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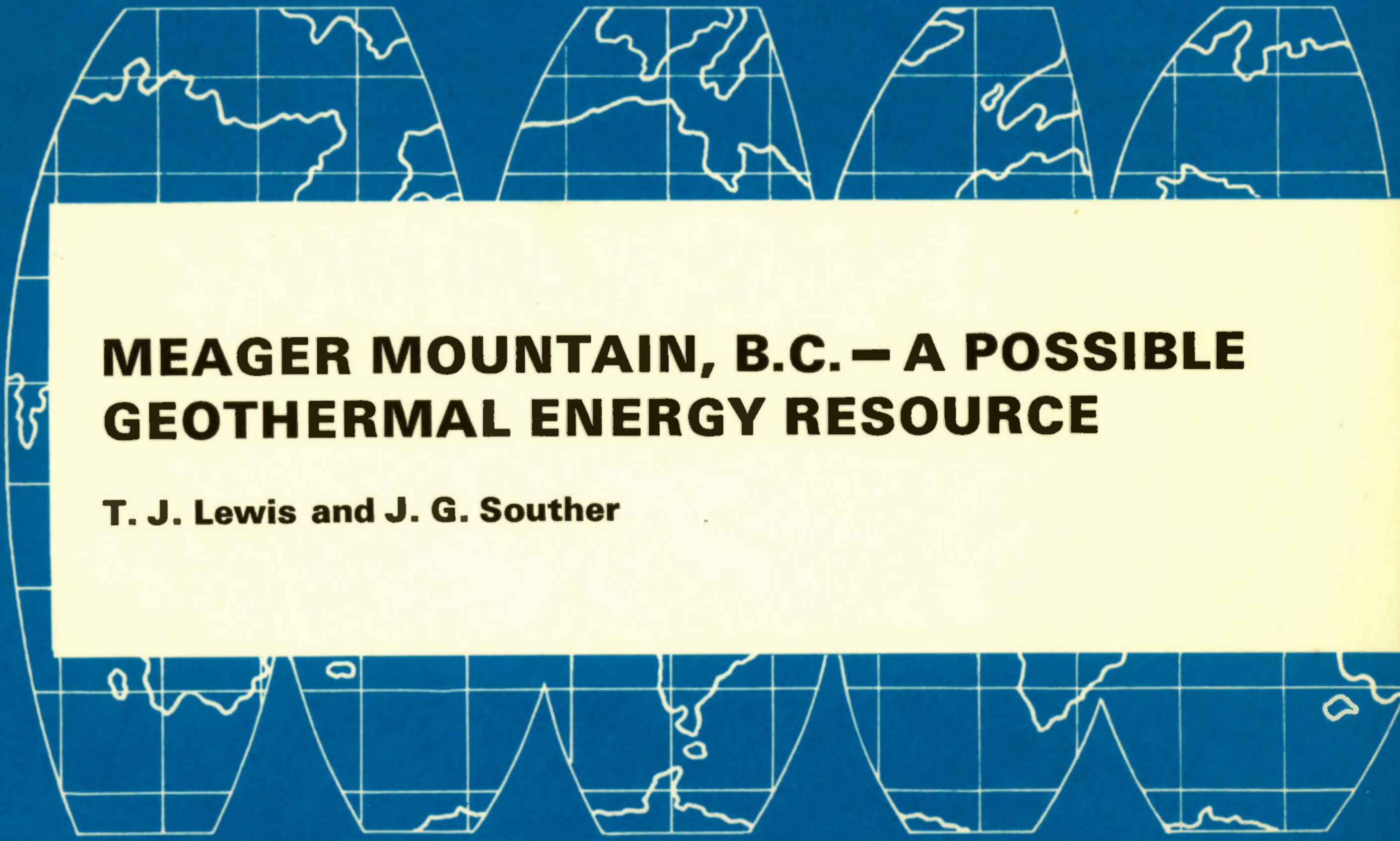

MEAGER MOUNTAIN, B.C. — A POSSIBLE GEOTHERMAL ENERGY RESOURCE

T. J. Lewis and J. G. Souther

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ABSTRACT

Meager Mountain, a volcanic complex 160 km north of Vancouver, B.C., is a possible geothermal energy resource. The dacite and andesite lava domes and associated pyroclastic deposits are products of more than 4 My of intermittent activity, the most recent being the Bridge River Ash eruption 2440 b.p. Geochemical temperatures from the natural hot-springs indicate relatively high temperatures in the hydrological system. Six drill holes in the surrounding quartz diorite of the Coast Plutonic Complex indicate extensive circulation of warm water through fractures.

The original explosive eruption produced basal explosion breccia from the surface of a cold, brittle crust and extensive fracturing in the granitic basement. This open fracture system may have subsequently sealed itself, producing a reservoir.

RÉSUMÉ

Le mont Meager, complexe volcanique à 160 km au nord de Vancouver (C.-B.), représente une ressource possible d'énergie géothermique. Les dômes de lave constituée de dacite et d'andésite et les dépôts pyroclastiques associés résultent de plus de 4 millions d'années d'activité volcanique intermittente, dont la plus récente était l'éruption de cendres de Bridge River, il y a 2440 ans. Des températures géochimiques de sources thermales naturelles indiquent des degrés relativement élevés dans le système hydrologique. Six forages dans la diorite quartzifère environnante du complexe plutonique côtier ont indiqué une intense circulation d'eau chaude à travers les fractures.

L'éruption explosive originale a formé une brèche d'explosion basique, à partir de la surface d'une croûte froide, fragile, et une zone de multiples fractures dans le socle granitique. Ultérieurement, ce système de fractures ouvertes a pu se refermer constituant ainsi un réservoir.

CONTENTS

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INTRODUCTION

Assessment of the geothermal resource potential of western Canada was begun by the Department of Energy, Mines and Resources in 1973. The initial effort was directed toward compilation of data on locations and ages of Quaternary volcanoes and young, high level plutons. This was followed by a geochemical survey of thermal springs in an attempt to identify those most likely to be associated with a high temperature reservoir (Souther, 1975). As a result of this reconnaissance, the Meager Creek area was selected as the most favourable target for more detailed investigation. An independent survey by Nevin, Sadlier-Brown, Goodbrand Ltd., consulting geologists, led to the same area on the basis of both geological considerations, and the economic factor resulting from its location only 160 km from Vancouver. During 1974 and 1975 various surveys were conducted by both the Geological Survey of Canada and the Earth Physics Branch of Energy, Mines and Resources, and by Nevin, Sadlier-Brown, Goodbrand Ltd. and their subcontractors, for B.C. Hydro & Power Authority.

A preliminary geological map of the area was prepared by R.G. Anderson (1975) and subsequently a more detailed study of the geology was made by P.B. Read (1977) under contract to Energy, Mines and Resources. In 1974 the Geological Survey and Earth Physics Branch carried out a preliminary study of the natural hotspring areas on Meager Creek and two shallow boreholes were drilled near the main Meager Creek springs. Subsequently the B.C. Hydro group carried out resistivity, I.P., and refraction seismic surveys and, on the basis of these results, drilled four more shallow boreholes. Rogers and McMechan (Rogers et al., 1976) of Earth Physics Branch have done microearthquake studies and Law of Earth Physics Branch, Dragert of the University of British Columbia (Law, 1977; Rogers et al., 1976), and Ngoc (1976) have carried out magnetotelluric studies in this region.

This report presents a synopsis of the regional and local geology and data on the natural hotsprings and their local environment, as well as downhole temperatures and thermal conductivity of core samples from all six boreholes. The corresponding heat flows are discussed and an attempt is made to place some physical constraints on the nature of the thermal reservoir.

REGIONAL SETTING

The area under investigation is in a rugged section of the Coast Mountains, near the axis of the Coast Plutonic Complex, a Tertiary and older granitic and metamorphic terrain that extends northwesterly from Vancouver the length of the Canadian Cordillera. In the Meager Creek area the Coast Plutonic Complex, comprised of granodiorite, diorite, quartz diorite and associated gneiss, is crossed by a north, northwesterly-trending belt (The Pemberton Belt) of late Tertiary and Quaternary plutons and a north-south-trending belt of Quaternary volcanoes (The Garibaldi Belt) (Fig. 1). The plutons give potassium argon ages that range from 18 My at Mount Barr, in the southwest, to 7.9 My at Salal Creek near Meager Mountain where the two belts intersect. Plutons of the Pemberton Belt are characteristic of high level epizonal intrusive bodies and are considered to be the subvolcanic roots of a Miocene volcanic front related to subduction of the Juan de Fuca Plate. The north-south belt of volcanoes that comprise the Garibaldi Belt is much younger. It includes six major andesite-dacite volcanoes, and a smaller number of basaltic centres, all of late Tertiary, Pleistocene or younger age. Potassium argon ages on rocks from the Garibaldi Group range from 4 My to less than 100,000 years which makes them roughly coeval with the high Cascade volcanoes of the western United States. Like the Pemberton Belt, the Garibaldi volcanoes are believed to be related to subduction of the Juan de Fuca Plate, now much less extensive than in the late Miocene when the Pemberton Belt was active. The youngest dated eruption in the Garibaldi Belt issued from a vent, now

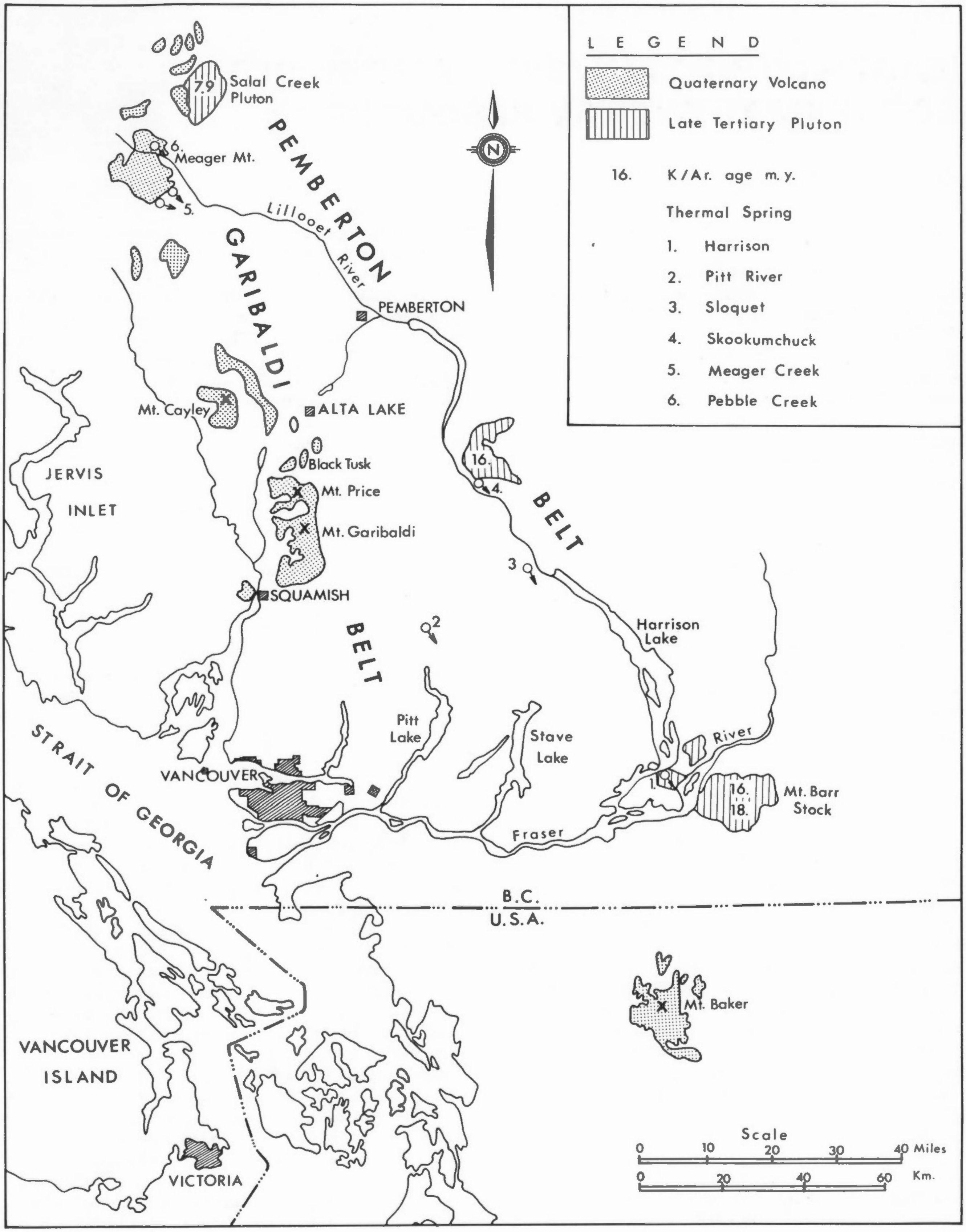

Fig. 1 The Pemberton belt of later Tertiary plutons and the Garibaldi belt of Quaternary volcanoes. Meager Mountain is located at the intersection of these belts.

covered by ice and debris, on the northeast flank of Meager Mountain. Explosive discharge of gas-rich dacite produced a plume of airfall pumice, the Bridge River Ash, that has been identified as far east as central Alberta. A carbon 14 age of 2440±140 b.p. has been determined on peat immediately below the Bridge River Ash (Nasmith et al., 1967).

LOCAL GEOLOGY

Upper Triassic to lower Cretaceous metavolcanic and metasedimentary rocks associated with migmatite complexes form a discontinuous septum that extends northwest from Lillooet Lake for more than 120 km (Fig. 2). It is surrounded by moderately well foliated quartz diorite and granodiorite of the Coast Crystalline Complex (Roddick and Woodsworth, 1976) and overlain unconformably by isolated patches of younger volcanic rocks. Near the head of Lillooet River, at Salal Creek, the older plutonic and metamorphic rocks are cut by epizonal plutons of quartz monzonite. The main mass, on the north side of Lillooet River, is about 6 km across and has been named the Salal Creek Pluton (Stephens, 1972). Smaller satellitic bodies of similar quartz monzonite are exposed south of the main pluton and underlie part of the edifice of Meager Mountain volcanic complex on the south side of Lillooet River.

Detailed mapping of Salal Creek Pluton (Stephens, 1972) reveals a roughly concentric textural zoning. An inner core of both fine-grained and medium-grained facies is surrounded by a cross-grained marginal phase that exhibits sharp discordant contacts with the older foliated rocks. All these phases are cut by irregular masses and dykes of quartz feldspar porphyry. According to Stephens the coarse-grained phase was first to crystallize, followed successively by the medium- and fine-grained facies and finally by the quartz feldspar porphyry. He notes that solidification of the pluton was accompanied by fractional crystallization and that the release of water pressure during the latter stages of emplacement is indicated by resorption of quartz phenocrysts in the quartz feldspar porphyry. It seems probable that the release of water-vapour pressure may have corresponded with discharge of magma and gases to the surface.

A potassium argon date of 7.9±0.2 My on granodiorite from the coarse outer phase of the Salal Creek Pluton (Roddick and Woodsworth, 1976) places it in the late Miocene. No extrusive rocks of equivalent age have been identified in the immediate area; however, dacite and andesite flows in the Lillooet Valley, 20 miles southeast of the Salal Pluton, have a potassium argon age of 17±2 My. It seems likely that these flows are remnants of a once extensive, linear volcanic pile that was both coeval and comagmatic with high level plutons of Salal type that lie along the Pemberton Belt. The relatively old, 17 My, flows are preserved in a down-faulted block in the Lillooet Valley, whereas any younger volcanic edifice that may have been directly related to the Salal intrusion has been eroded away. The apparent age difference between the Lillooet Valley flows and the Salal Creek stock is a difference in cooling age as well as emplacement age. Whereas the extrusive rocks cooled quickly, setting the potassium argon clock at their time of eruption, the deeply buried plutonic mass may not have cooled through the critical potassium-argon isotherm for a couple of million years. Thus the Salal Pluton and the down-faulted masses of andesite and dacite in Lillooet Valley are a little closer in age than suggested by their respective potassium-argon dates.

Meager Mountain is a complex of several closely related dacite and andesite lava domes and associated pyroclastic deposits that rest on a surface of high relief developed on the Salal and older rocks (Read, 1977; Anderson, 1975). A basal breccia, exposed on the south side of the complex contains jumbled blocks of quartz diorite with dimensions up to 20 m in a tuffaceous matrix. The initial eruption was obviously an explosive discharge of gas-rich magma accompanied by extensive fracturing of the granitic basement. The basal breccia is followed successively by dacite flows and up to 500 m of acid tuff that comprise unit 1 (Fig. 2 and 3).

Porphyritic andesite of unit 2 (Fig. 2 and 3) forms the main mass of the complex. It consists mainly of flows associated with minor breccia and cut by comagmatic dykes and plugs. Potassium-argon ages of 4.2±0.3 My and 2.1±0.2 My (Anderson, 1975) indicate that it was the product of a long episode of intermittent andesitic volcanism.

The summits of Meager Mountain and Capricorn are underlain by dacite flows, breccia and tuff and by hypabyssal intrusives of unit 3. These rocks, which are restricted to the central and northeast part of the complex, represent the youngest major stage of activity.

The dacites of unit 3 were deeply

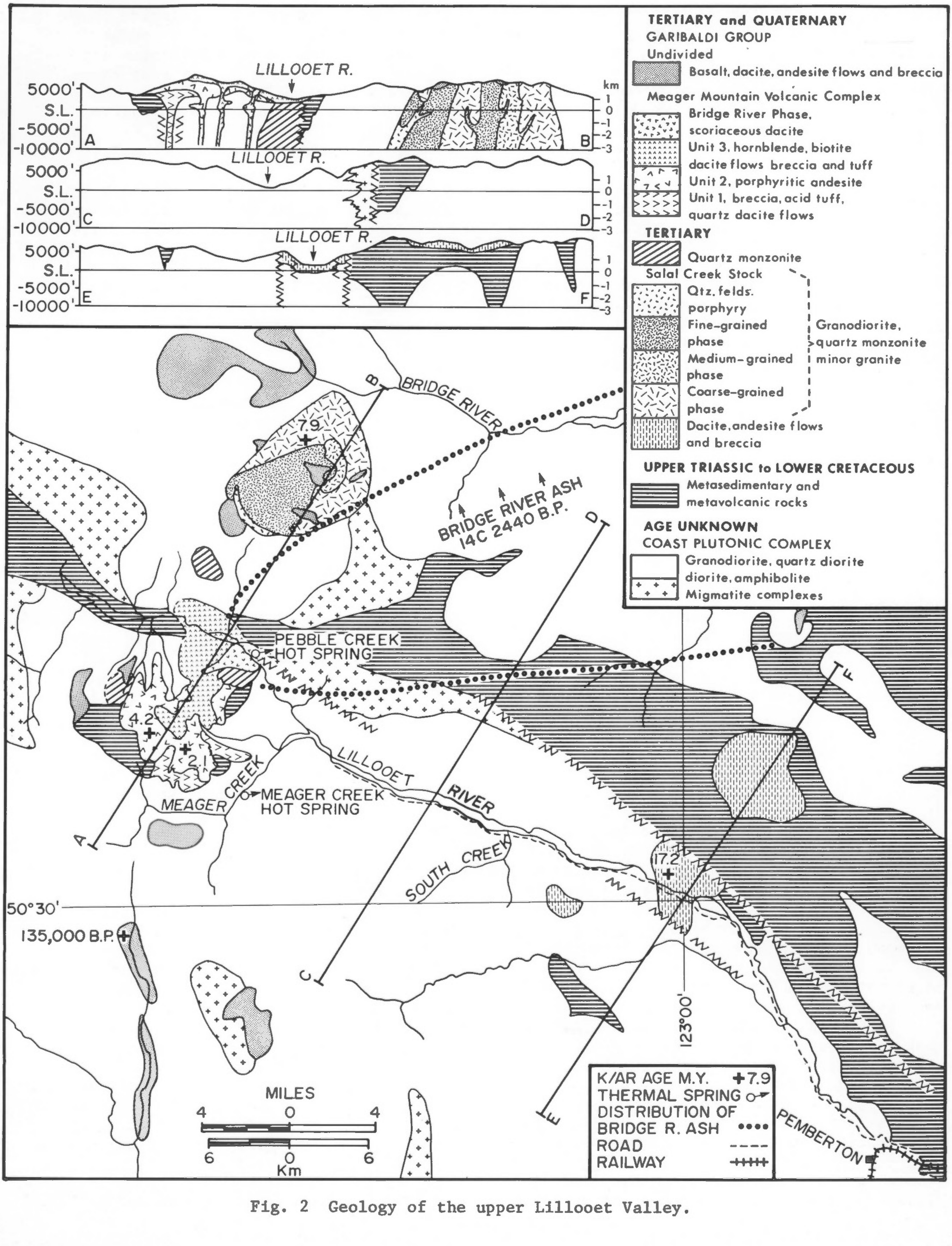

Fig. 2 Geology of the upper Lillooet Valley.

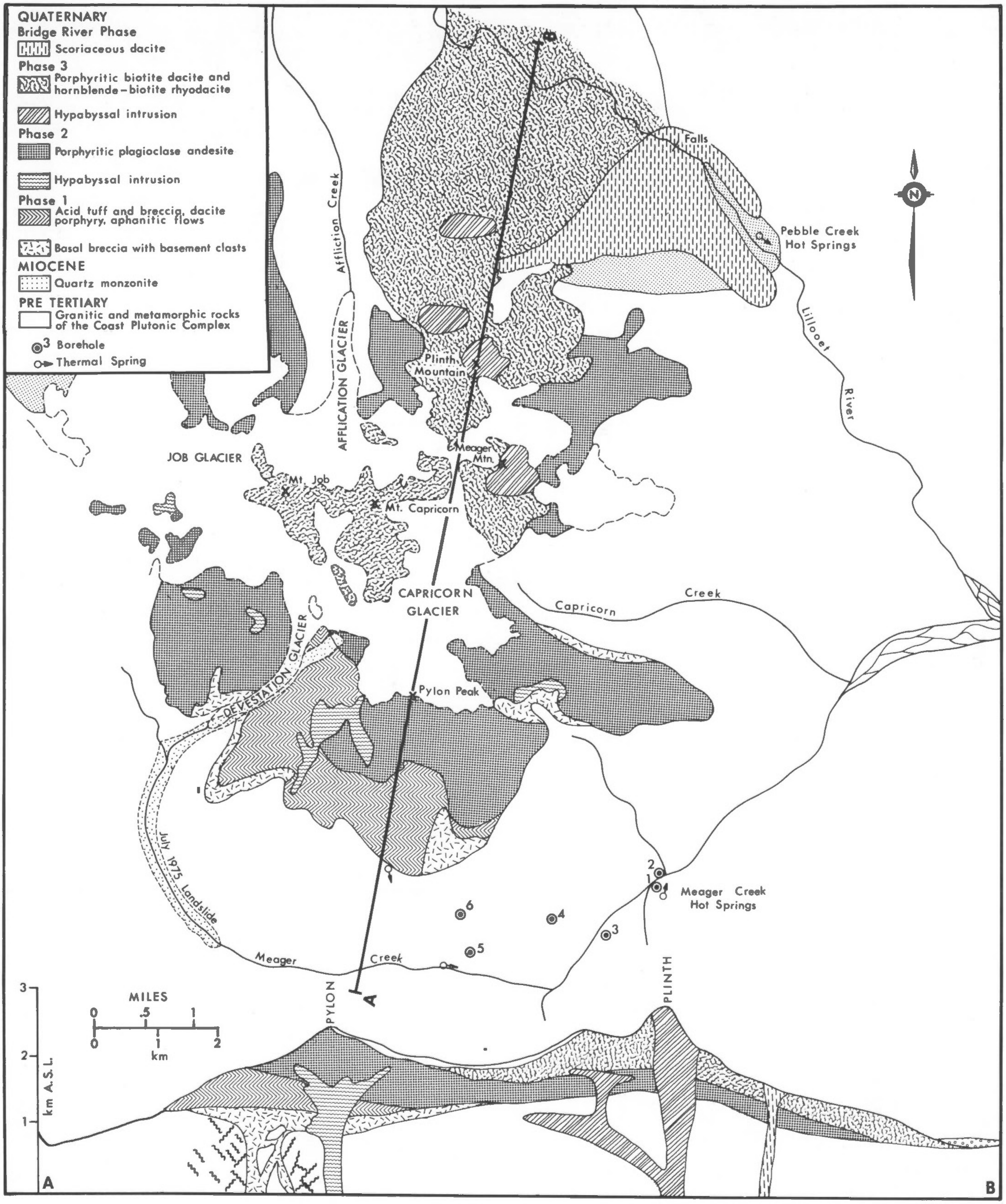

Fig. 3 The detailed geology of Meager Mountain and the cross-section showing the basal breccia associated with the original eruption, and the migration northwards of the younger centres.

TABLE 1

Chemistry of Thermal Spring Water (ppm)

SPRING NO.	NAME	Ca	Sr	Mg	Mn	Na	K	Li	As	HCO_3	SO_4	Cl	F	SiO_2
1	Harrison	80.7	.640	.05	.002	331.0	12.8	.168	.018	19.3	503.0	279.0	2.720	107.0
		81.5	.560	0.1	.005	332.0	12.6	.168	.006	21.8	497.0	275.0	2.720	75.9
2	Pitt River	83.5	.440	.05	.002	212.5	8.2	.145	.038	20.5	362.0	196.0	1.460	68.2
3	Sloquet	82.5	.240	.05	.002	112.8	3.3	.030	.004	10.6	347.0	49.8	.730	86.9
		87.7	.240	.05	.005	125.6	3.5	.033	.006	12.8	352.0	68.7	.800	80.3
4	Skookumchuck	153.0	1.440	0.2	.020	243.0	8.3	.233	.001	12.3	398.0	335.0	2.400	77.0
5	Meager Creek	78.0	n.d.	24.5	n.d.	410.0	84.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	201.0
		89.0	n.d.	27.2	n.d.	440.0	91.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	220.0
		81.0	n.d.	25.0	n.d.	450.0	47.0	n.d.	n.d.	468.0	110.0	675.0	n.d.	164.0
6	Pebble Creek	54.0	n.d.	5.3	n.d.	415.0	10.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	99.0

n.d. is not determined

dissected prior to eruption of the Bridge River Ash, suggesting that the complex was dormant for a long period prior to the most recent eruption. Stratified deposits of ash up to 20 m thick are preserved on Plinth Mountain. They consist mainly of dacite pumice in blocks that range from a maximum of 10 cm on the summit to as much as 4 m in the creek north of Plinth, yet no ash is found on the dacite flow of unit 4. According to Read (1977) this unit is younger than the Bridge River Ash and probably covers the ash vent.

THERMAL SPRINGS

Six thermal spring complexes lie roughly along the same northwesterly trending Pemberton Volcanic Belt that includes the high level plutons of Salal type (Fig. 1). Compared with other thermal springs in southern British Columbia those of the Pemberton Volcanic Belt have a relatively high silica content (Table 1). The silica and sodium-potassium-calcium geothermometers (Fournier et al., 1966 and 1973) suggest that all of these springs may be associated with relatively high temperature flow systems. The Meager Creek springs, in Meager Creek Valley on the southeast side of the volcanic complex and Pebble Creek spring in Lillooet Valley northeast of the volcanic complex, are the principal thermal areas that may be related to recent volcanic activity. Preliminary assessment of chemical data from the two spring areas (Hammerstrom and Brown, 1977) suggests that the two springs may discharge from separate thermal reservoirs. The Meager Creek springs appear to yield predominantly NaCl waters whereas the Pebble Creek waters are predominantly Na_2CO_3. The conclusion of a more detailed analysis of the thermal waters and the mineralogy is that these samples are not in equilibrium with rock at any one higher temperature. Consequently simple calculations using the geothermometers are inaccurate.

The main Pebble Creek spring issues from a group of small pools on a heavily forested bench about 60 m above the north side of Lillooet River. The pools and the small warm stream that flows from them are lined with a soft ochre-coloured precipitate of iron oxide, beneath which is a layer of hard calcareous travertine. Several additional seeps issue from fractured quartz monzonite near the river and from overlying unconsolidated gravels and pyroclastic debris. The bench on which the main springs are located is covered but it is at the same elevation as the top of a thick welded ash flow from Meager Mountain that outcrops on the opposite bank of the river and upstream where it forms the lip of a 30 m waterfall in Lillooet River. A portion of this flow probably underlies the main spring orifice as sketched in Figure 4.

Meager Creek Hotsprings, Figure 5, comprise a group of more than 30 springs and seeps that issue from coarse gravel deposits on the southeast bank of Meager Creek about 6 km from its confluence with Lillooet River. An area of about 1 hectare (3 acres) surrounding the main vent remains bare most of the year, despite a heavy annual snowfall. Temperatures and discharge rates shown in Figures 5 and 6 were measured in February 1974 at which time the warm,

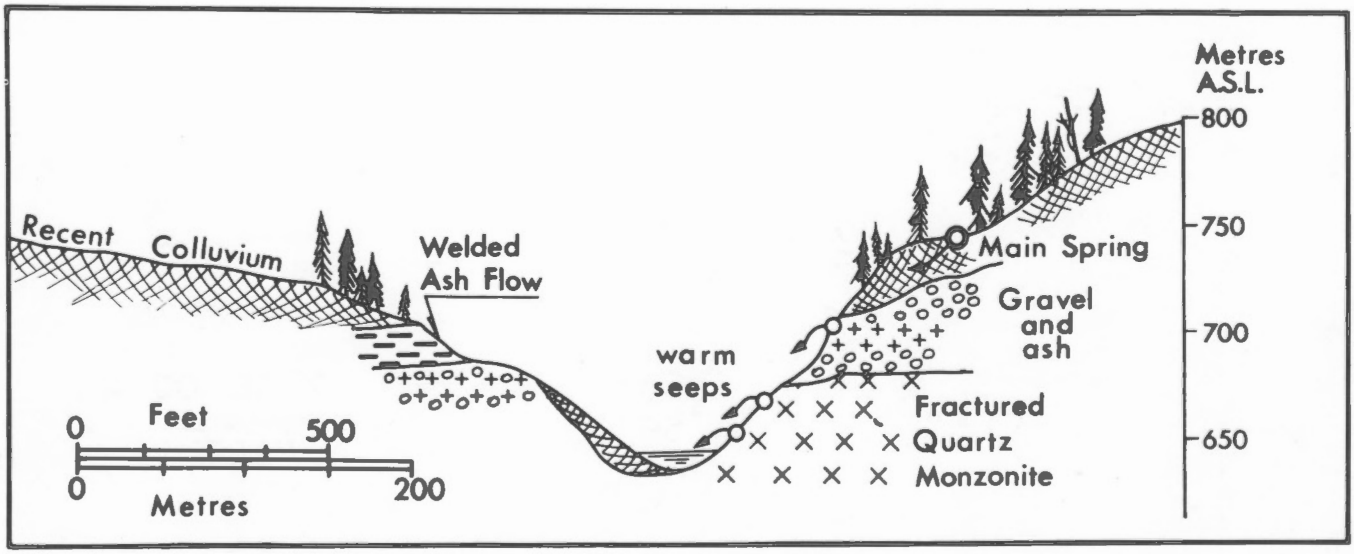

Fig. 4 A sketch of Pebble Creek Hot Springs.

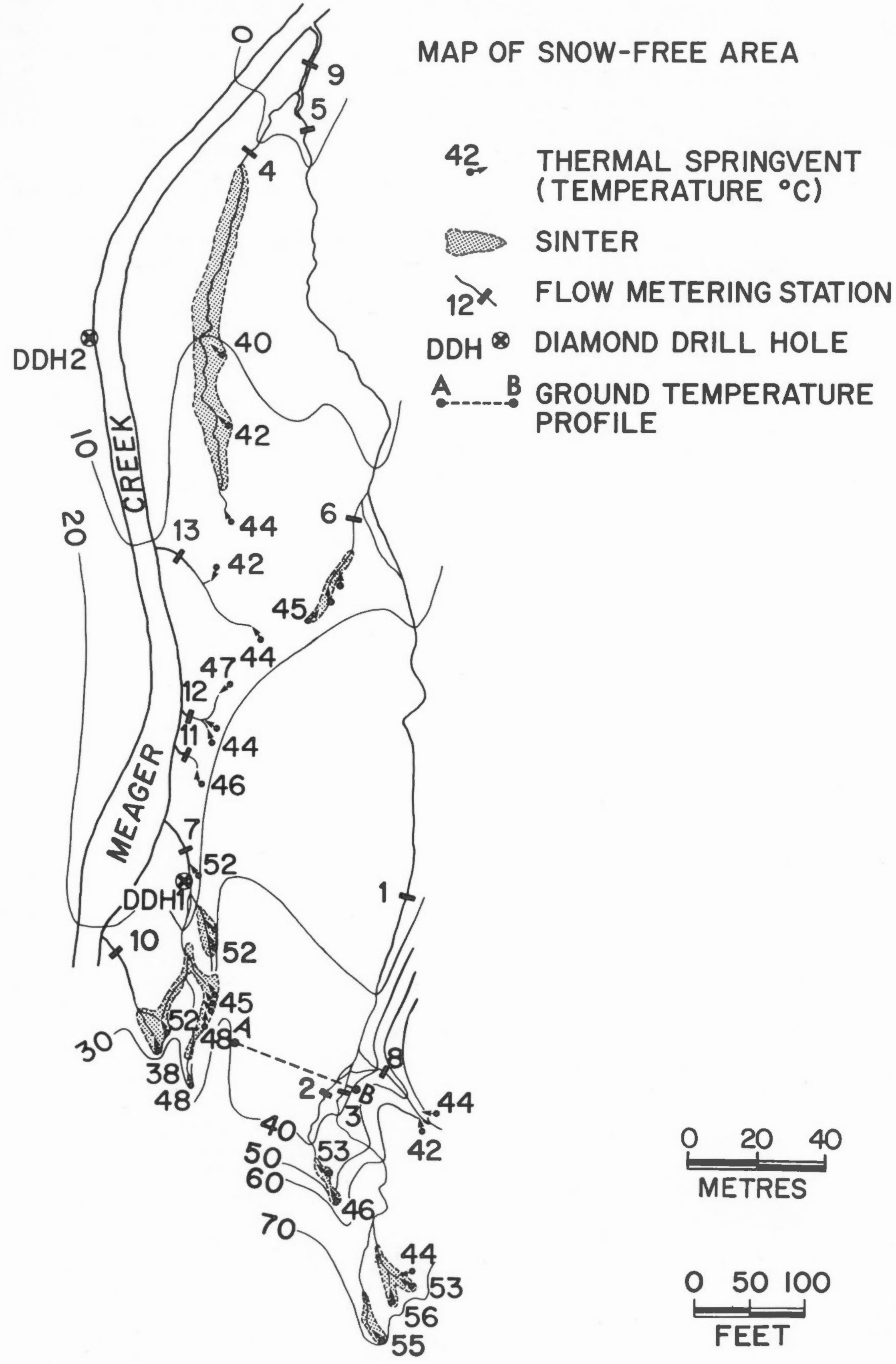

Fig. 5 A map of the snow free area containing the Meager Creek Hot Springs. Contours are for 10 foot intervals (3.2 m intervals).

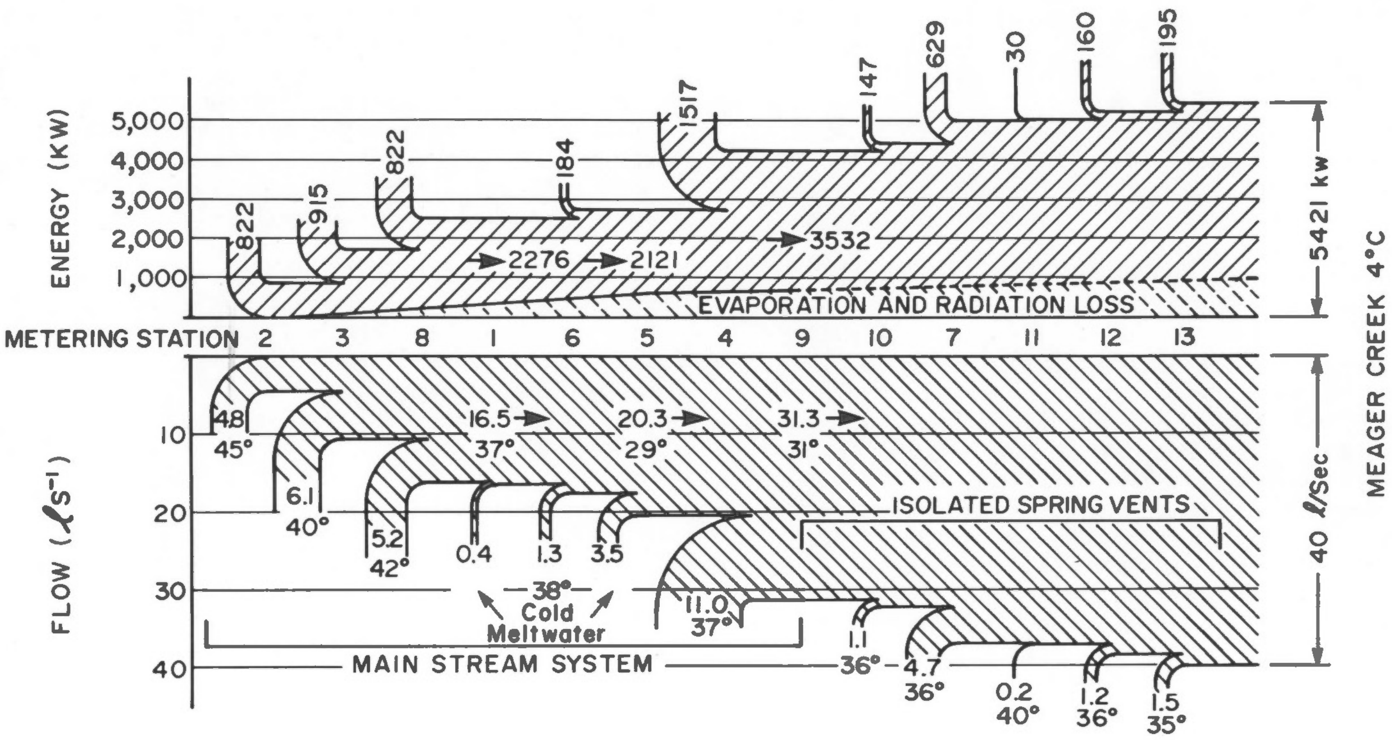

Fig. 6 Cumulative curves for water flow and energy from Meager Creek spring system. Energy content is relative to the temperature of the creek, 4°C.

snow-free ground in the spring area was surrounded by ground covered with 2 to 3 m of snow. Opposite the springs, on the northwest side of Meager Creek, glacially polished outcrops of gneissic granodiorite rise abruptly from the edge of the stream to form the steep southwest slope of Pylon Peak. The old bedrock valley is deeply filled with river gravels and landslide debris from both the Meager Mountain Volcanic Complex and from granitic mountains southeast of the springs. Borehole data indicate that clay deposits are interlayered with the gravel. These are probably lacustrine deposits formed in temporary lakes ponded behind landslides. This thick, porous, valley fill is the near surface aquifer through which the thermal water is channeled to its present discharge area. Where it enters the gravels is not known, but the presence of warm seeps 3 kilometers upstream suggests that the reservoir of thermal water extends a considerable distance west of the main spring outlets. The hot water may be in part contained by clay layers in the gravel but, more important is the development of an impervious seal of travertine and opaline silica deposited around all of the vents. As discussed in a later section boreholes through this impervious cap indicate that the underlying thermal water in the gravels is under artesian pressure. Temperatures of the natural spring waters at Meager Creek were measured with a thermistor probe. Flow rates were determined by installing weirs at several points on the larger discharge streams and by timing the discharge of a measured quantity of water from the smaller seeps (Fig. 5). From these data the thermal energy output of the spring system can be calculated (Fig. 6). If 4°C, the temperature of Meager Creek, is taken as the base temperature then the spring waters are producing about 5.4 MW (1.3 x 10^{6} cal/s).

BOREHOLES

Both Energy, Mines and Resources and B.C. Hydro have drilled shallow holes at Meager Creek in an attempt to determine the thermal structure at greater depths. The temperature gradient and heat flow may be extrapolated to predict temperatures at greater depths only where heat flows by conduction and fluids neither flow nor migrate through the rock. All six holes at Meager Creek are affected directly or indirectly by water circulating through fractures in the rock. Where a hole penetrates such a fracture, water may flow to or from this fracture to other fractures or the surface. It was impractical to cement casing into these holes in order to seal off these flows.

It is impossible to determine how much water is flowing along a fracture before the drill penetrates it. Afterwards, the water flowing to or from the fracture changes the temperature in the borehole, and probably in the fracture, where the amount of water flowing probably increases. The drilling action and circulation of the drilling fluid also change the temperature in the hole. Under these conditions the best estimate of the undisturbed temperature of the rock was measured each morning in the bottom of the hole just before the drilling operation commenced. Water was not circulated in the hole during the night and artesian water probably did not flow below the deepest fracture penetrated. Also the drilling disturbance had the least time to affect this part of the hole. The best measurements, the bottom-hole temperatures, are unlikely to be affected by water flowing up the hole.

In addition to giving an estimate of temperature gradients, the boreholes provide significant data on the nature of the hydrology in the upper part of the reservoir. Locations of the six drill-holes are shown in Figure 3; the holes are listed in Table 2.

Borehole No. 1 The first Energy, Mines and Resources hole was drilled on the east bank of Meager Creek where a series of small warm seeps depositing sinter issue from gravel on a low terrace about 2 m above the bedrock of the old valley wall which outcrops on the opposite side of the creek (Fig. 5). The upper 10 m of the drillhole is through impervious gravel which is tightly cemented by deposits of travertine and opaline silica. At 10 metres the drill broke through into porous, water saturated gravel and sand. Hot water (59°C) began flowing from the well at 2.3 ls^{-1} (30 gpm) and increased to 6 ls^{-1} (80 gpm) as drilling progressed through the gravel and into bedrock at 18 m. Since the surface casing was not cemented into bedrock, the increased artesian flow might be due to either channelling in the unconsolidated sandy gravels or to significant contribution from fractures in the bedrock.

The bedrock is hornblende-biotite quartz diorite gneiss cut by greenstone and aplite dykes. All of these rocks are fractured, and the fractures are filled with the calcium-rich mineral assemblages comprising mainly laumontite, calcite and minor gypsum (Read, in Nevin et al., 1975).

Surface temperature profiles of the snow-free area near hole 1 (Fig. 5) were measured. At a depth of approximately 15 cm the temperature at locations approximately 2m apart along three profiles was 15.4 ± 4.1°C. The temperature measured at one station over a period of eight days varied from 24.9°C to 18.6°C; the minimum temperature occurred just after a period of rain. It is concluded that some of the variation between temperatures at the 57 stations is caused by the response to the differing weather conditions on the different days.

TABLE 2. Boreholes Near Meager Creek

Hole	Original Designation	Date	Total Length (m)	Dip at Collar	Sponsor
1	301-1	March 74	45	70	E.M. & R.
2	301-2	March 74	118	90	E.M. & R.
3	74-H-1	Nov. 74	347	90	B.C. Hydro
4	75-H-1	Sept. 75	91	90	B.C. Hydro
5	75-H-2	Sept. 75	87	90	B.C. Hydro
6	75-H-3	Sept. 75	60	70	B.C. Hydro

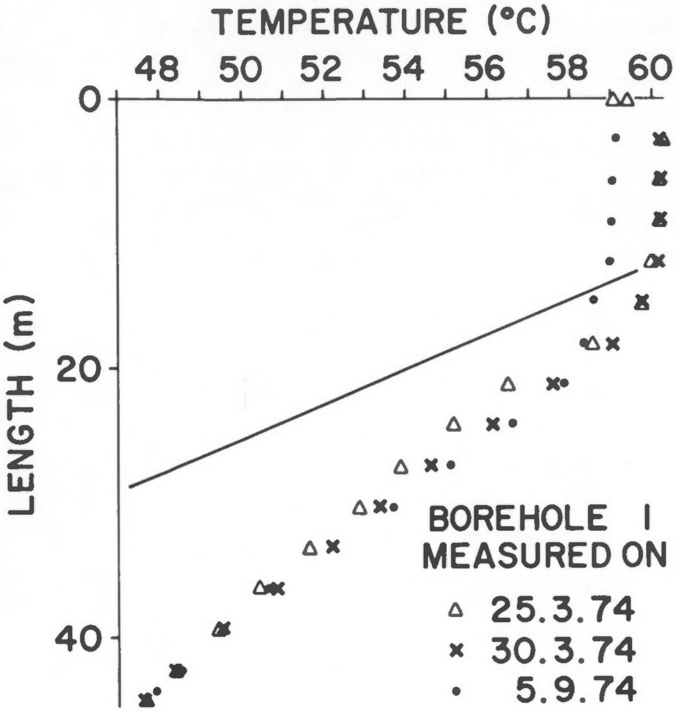

Fig. 7 Temperatures measured in hole 1 at three different times. The solid line gives the calculated temperature for conductive heat flow beneath a surface having an elevated temperature (see text for additional details).

Figure 7 shows three logs of the temperature in borehole 1. The temperatures are interpreted to indicate the existence of a shallow, horizontal aquifer under this site, which is about 100 m down the valley from the Main Meager Springs. The geochemistry of the spring waters and water from this borehole is very similar (Nevin et al., 1975). Above approximately 15 m depth the change in temperature of the aquifer with time may be due to either a varying volume of cool water mixing with the hot water or a varying flow of hot water through an aquifer with constant heat loss. The former is more likely, because of the relatively large change in temperature. The increase with time in temperatures below 20 m is probably evidence of the longer decay time of the drilling disturbance below the aquifer where heat moves only by conduction. The cold creek water (4°C) used for circulation cooled the borehole during drilling. The change in temperature gradient at 37 m may indicate a change in thermal conductivity although there is no apparent change in the rock type.

The negative temperature gradient below 20 m is controlled by the average temperature and areal extent of the aquifer above it, and either by cooler water flowing at depths below 100 m, or by the conductive heat flow. The temperatures below the aquifer have been calculated, assuming the heat moves away from it only by conduction. The steady state, two dimensional model used includes a 60°C aquifer 90 m wide, with its impermeable bottom 12 m below the collar of the borehole. The collar of the borehole is located on the aquifer 30 m from one side; the temperature of the rock further than 10 m from each side of the aquifer at the same depth as the bottom of the aquifer is assumed to be 7°C. The calculated temperatures in the borehole, shown as a solid line in Fig. 7, decrease with depth much too quickly, indicating that either the aquifer is much more extensive than it is modelled, or warm water flows through a system of fractures in the rock beneath this borehole. Results from borehole 2 support the latter alternative.

Borehole No. 2 The second, Energy, Mines and Resources hole was collared in outcrop of tightly jointed, stream polished quartz diorite gneiss about 1 m above normal creek level on the west side of Meager Creek. No seeps were visible at the surface and the area was covered by a normal accumulation of snow. At 12 m the well began to produce a small flow of warm water (29°C). This increased progressively to a maximum flow of 1.7 ls^{-1} (22 gpm) when drilling was stopped at 118 metres. The entire hole is in quartz diorite gneiss. The only significant variations are fractured zones where the rock is cut by a stockwork of laumontite-calcite veinlets.

Figure 8 shows some of the temperatures logged in this hole. The creek water used for circulation was about 4°C, so the hole was cooled during drilling, normally a ten hour period each day, and it was allowed to warm during the night. Logs 2 and 3 were measured consecutively: 2, after the drilling was finished on March 27, and 3, the next morning after water had flowed from the hole all night. The change in bottom hole temperature indicates that either the water being circulated cooled the bottom of the hole before the warm water started to flow into the hole, or the water flowing into the hole is warmer than the rock penetrated by the drill. In most cases drilling procedures prohibited temperature measurements in the deepest .5 m of the boreholes, and the bottom hole temperatures specified are measured near the bottom of the hole.

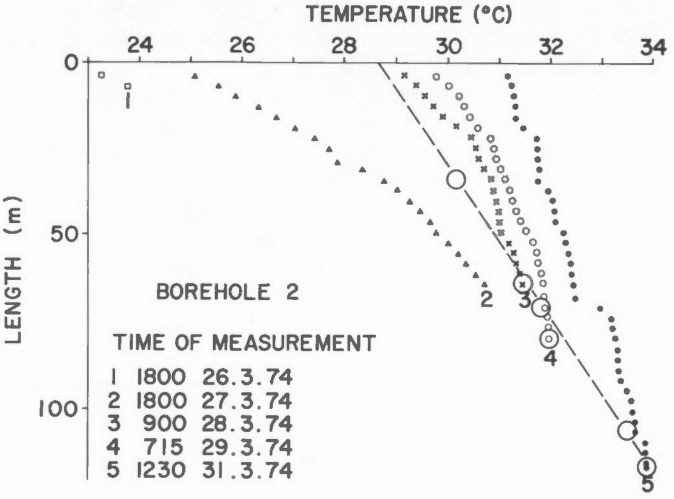

Fig. 8 Five temperature logs run in hole 2 at different times during the drilling operations. Large circles are bottom hole temperatures from various logs run at least 12 hr after the last circulation.

In the final log, 5, there are at least six steps, indicating that water enters the hole from at least six fissures. The best straight line through bottom hole temperatures obtained after the hole had flowed at least 12 h gives a geothermal gradient of 44 mKm^{-1} with a surface intercept of 29°C. Unfortunately no holes were cased nor grouted because of the large transportation costs for moving casing and cement to this site. It is probable that the geothermal gradient, shown in Figure 8 by the dashed line, reflects the amount of heat conducted towards the surface, and that water never flowed vertically in this rock until the borehole connected the fissures to each other and to the surface. If water were flowing before the hole was drilled, then the geothermal gradient would probably be non-linear. The bottom hole temperature of log 4 is the only indication of such a non-linear gradient. Figure 9 shows some temperatures from this hole in more detail. The logs in Fig. 9 show that the water flowing into the hole is cooler than water flowing up the hole from deeper fissures, and that where one or two temperature measurements were made complete mixing has not yet occurred within the borehole.

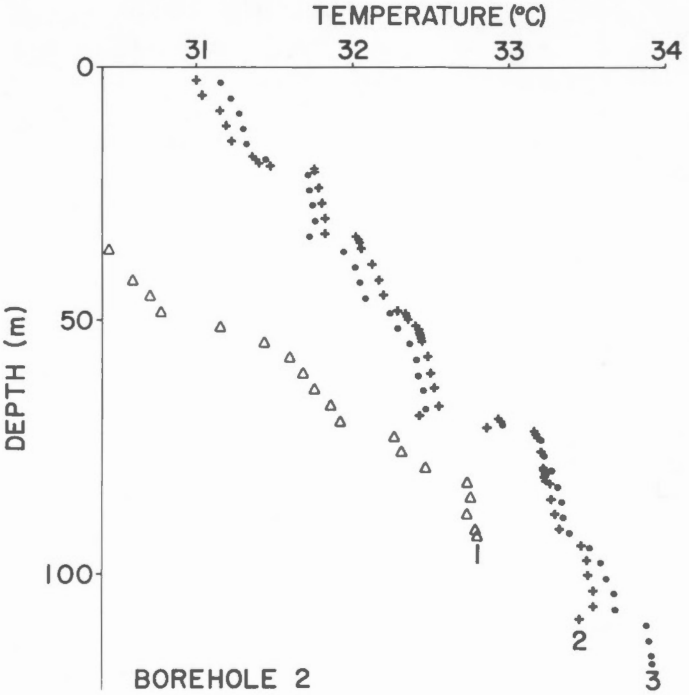

Fig. 9 Some detailed temperature logs of hole 2, indicating depths at which water enters the hole.

Borehole No. 3 The first B.C. Hydro hole was drilled on a resistivity anomaly about a kilometre upstream from the main Meager Creek springs. It is near an area of warm seeps that issue from slumped colluvium on the east bank of the stream. The hole penetrates 125 m of unconsolidated material before entering bedrock of quartz diorite gneiss. The unconsolidated valley-fill comprises alternate layers of boulders, sand and clay, with a thick varved clay forming an impervious blanket resting directly on bedrock. No artesian water was encountered until the drill stem passed through the lower clay horizon into the fractured upper surface of the bedrock. At that point a flow of scalding water (55°C) entered the hole and persisted until drilling was halted at 345 m by which time the temperature had increased to 60.5°C. Before being shut off the flow reached the maximum rate of 3.0 ls^{-1} (40 gpm).

The bedrock comprises quartz diorite gneiss throughout, similar to that of holes 1 and 2, and it is similarly fractured and veined with stockworks of calcite and clay minerals.

Figure 10 shows the highest temperatures measured at various depths, chosen from over 20 logs taken during the drilling; where very warm water from fractures heated the overlying water column such temperatures are not shown. The temperature of the creek water circulated down the hole was 2°C. The individual logs indicate numerous places

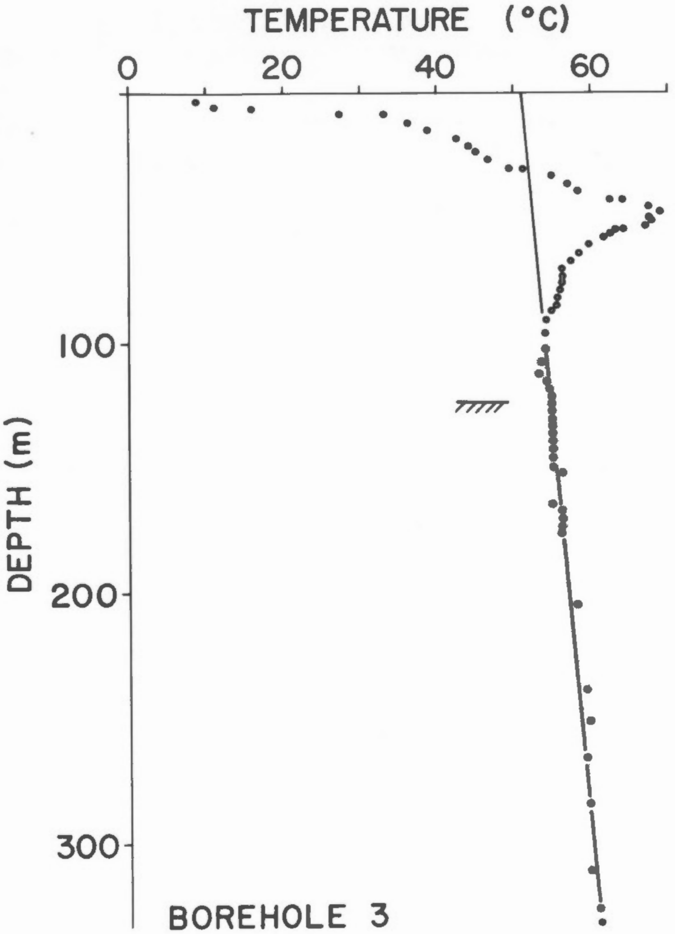

Fig. 10 Maximum undisturbed temperatures in hole 3. Bedrock is at a depth of 125 m.

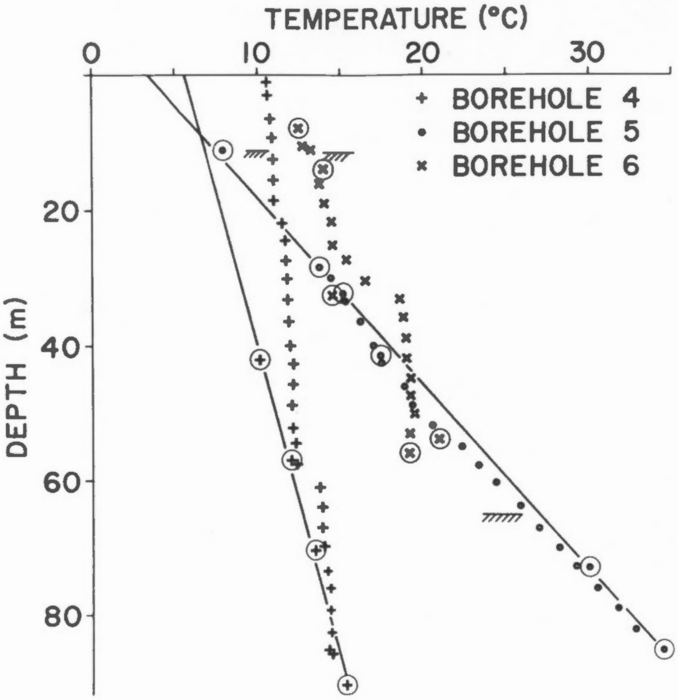

Fig. 11 Final temperature logs of holes 4, 5 and 6. Circled symbols are bottom hole temperatures measured during drilling as well as after drilling. Depths to bedrock are indicated for each hole.

where small flows of water are entering the hole from the gravels. The linear gradient, indicated on Figure 10, is 30 mKm^{-1}. Hot water is flowing horizontally at 45 m depth near this borehole, and may supply the main Meager springs downstream near borehole 1.

Boreholes No. 4, 5 and 6 Geophysical work done for B.C. Hydro in 1975 revealed a deep resistivity anomaly on the north side of Meager Creek, west of the main spring area. Holes 4, 5 and 6 were drilled to test this anomaly. Each of the three holes passed through a layer of dry overburden and into fairly uniform foliated quartz diorite. The lower 20 m of hole 6 is in highly altered volcanic porphyry that may be part of a feeder dyke, cutting the quartz diorite and related to an early phase of the Meager Mountain volcanic complex. A small flow of cold water entered hole 4 at a depth of about 38 m whereas no artesian flow occurred from holes 5 and 6.

The holes are about 90 m deep; the vertical temperature gradients determined were 112, 365 and 289 mKm^{-1} (Nevin et al., 1975) Figure 11 shows three temperature logs. Large, variable geothermal gradients suggest that hot water of unknown temperature and depth is circulating in the quartz diorite below the holes. In general all six boreholes show that hot water flows through fractures in the quartz diorite after the fractures are connected to each other or the surface.

Bottom hole temperatures give the best approximation to the undisturbed temperatures before drilling is started. Temperatures measured after the completion of drilling indicate that the water in some parts of each hole was heated when compared to bottom hole temperatures measured at the same depth during pauses in the drilling. Since the drillers are circulating cold water, it is possible that these near bottom hole temperatures are low compared to the temperature of the rock before it was penetrated. Bottom hole temperatures from holes 4 and 5 indicate high, linear geothermal gradients, as shown in Figure 11.

The linearity of these gradients indicates that heat was originally flowing to the surface by conduction, and that water started to flow only after the boreholes connected fissures to the surface and to each other.

HEAT FLOW AND CRUSTAL TEMPERATURES

The thermal conductivity of core samples from the six boreholes is listed in Table 3. These measurements were made on water-saturated core samples in a divided bar, as described by Jessop (1970). For borehole 5, the average value of 4 discs is 2.64±.36 $Wm^{-1} K^{-1}$. Combined with the high gradient, this indicates a conductive heat flow of 930 mWm^{-2}, or about 15 times the normal heat flow. This is the largest flow in any of these holes. The variations in conductivity in the sparse data from this borehole indicate the conductivity could correlate inversely with variations in the geothermal gradient at about 41 m depth in this hole. Also, the conductive heat flow appears to be continuous across the overburden-bedrock interface (see fig. 11).

The heat flows for boreholes 2, 3 and 4 are 120, 100 and 290 mWm^{-2}. Borehole 6 does not appear to have penetrated rock where conduction was the only heat transfer mechanism, but the conductive heat flow in parts of it are probably greater than 450 mWm^{-2}. These higher than normal heat flows indicate a heat flow anomaly over an area of approximately 4 km^2. It is possible that these large amounts of heat are conducted from hot water flowing through fissures just below the bottoms of the holes; this cannot be determined from only the heat flow data (Blackwell et al., 1974). Water may have flowed horizontally at some depths beneath the site of borehole 6 before drilling started.

Corrections normally applied to the measured heat flow to acquire an equilibrium value representing the average terrain are not warranted for these holes. For example, the rugged topography and erosion affect the heat flow in this area by relatively large amounts compared to most heat flow sites; but any mass movement (water flows) causes much larger changes locally.

Table 4 contains the values of heat generation in samples representing the upper crust of this region. The quartz monzonites of the Salal Creek Pluton produce about four times as much heat as the other rocks in this region, which are typical of the whole Coast Plutonic Complex (CPC). The heat generation in surface samples of CPC is very low, averaging 0.8 μWm^{-3} (Lewis, 1976).

TABLE 3. The Thermal Conductivity of Borehole Cores

Borehole	Length	Conductivity
1	(m)	($Wm^{-1} K^{-1}$)
	24	3.41
	38	3.29
2	59	3.32
	95	2.06
3	144	2.72
	159	2.71
	178	5.27
	185	2.95
	205	2.68
	230	2.89
	236	4.43
	244	2.92
	253	2.83
	259	2.47
	267	3.18
	273	3.23
	285	2.93
	291	3.11
	297	3.26
	305	2.67
	312	2.87
	319	2.53
	326	2.71
	334	2.84
	345	2.82
	average for n = 21	3.05±.63
4	27	2.88
	70	2.59
	73	2.60
5	42	1.97
	53	3.30
	69	2.33
	79	2.97
6	25	2.80
	37	2.50
	59	2.03

Temperatures in the normal crust are quite low in CPC, but are higher near the Salal Creek Pluton. The sparse heat flow measurements in CPC indicate a heat flow of approximately 55 mWm^{-2}, and a very high reduced heat flow of 43 mWm^{-2} (Lewis, 1977). The reduced heat flow, interpreted as

TABLE 4

Gamma-ray Measurements

Sample			U ppm	Th ppm	K %	Heat Production μWm^{-3}
		Surface samples from within 30 km of Meager Mountain				
14226	b>h*	quartz monzonite	3.74	14.5	3.91	2.37
14266	h>b	quartz monzonite	2.83	8.08	2.31	1.54
14275	b	quartz monzonite	.78	1.67	3.32	.64
14280	b>h	quartz diorite	1.42	2.04	.74	.59
14362	b	quartz monzonite	.87	2.49	2.52	.64
44120	b	quartz monzonite	4.49	15.1	4.68	2.70
44149	b>h	granodiorite	.93	1.78	1.87	.55
44219	h>b	quartz diorite	.88	1.31	1.37	.45
54399	chl.	quartz diorite	1.60	2.61	.54	.66
averages		n=9	1.95±1.31	5.51±5.33	2.36±1.33	1.13
omitting 14226 and 44120, n=7			1.33± .68	2.85±2.17	1.81± .92	.72
		Borehole samples from Salal Cr. pluton (8My)				
Depth (m)						
134			6.81	12.7	4.09	3.04
198			6.62	12.2	3.98	2.94
408			9.03	13.4	4.11	3.66
594			16.0	12.9	3.91	5.40
average			9.61±3.8	12.8±.43	4.02±.08	3.76±1.14
		Borehole samples from Meager Cr.				
Hole	Length (m)					
1	20		1.65	3.63	1.42	.82
2	59		1.29	2.91	1.16	.65

* Abbreviations used are: b - biotite, h - hornblende, chl. - chloritized

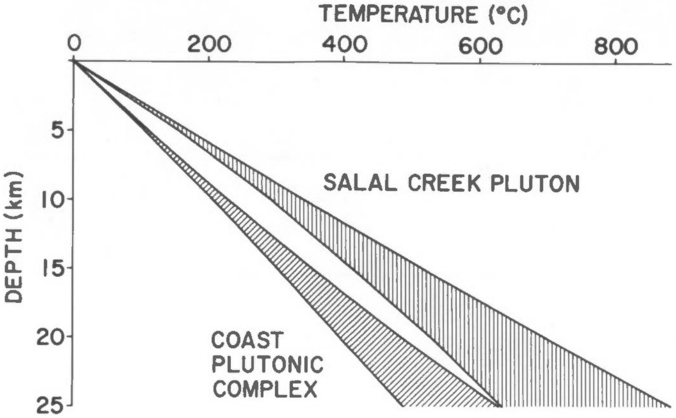

Fig. 12 Crustal temperatures expected for areas of differing conductive heat flow and heat production in the Coast Plutonic Complex.

the heat flow from the lower crust and upper mantle, is not expected to be lower beneath the Salal Creek Pluton. Using these data, and the average heat production of the Salal Creek Pluton (2.8 μWm^{-3}), it is possible to calculate crustal temperatures, assuming there is no mass flow. Figure 12 shows two temperature depth profiles, assuming an exponentially decreasing heat production within the crust with a characteristic depth of 5 km and a large volume for the pluton. At a depth of 10 km the calculated temperature is 100 K higher under the Salal Creek Pluton. Although such a calculation shows the maximum difference in temperature caused by the increased heat generation and indicates the effect of differing heat generation, the actual temperatures are probably controlled by fluids moving in the rock. Magma has moved upwards in this area, so that in at least the upper crust temperatures will be higher than shown.

INTERPRETATION

Meager Mountain is in a region of both high local relief and high annual precipitation, where circulation of large volumes of surface water through fractures should be expected. Because the basement rocks are crystalline, non-porous and structurally anisotropic, the fractures are more likely to form open systems through which water may be channeled to great depths along hydraulic gradients rather than confined aquifers. Yet the presence of hot artesian water at Meager Creek suggests that the water moves in a confined aquifer coming either from great depth or through a region of anomalously high temperature at moderate depth. Temperature logs in the boreholes reveal large but differing geothermal gradients, probably indicating that hot water is flowing through fractures in the rock in which these shallow holes were drilled. The enhanced heat production of the Salal Creek Pluton causes crustal temperatures to be higher than under most of Coast Plutonic Complex. It may be the cause of magma generation at great depths, but it does not produce high temperatures at shallow depths. The water is heated either at great depths or by a cooling intrusive phase related to volcanic activity on Meager Mountain. Either of these mechanisms could produce an important geothermal resource.

Regardless of how the heat originated the chemistry of the thermal spring waters shows that silica plus calcium and other ions taken into solution at the higher temperatures have been precipitated in fractures in the cooler peripheral part of the thermal zone. Thus a fracture system that may have originally been open has been effectively capped through a process of self-sealing. The present flow of water through this system is throttled by continued precipitation in any channels that are forced through the cap by artesian pressure. The existing boreholes go only deep enough to see the outer part of this cap zone where fractures are sealed by an assemblage of calcium-rich minerals. A deeper much hotter zone, sealed with silica may reasonably by expected from the high silica content of the thermal spring waters.

The difference in chemical composition of water from the Meager Creek and Pebble Creek springs has already been noted. The Pebble Creek springs (Na_2CO_3) lie along a major fault zone that cuts metavolcanic and metasedimentary rocks as well as plutonic rocks. It seems probable that this fault is the controlling element in a different flow system that is not linked with the Meager Creek system. The Meager Creek springs (sodium chloride) do not lie on any known fault zone. Nevin (1975) notes a broad zone of east-west fracturing in upper Meager Creek valley that may influence the reservoir geometry. Another possibility is the buried vent from which unit 1 of the Meager Mountain complex was erupted. Angular chunks of granitic basement up to 6 m across in the basal explosion breccia of this unit are a clear indication that extensive fracturing accompanied the eruption. A deep breccia-pipe beneath this part of the volcanic pile may provide sufficient porosity to allow deep circulation of groundwater, or it may also have served to channel magma of later stages into high level chambers which still contain residual heat. Such a model would seem to offer a useful working hypothesis on which to base further study.

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