en collaboration avec des compagnies minières, fait la cueillette de mesures de température dans plusieurs sites de la région des collines de Povungnituk, entre le cap Smith et la baie de Maricourt. On introduit, dans des trous de forage, des câbles contenant jusqu'à vingt thermistors, puis on les abandonne au froid. À la colline de l'Amiante, trois profils thermiques présentent des gradients géothermiques peu élevés; la conductivité thermique des carottes étant de moyenne à basse, il en résulte un faible flux de chaleur terrestre. En extrapolant les profils thermiques à de plus grandes profondeurs, on est parvenu à évaluer l'épaisseur du pergélisol à au moins 540 m. Les taux non corrigés des flux de chaleur terrestre provenant des trous de forage peu profonds représentent les deux tiers de ceux des parties inférieures des trous plus profonds. Ces différences de calcul entre les flux de chaleur sert à l'élaboration d'un modèle simple de reconstitution des variations de températures de surface depuis 85 000 ans dans la région. Les données géotechniques permettent le calcul de certains paramètres tels que l'épaisseur maximale de la couche active et l'ampleur du dégel dans les murs de mines à ciel ouvert ou de galeries souterraines.

ZUSAMMENFASSUNG *Dauerfrostforschung im nördlichen Québec.* In Zusammenarbeit mit Bergwerksgesellschaften werden Temperatur Daten von verschiedenen Orten in dem Cape Smith-Wakeham Bay Gürtel in Nord-Québec gesammelt. Kabel, die bis zu zwanzig Thermistoren enthalten, werden in Probebohrlöcher versenkt und dort festfrieren gelassen. Drei Temperaturprofile aus den Asbestos Hills ergeben schwache geothermale Kurven, die thermale Leitungen der Kerne sind moderat bis schwach und daher sind schwache Werte des Erd-Wärme-Flusses beobachtet worden. Extrapolation der Temperaturprofile auf grössere Tiefen ergibt eine Dicke des Dauerfrostes von mindestens 540 m. Die unkorrigierten Erd-Wärme-Bewegungen, für die flachen Löcher errechnet, betragen ungefähr zwei Drittel der Sektion der tieferen Löcher. Solche Kontraste im Wärmefluss werden zur Entwicklung von einfachen Modellen der Oberflächen-temperatur Geschichte der Gegend für die vergangenen 85,000 Jahre benutzt. Der Gebrauch dieser Daten, erlaubt Ingenieuren das Vorhersagen auf solchen Gebieten wie Höchstdicke der Tautzone und Tautiefe in offenen Gruben und unterirdischen Gräben.

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INTRODUCTION

The Geothermal Service of the Earth Physics Branch, EMR, is accumulating subsurface temperature and rock thermal conductivity data throughout Canada. Of particular interest are the data used to determine permafrost thickness at nearly 100 sites in the north (JUDGE *et al.*, 1979) (Fig. 1). While most northern measurements are taken in oil exploration wells, a growing number of determinations have been made in diamond drillholes in mining areas. This paper outlines observations undertaken in one such mining area, describing in detail the data obtained in the Ungava region of Québec and the resulting information of interest to both the scientist and mining engineer.

THE PROGRAM

Drilling deep boreholes for strictly scientific or engineering purposes in the north is generally prohibitively expensive. The Geothermal Service has entered into cooperative programs with a number of companies to instrument or otherwise use holes drilled during the course of mineral exploration. Valuable geothermal data in permafrost and near-permafrost areas have been gathered with Cominco in the Yellowknife, Bathurst Inlet and Little Cornwallis areas of the Northwest Territories, with Whitehorse Copper, Cassiar Asbestos and

Cyprus Anvil Mines, in the Yukon, and with several companies in northern British Columbia and in the Ungava.

Inexpensive, lightweight cables containing temperature sensors (thermistors) at predetermined intervals are normally lowered in diamond drillholes and are left as the hole freezes. Periodic logging using a Wheatstone bridge produces a series of temperature profiles with depth; routine laboratory measurements on selected core samples give such physical properties as rock thermal conductivity, density and porosity. An estimate of permafrost thickness may readily be made but further analysis is undertaken to determine its characteristics and dynamic behaviour. Of interest to the earth scientist are estimates of the terrestrial heat flux and some information derived on the quaternary palaeoclimatology of the area.

DATA FROM NORTHERN QUÉBEC

The most northern part of Québec, the Ungava peninsula, is an arctic environment of considerable geophysical interest (Fig. 2). The boundary of the Churchill and Superior geologic provinces is manifest in the Proterozoic sedimentary, volcanic and intrusive rocks comprising the Cape Smith foldbelt crossing the area (GÉLINAS, 1961; TAYLOR, 1974) and is the locus of

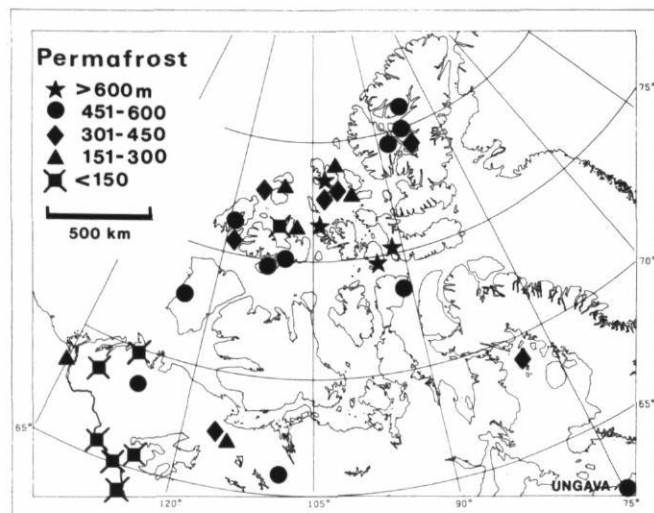


FIGURE 1. Permafrost thicknesses in northern Canada. Some symbols represent several determinations, and not shown are 40 sites in the Mackenzie Delta. Data from the Ungava region of Québec is represented by the symbol in the lower right corner.

Estimations de l'épaisseur du pergélisol en divers points du nord du Canada. Certaines mesures sont le résultat de plusieurs évaluations. Les quarante sites du delta du Mackenzie n'apparaissent pas ici.

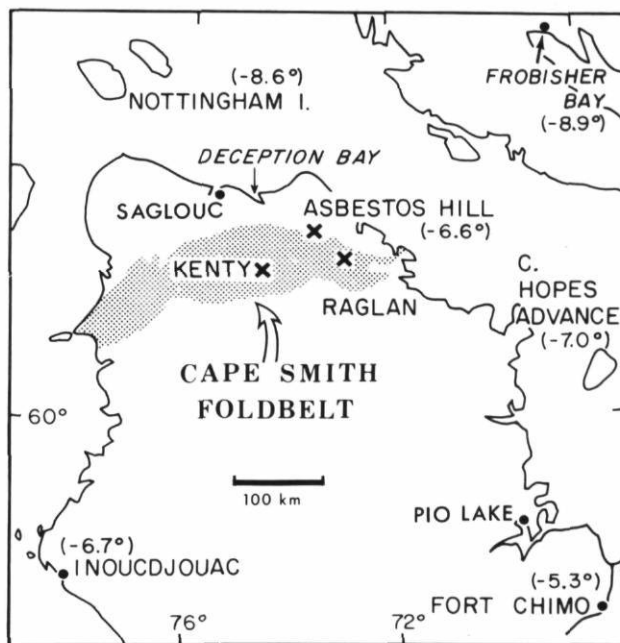


FIGURE 2. Locations (x) of geothermal measurements in northern Québec. Figures in brackets are approximate mean annual air temperatures.

Les sites du Nouveau-Québec où ont été obtenues les mesures géothermiques. Les chiffres entre parenthèses représentent des températures moyennes annuelles.

much of the mineralization being explored or exploited. The climate is severe; mean annual temperatures are well below 0°C at coastal stations (Environment Canada, 1975) and probably considerably lower inland, where highland plateau elevations rise to over 500 m. Most of the peninsula is lightly covered with vegetation, being north of the tree-line, which lies somewhat north of Fort Chimo. It has been generally assumed that the peninsula was covered by the Laurentide Ice Sheet until seven thousand years ago and since then has experienced over 100 m of post-glacial rebound, implying that a considerable margin of the peninsula has recently emerged from the sea (PATERSON, 1972; MATTHEWS, 1966, 1967). SUGDEN (1977) has reconstructed the physical characteristics of the Laurentide Ice Sheet at its maximum. He predicts that if the ice sheet attained this maximum condition and was in thermal steady state, then the basal ice sheet temperature in the Ungava peninsula would have been -5° to -10°C , based on an assumed mean air temperature over the ice sheet of the order of -40°C . Recently, IVES (1978) has suggested that the maximum extent of the Laurentide Ice Sheet may have been more restricted than previously thought; D. R. Grant (pers. commun., 1979) suggests that the Ungava peninsula may have been covered by only a thin, cold ice-sheet, or none at all for the past several tens of thousands of years.

The Geothermal Service has been accumulating geothermal data at mining exploration sites within this area for a number of years. A small program was carried out several years ago with Falconbridge at Raglan, and data are currently being collected at one site at Kenty Lake (Cominco) and six sites, two of the underground, at Asbestos Hill (with the assistance of the Asbestos Corp.) (Fig. 2). This paper is based largely on data from three sites at Asbestos Hill; a more detailed paper including data from the remaining sites will be published later.

The deepest temperature measurements at Asbestos Hill, near the mine site, are shown in Figure 3. The inversion in the upper part of the measured temperature profile may arise from either the unusually complex drilling history of this particular borehole or from a recent climatic warming in the last century. The temperature gradient below the inversion is uniform at about 12 mK/m , similar to that at other sites in the Ungava and typical of the low values normally found in shield areas. A modest extrapolation of the temperatures to a greater depth suggests a permafrost base at 540 m, a thickness similar to or greater than that found further north (Fig. 1), but twice the thicknesses predicted from shallow drilling during site development (SAMSON and TORDON, 1969). The rock thermal conductivity profile with depth for that borehole correlates well with the lithology of the logged core. For example, the higher conductivity at 300 m corresponds to a zone

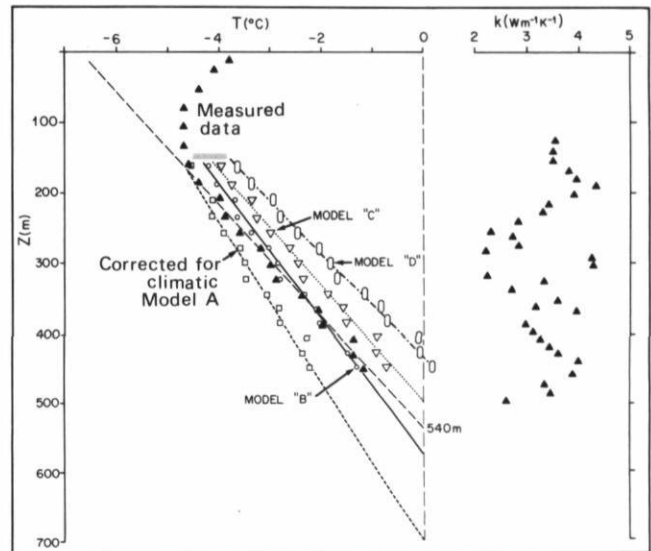


FIGURE 3. Measured temperature and conductivity data (solid symbols) versus depth z for the deepest borehole at Asbestos Hill. The extrapolated permafrost thickness is 540 m. Hypothetical subsurface temperatures in equilibrium with present conditions (open symbols) are shown for plausible palaeoclimatic reconstructions (Fig. 4, lower).

Mesures de température et de conductivité thermique (triangles noirs) mises en rapport avec la profondeur z du trou de forage le plus profond de la région. L'épaisseur du pergélisol a été évalué à 540 m. Des températures souterraines hypothétiques (triangles blancs) en équilibre avec les conditions actuelles servent à l'élaboration de modèles plausibles de reconstitution climatique.

of pyroxenite, contrasting with the lower conductivity of serpentine just above it.

Such intervals of higher and lower conductivity normally correlate with similar intervals of lower or higher (respectively) temperature gradients such that their product yields a uniform terrestrial heat flux with depth. Within the limits imposed by the numbers of measuring points, the temperature-conductivity profile in Figure 3 yields a measured heat flux of 38 mWm^{-2} over a depth interval 150 m to 450 m. Other shallower holes in the Asbestos Hill area yield heat fluxes of 39 mWm^{-2} (80 to 225 m) and 24 mWm^{-2} (15 to 121 m).

PALAEOCLIMATE AND PERMAFROST

The terrestrial heat flux originates deep within the crust and upper mantle and may be considered to be constant to depths of a few thousand metres. However, because of the very slow response of the earth to changes in temperature at its surface, the temperature profiles observed today are considerably disturbed by climatic changes occurring in recent geologic time. The differences in the apparent terrestrial heat flux values

calculated above for different depth intervals may be attributed largely to climates in the past impressing a somewhat different temperature on the ground surface. By mathematical analysis, these recent transitory effects due to climatic change can be stripped from the temperature profiles, leaving a thermal regime reflecting solely the earth's heat flux from the deeper regions of the earth. The procedure is non-unique but can lead to an understanding of the interaction of climate and the sub-surface and hence to an understanding of the dynamic behaviour of permafrost.

Evidence of palaeoclimates in the Arctic is available from other disciplines, and some models are depicted diagrammatically in Figure 4. Palynologic studies at Saglouc (100 km NW of Asbestos Hill, Fig. 2) have suggested several periods of cooler and warmer conditions since deglaciation about 6700 years ago (BARTLEY *et al.*, 1969). These trends are substantiated more generally at other areas (NICHOLS, 1972; DANSGAARD *et al.*, 1970). While studies such as palynology distinguish warmer or cooler, wetter or drier conditions and radiocarbon analysis date these climatic intervals, geothermal data are most sensitive to the magnitudes of the ground temperature changes involved. In this study, various model palaeoclimates have been hypothesized for the Asbestos Hill region, adopting the approximate time intervals indicated for Saglouc. A range of temperatures is then considered for each interval, and a provisional heat flux is calculated for the temperature range for each site. The more unlikely models are discarded on the premise that the different heat flux values measured in the three separate boreholes should be roughly equal when climatic influences are eliminated. Using essentially a trial-and-error method, a simplified climatic model since 6700 years ago was eventually found that caused the provisional heat flux values from the three boreholes to converge to approximately the same value: $36 \pm 3 \text{ mWm}^{-2}$. This model is shown in Figure 4. Eliminating climatic effects more distant in time, such as the Pleistocene glaciation, changes the individual measured heat fluxes but produces little tendency for convergence. The present data, therefore, cannot be used to distinguish the most likely Pleistocene surface temperature model; temperature measurements to more than 1000 m would be required.

However, the geothermal regime has important implications for the nature of Pleistocene ice sheets. Extending the recent climatic history established above to further than 6700 years ago allows the impact of a range of Pleistocene surface temperatures on the geothermal regime to be considered. Models A to D are representative (Fig. 4). In model A, a temperature 4K warmer than the present surface temperature (about -6.6°C) is postulated for the period from 6700 years to 85,000 years before present. This represents the case of a thick

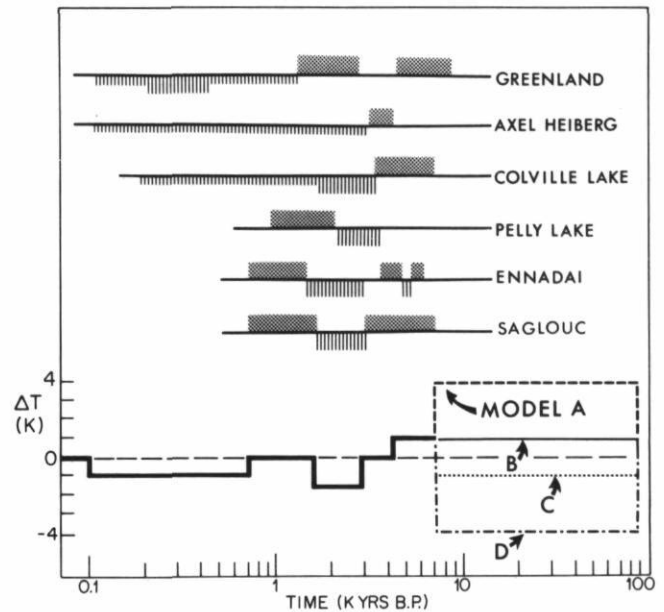


FIGURE 4. (Upper) Palaeoclimates from the literature (NICHOLS, 1972; DANSGAARD *et al.*, 1970). Stripes indicate surface temperatures cooler than today; coarse screening, a climate warmer than at present. (Lower) The general tendencies are used to postulate past surface temperatures for Asbestos Hill consistent with the geothermal results. Models A to D differ only in the temperatures postulated for the glacial period, prior to 6700 years ago. Model A postulates temperatures 4K warmer than present surface temperatures; model B, 1K warmer; model C, 1K cooler than present; and model D, 4K cooler. The present surface temperature is about -6.6°C .

*Haut: paléoclimats selon diverses sources (NICHOLS, 1972; DANSGAARD *et al.*, 1970). Les rayures correspondent à des températures de surface plus basses que celles que nous connaissons actuellement; le grisé, des températures plus douces. Bas: l'observation de ces tendances générales sert à reconstituer un paléoclimat qui concorde avec les données géothermiques de la région. Les modèles A, B, C et D ne divergent que pour la période glaciaire avant 6700 ans BP. Le modèle A présente des températures plus chaudes de 4K que celles d'aujourd'hui; le modèle B, plus chaudes de 1K; le modèle C, plus froides de 1K; le modèle D, plus froides de 4K. Actuellement la température de la surface est d'à peu près $6,6^\circ\text{C}$.*

ice sheet with the base at its pressure melting point. Models B and C assume surface temperatures over this period slightly warmer or cooler, respectively, than at present, namely -5.6°C and -7.6°C . These are similar to temperatures predicted by SUGDEN (1977) beneath the ice sheet at its maximum. A cold-based ice sheet is simulated by model D, with a temperature 4K cooler than at present, or about -10.6°C from 6700 to 85,000 years BP.

With the effects of these climatic models eliminated, this analysis yields terrestrial heat flux values, averaged

over the three sites, of (in mWm^{-2}): 28 (model A), 34 (B), 38 (C), and 44 (D). The values are low, ranging from one half to three quarters the world average continental heat flux (JESSOP *et al.*, 1976) but within the range expected typically of a shield area. The glacial conditions implied by model A, however, seem unlikely.

Had the Ungava peninsula been ice-free for a much longer period or covered by a thin, cold ice sheet as discussed previously, corrected terrestrial heat flux values increase even further. Assuming a surface temperature 10K to 20K colder than at present from 6700 to 30,000 years BP yields corrected heat flux values from 50 to 70 mWm^{-2} . Such high undisturbed terrestrial heat fluxes are unlikely from what is known of other shield areas (RAO and JESSOP, 1975).

Further data are being obtained in northern Québec, and refinements to the surface temperature history should result. At present, this limited analysis justifies a probable terrestrial heat flux (corrected for climatic effects) of $38 \pm 5 \text{ mWm}^{-2}$. The difficulty of utilizing temperatures from very shallow holes to determine either the geothermal flux or the local thickness of permafrost is apparent. BECK (1977) underlines the importance of correcting measured heat flux values for local climatic influences; in view of this, caution should be exercised in using uncorrected data, as reported for Purtuniqu (Asbestos Hill) by SEGUIN (1978).

The profiles labelled A to D in Figure 3 result from the mathematical removal of the climatic and glacial variations of these models from the measured profile at Asbestos Hill, giving temperature curves that would exist had the climate been always the same as that today. They demonstrate that permafrost thicknesses considerably different from what is measured today are required by the various models to achieve thermal equilibrium with present surface conditions. Hence, permafrost may be currently increasing slowly in thickness (if climatic models A or B were adopted) or decreasing in thickness (models C and D).

PERMAFROST DISTRIBUTION

The value of 540 m for the permafrost thickness at Asbestos Hill was derived from data (Fig. 3) at a site in the upper reaches of a broad drainage valley. The hills in the surrounding area create a relief of at most 180 m above this site. The permafrost base would be expected to follow the topography with a relief somewhat attenuated, so permafrost thickness measured from the crowns of nearby hills may exceed 600 m.

Combining the probable, corrected heat flux for the region, and estimates of the local surface temperature and of the thermal conductivity of the formation permits prediction of permafrost thickness at other localities

within the region (JUDGE, 1973). Surface temperatures measured by the National Research Council (G. Johnston, pers. comm.) within 10 km of the coast are 2 to 3K warmer than at the Asbestos Hill minesite. Adopting the terrestrial heat flux values calculated for Asbestos Hill as being regionally typical and a reasonable value of the thermal conductivity for the granitic gneiss of the area suggests permafrost may not exceed 300 m near the coast. A more refined calculation would take into account the uplift following deglaciation and the considerable effect of a regressing shoreline on permafrost thickness (LACHENBRUCH, 1957). Isolated cases of frozen sands were detected under Deception Bay (Fig. 2), about 150 m offshore in 10 m of water (SAMSON *et al.*, 1969).

Spacing of the thermistors on the cables used in this study and the frequency of measurements did not permit direct temperature measurements within the active layer. However, thermal conductivity and density measurements were made on several major rock types within the mine area, permitting a reasonable average value of thermal diffusivity of $1.4 \times 10^{-6} \text{ m}^2\text{s}^{-1}$ to be calculated. The meteorological records kept by the Asbestos Corp. show an annual periodic variation in monthly mean air temperatures of approximately 16K amplitude (R. Scalzo, pers. commun.). With these parameters we can estimate (e.g. GOLD and LACHENBRUCH, 1973) a maximum thickness of about 3 m for the active layer in low porosity exposed bedrock at Asbestos Hill; thaw would attain this maximum thickness about 1.5 months after the summer air temperature peak. Active layer thickness of 1.0 to 1.4 m in the sand and silty gravel overburden at Asbestos Hill was measured in late August and early September, 1962 (SAMSON *et al.*, 1969). Estimates of the active layer in bedrock at Pio Lake (400 km SE of Asbestos Hill, Fig. 2) range from 2.2 to 5.0 m in mid-August (GRAY and PILON, 1976). In moist sand, vegetation covered or swampy sites the active layer will be considerably thinner and variable due to latent heat effects associated with soil moisture, retarding the penetration of surface temperature changes. ROBITAILLE (1967) reports a considerable variation in the active layer thickness near Fort Chimo, and relates it to soil types and vegetation cover.

ENGINEERING CONCERNS

Thaw of the rock may be important to several aspects of both open-pit and underground mine design. The development during the summer months of an active layer in the walls of an open-pit is also a concern in slope stability design. Operation of an underground mine generally involves the use of heat-producing equipment and rock thermal properties are needed to calculate the ventilation required underground. Data collected

during this study permit estimates of the rate of development of thaw surrounding an underground drift, a situation that could have serious consequences when drifting through highly fractured, initially frozen rock. Figure 5 shows the growth of a thaw bulb around a drift in which 5°C air is circulated for periods of time between 6 months and 10 years. Of particular interest is the increased size of the thaw zone at greater depths where excess heat from mining operations would be most difficult to control. The increased size of the thaw bulb is, of course, a result of the increase in natural rock temperatures with depth.

The depth to the base of the permafrost may be very important in mine design. Whereas fractures and pores may be effectively sealed by ice within the permafrost, considerable water-related problems may be encountered at depths below permafrost.

CONCLUSION

This brief paper has attempted to show how a simply acquired parameter such as underground temperatures

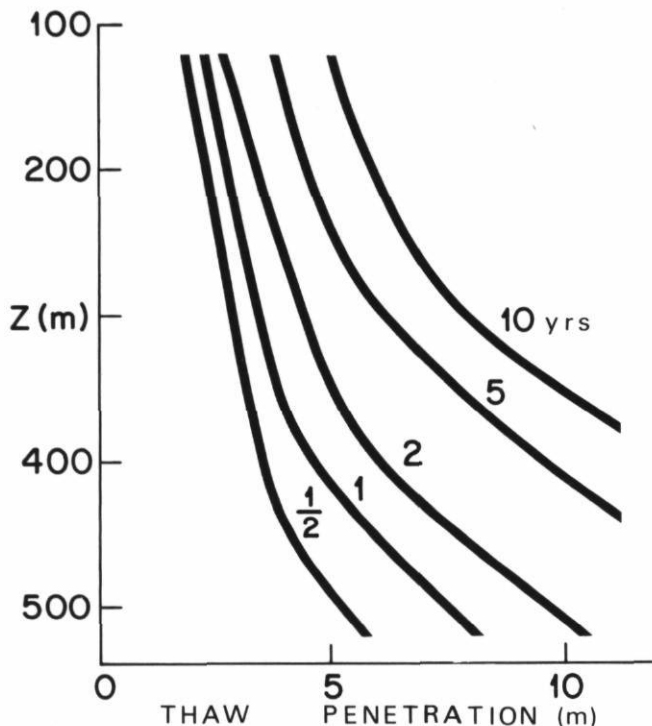


FIGURE 5. Predicted extent of thaw around a 3 m diameter drift or decline at various depths, z , at Asbestos Hill. Calculation assumes that 5°C air is circulated for periods of 6 months to 10 years.

Ampleur du dégel autour d'une galerie de 3 m de diamètre, à différentes profondeurs, à la colline de l'Amiante. Les calculs tiennent compte d'une circulation d'air à 5°C pendant des périodes qui peuvent varier entre 6 mois et 10 ans.

can be of use to both the earth scientists in investigating the earth's heat flux and climatic history and to the mine engineer in ensuring a safer, more effectively operated mine.

Permafrost is 540 m thick in a valley at Asbestos Hill, and is probably thicker under the crowns of nearby hills. Such thickness, although typical of locations much further north, results from a severe climate, a low terrestrial heat flow typical of shield areas and only moderate thermal conductivities in the rock. The geothermal data examined in this study generally support palaeoclimates proposed by other disciplines for the past several thousand years. The probable heat flux for this area, corrected for a reasonable climatic history, is $38 \pm 5 \text{ mWm}^{-2}$.

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