NOTES

Geothermal Data from the Granduc Area, Northern Coast Mountains of British Columbia

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Temperature measurements have been obtained from 80 points along the Granduc haulage tunnel, at depths of as much as 1.5 km below the surface. These fit, within 1 °C, a simplified model assuming, among other things, uniform thermal conductivity of the rocks and a temperature at rock–glacier contacts of 0 °C. For these assumptions a generalized thermal gradient (with effects of topographic irregularity removed) is about 26 mK m^{-1} (26 °C/km). With the thermal conductivity of a suite of rocks from the tunnel averaging 2.72 ± 12 W $m^{-1}K^{-1}$ (6.50 ± .28 cal/cm s °C) present heat flow of about 73 mW m^{-2} (1.74 μcal/cm^2 s) can be derived.

Nous avons mesuré la température de 80 points situés le long de la galerie de roulage de Granduc, à des profondeurs pouvant atteindre jusqu'à 1.5 km sous la surface. Ces mesures concordent à 1 °C près, avec un modèle simplifié pour lequel nous devons supposer, entre autres choses, une conductivité thermale uniforme pour toutes les roches et une température de 0 °C au contact de la roche et du glacier. En se basant sur ces prémisses, nous obtenons un gradient thermal moyen (corrigé pour les effets d'une topographie irrégulière) d'environ 26 mK m^{-1} (26 °C/km). Pour une conductivité thermale moyenne de 2.72 ± .12 W $m^{-1}K^{-1}$ (6.50 ± .28 cal/cm s °C) pour la séquence de roches de ce tunnel, nous déduisons le flux actuel de chaleur comme étant d'environ 73 mK m^{-2} (1.74 mcal/cm^2 s). [Traduit par le journal]

Introduction

During a 3.5 year period from July 1965 to December 1968 a low-level haulage tunnel was driven for 18 km beneath the peaks and glaciers of the northern Coast Mountains to provide access to the Granduc copper mine (Lat. 56°12′ N, Long. 130°20′ W). In places this tunnel is as much as 1.5 km below the surface. Recognizing an opportunity of obtaining new geothermal data from a region in which very little was known previously of temperature conditions, the writer sought the cooperation of the Granduc Operating Company in this study. In response the company undertook to drill a series of holes about 2 m deep into the walls of the tunnel at 305 m intervals (later changed to 157 m intervals) and to observe the temperatures within them. The writer provided thermistors, bridge, and checked calibration and techniques during annual visits to the mine.

In 1969–71, after completion of the haulage tunnel, the study was extended into the Granduc mine, in the hopes of obtaining data over a significant vertical range as well as from points beneath and close to a large valley glacier. This latter study has, however, had only limited success and is not reported here.

Temperatures

The record of temperatures measured in the haulage tunnel is given in Fig. 1. The first observations in the eastern end of the tunnel were made as much as 21 months after it had been driven past the sites; moreover a seasonal fluctuation of 1 to 2 °C, which can be associated with the passage of warm summer air or cool winter air drawn inward through the tunnel for ventilation, is clearly observable. For this part of the tunnel the record of April–May, 1967, is considered more nearly that of the original rock temperature than is that of the following August or February. Observations at points 6.7 to 15.1 km from the east portal were generally made less than 1 month, and on occasions less than 1 week, after exposure by tunneling and are considered more reliable.

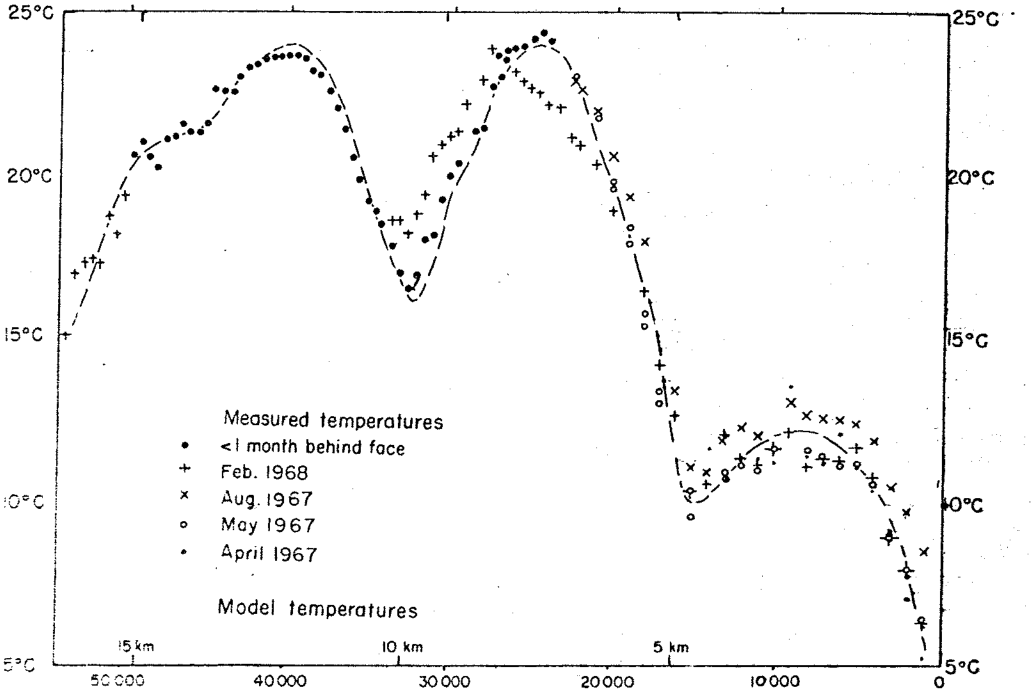

FIG. 1. Rock temperatures, Granduc Haulage tunnel.

Much of the energy transferred to the tunnel walls by mining activities had probably dissipated and modification of temperature as a result of prolonged ventilation was probably still minor. It is clear, however, from observations taken 3 to 7 months later at the same sites that temperatures had changed during the interval by as much as 2.5 °C, falling or rising in keeping with rock temperatures closer to the east portal and hence with temperature of air drifting inward. Because of these problems probably the best observations in the series may differ as much as 0.5 °C from the virgin rock temperatures. Precision of measurements (±0.15 °C) and errors in calibration (±0.1 °C?) are probably negligible by comparison.

Disturbance of temperatures by circulating ground water is considered negligible along the haulage tunnel (but not in the mine): significant water flows encountered during tunneling were localized (chiefly at 1.5 and 15.1 km from the east portal) and no significant perturbations of temperature were noted in their vicinity. Drill holes for temperature measurements were, moreover, not used if they were close to heat-generating mine equipment.

Temperature Gradient

Derivation of the temperature gradient near the haulage tunnel presents a problem in that all the measurements are from a single altitude. The same problem was faced, for example, by Birch (1950) for measurements in a Colorado tunnel. For a solution he estimated surface temperatures on the basis primarily of the vertical gradient of mean annual air temperature as determined from meteorological observations at 33 stations within 200 km of the tunnel and covering a vertical range of 2770 m. No such information is available for the Granduc area.

At Granduc the widespread occurrence of glaciers above the tunnel provides a useful limiting condition in estimating the temperature gradient. At the ice–rock interface, regardless of its altitude, the temperature should be at or close to 0 °C; certainly it cannot be significantly above it. Requisite conditions for 'temperate' glaciers (those attaining the pressure melting point throughout their depth) including heavy winter snowfalls and intense summer melting (Paterson 1969, p. 176) with meltwater percolation occurring over the entire firn area, are known to prevail, although there is some evi-

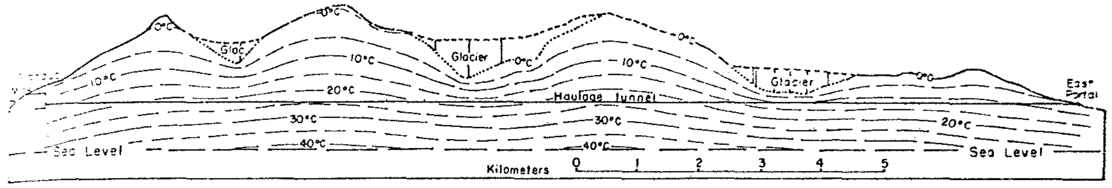

FIG. 2. Inferred temperature distribution, Granduc tunnel section.

dence from the Granduc mine (Mathews 1964, p. 238) that the temperatures within the valley glacier nearby may be a few degrees below freezing.

Most ice-free slopes in the Granduc area, such as occur below the 1600 m level on south-facing slopes and below 1200 m on east-facing slopes, can, moreover, be suspected as having mean annual rock temperatures slightly above 0 °C, being sheltered from extreme winter chill by a deep snow cover, and exposed to summer warming during the snow-free period. However a few rocky mountain sides are so steep that they shed their snow cover and are so well sheltered from sunlight that their temperatures may lie perenially below the freezing point of water.

Surface rock temperatures at or close to the tunnel level (800 m) must be close to 4 °C as indicated both by the observations near the east portal of the haulage tunnel and in the 3600 adit (1100m) of the Granduc mine (Mathews 1964). Higher ice-free slopes presumably have temperatures between this value and 0 °C.

The elevation of the rock surface above the tunnel can be determined directly for a length of 7.3 km (44% of the length of the tunnel) from a detailed topographic map prepared for the Granduc Operating Company. For another 2.9 km, the steep, irregular firn surface and occasional crevasses exposing bedrock, make it clear that the glacier cover is thin, generally less than 50 m. Three major valley glaciers, with an aggregate width of 6.3 km, cross the tunnel line, and here only the record of 10 widely-spaced drill holes (Fig. 2) provide a clue on the position of the bedrock surface.

Configuration of the rock surface, as well as its elevation above the tunnel, influences the temperature gradient. A topographic correction can be worked out by a laborious summation of mean altitude within a 3-dimensional pattern of sectors surrounding successive points along the tunnel (Birch 1950, p. 590). However as the topography at Granduc consists of a series of ridges and valleys with essentially parallel contours, a limited number of representative vertical cross sections allow a much simpler 2-dimensional analysis of the topographic effects. To facilitate this analysis a series of electric analogues were prepared on metal-coated paper for appropriate transverse sections across the eastern part of the tunnel, and along the tunnel line itself in its western part where it, fortunately, crosses the dominant topography at right angles. The model was prepared with the following assumptions:

1. The 0 °C isotherm (represented by a sinuous electrode attached to the paper by a conducting silver cement); (a) follows the base of any glacier ice, (b) lies about 150 m above ground on bare southerly or southwesterly facing slopes at the 800 m level (thereby giving in the model a temperature of about 4 °C at the ground surface), (c) makes contact with the ground at the ice limit (about 1600 m a.s.l. on east facing slopes), and (d) lies as much as 60 m below the surface beneath the high ridges and summits and on steep northerly-facing slopes.

2. At a depth of 2000 m and more below sea level the prevailing temperature is essentially constant (*i.e.* a horizontal isotherm represented on the model by a straight electrode).

3. The rocks have a uniform thermal conductivity (just as the metal-coated paper has a uniform electrical conductivity) and that advection of heat by moving ground water can be ignored (see above). The electrical analogues permit representation of the form of the isotherms between the surface and the −2000 m level (See Fig. 2). Observations within the tunnel permit the assignment of particular values of temperature to these isotherms. Model temperatures so derived agree within 1 °C for all

TABLE 1. Thermal conductivity of Granduc samples

Granodiorite	East Portal	3 discs	2.68 W $m^{-1}K^{-1}$	6.40 cal/cm s °C
			2.78	6.64
			2.72	6.50
		Average	2.73 ± .04	6.52 ± .10
Granodiorite	3650 m from Portal		2.83	6.76
			2.78	6.64
			2.87	6.85
		Average	2.83 ± .04	6.75 ± .09
Green schist	8450 m		1.96	4.68
Andesite	8502 m		2.73	6.52
Argillite–graywacke	8568 m		2.65	6.33
Latite	9200 m		2.48	5.92
Andesite	10 590 m		2.88	6.88
Agglomerate	13 200 m		3.08	7.36
Diabase	13 900 m		2.73	6.52

NOTES: All samples measured in the dry state, except for surface contact fluid. No water saturation was attempted. Rocks are probably of low porosity with the possible exception of the argillite–graywacke.

but a few of the individual readings (Fig. 1).

The general agreement of the model temperatures and those observed indicates both that the basic assumptions on which the model was constructed are reasonable, though not necessarily correct in all details, and that the observed temperatures are consistent with one another.

One area (8.4 to 9.15 km from the east portal) where observed temperatures were more than 1 °C less than those of the model, is one for which information on the ice–rock interface is poor, and by assuming an ice-filled valley here it is possible to reduce the anomaly. The existence of such a valley is, moreover, suggested by the configuration of rock exposures south of the tunnel line in this vicinity.

The mean temperature gradient that would exist in the absence of mountainous topography (*i.e.* for plane horizontal isotherms with the same heat flow) can be derived from the model as approximately 26 mK m^{-1}. Should the assumption of 0 °C for the temperature at the base of the glaciers be in error, and that, say −2 °C be applied instead, the thermal gradient would be approximately 10% higher, *i.e.* more like 29 mK m^{-1}. Such a value is not considered likely, but cannot in our present state of knowledge be precluded.

Thermal Conductivity

Thermal conductivity of a group of rock samples from the tunnel has been measured by Dr. A. M. Jessop (Earth Physics Branch, Department Energy, Mines and Resources, Ottawa) who provides the following data given in Table 1.

Considering that the abnormal values (for the greenschist and the agglomerate) are from rocks of rather limited occurrence along the tunnel line (G. Partridge, mine geologist, personal communication), a mean and uniform value of 2.72 ± 0.12 W $m^{-1}K^{-1}$ (6.50 ± .28 cal/cm s °C) seems appropriate.

Heat Flow

Heat flow derived from this mean thermal conductivity and the thermal gradient of 26 mK m^{-1} (26 °C/km) amounts to 73 mW m^{-2} (1.74 μcal/cm^2 s), a value not abnormal for mountainous terrain undergoing active denudation (Blackwell 1969, Jessop and Judge 1971, Roy *et al.* 1968, Sass *et al.* 1967). Such denudation is estimated to be responsible for a small proportion of the observed heat flow (up to 20%, depending on assumptions on geomorphic history in the case of the Colorado study (Birch 1950), less than 5% in the northwestern United States (Blackwell 1969), less than 10% in the Snowy Mountains of Australia (Sass *et al.* 1967), but from 30 to 50% in the Alps (Clark and Jäger 1969). The lack of information on the denudation history of the Granduc area prohibits any useful estimates, beyond these comparisons, of the contribution of denudation to the observed temperatures and calculated heat flows. A correction for glacial conditions of the Pleistocene epoch (Jessop

1971) is unlikely to be important at Granduc where glacial conditions still exist over much of the surface.

Acknowledgments

For provision of the necessary drill holes and the recording of the temperatures within them the author is indebted to the management and staff of the Granduc Operating Company. Messrs J. McCue, mine geologist until 1968, and D. Brown, mine surveyor, were particularly helpful in collecting the data. Dr. A. M. Jessop, Earth Physics Branch, Ottawa, provided major assistance in measuring thermal conductivity of rock samples; Mr. G. Partridge, mine geologist, helped in collecting the samples and Connors Drilling Co. in preparing them for measurement. The Geological Survey of Canada provided funds for thermistors and bridge. Drs. Jessop and Judge and Mr. Lewis of the Earth Physics Branch provided valuable criticisms in the preparation of this report.

BIRCH, F. 1950. Flow of heat in the Front Range, Colorado. Geol. Soc. Am. Bull. **61**, pp. 567–630.

BLACKWELL, D. D. 1969. Heat flow determinations in the northwestern United States. J. Geophys. Res. **74**, pp. 992–1007.

CLARK, S. P. JR. and JÄGER, E. 1969. Denudation rates in the Alps from geochronologic and heat flow data. Am. J. Sci. **267**, pp. 1143–1160.

JESSOP, A. M. 1971. The distribution of glacial perturbation of heat flow in Canada. Can. J. Earth Sci. **8**, pp. 162–166.

JESSOP, A. M. and JUDGE, A. S. 1971. Five measurements of heat flow in southern Canada. Can. J. Earth Sci. **8**, pp. 711–716.

MATHEWS, W. H. 1964. Water pressure under a glacier. J. Glaciol. **5**, pp. 235–240.

PATERSON, W. S. B. 1969. The physics of glaciers. Pergamon Press, London.

ROY, R. F., DECKER, E. R., BLACKWELL, D. D. and BIRCH, F. 1968. Heat flow in the United States. J. Geophys. Res. **73**, pp. 5207–5221.

SASS, J. H., CLARK, S. P., and JAEGER, J. C. 1967. Heat flow in the Snowy Mountains of Australia. J. Geophys. Res. **72**, pp. 2635–2647.

A Note on the Age of Basalt Dikes in the Mealy Mountains, Labrador, Canada

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K–Ar ages of 1123 and 1078 m.y. were obtained on two specimens from basalt dikes occupying joints in the Mealy Mountains anorthosite massif, Lake Melville, Labrador.

Des âges de K–Ar de 1123 et 1078 m.a. ont été obtenus sur deux spécimens provenant de filons basaltiques, qui se trouvent dans les joints trouvés dans le massif anorthositique de Mealy Mountains, Lake Melville, Labrador. [Traduit par le journal]

The Mealy Mountains along the south shore of Lake Melville are a large anorthosite massif that has received very little study. The massif reaches elevations of approximately 3800 ft (1362 m) which is decidedly higher than the surrounding Precambrian Shield. The striking north-facing escarpment which bounds the massif and the great depth of Lake Melville (up to 1000 ft (305 m)) suggest that Lake Melville and the Mealy Mountains may constitute a horst and graben system.

A most striking feature of the anorthosite massif is the well-developed joint system, with many joints occupied by basalt dikes. Since no dates have been published for the dikes of this region it was decided to date two that were collected in the vicinity of Eskimo Paps in the hope that they might elucidate the earth movements responsible for the formation of Lake Melville and the Mealy Mountains.

The two specimens gave Grenville ages of 1123 and 1078 m.y., so that little can be

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