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Geothermal measurements in northern British Columbia and southern Yukon Territory[1]

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Measurements at seven sites in the Intermontane region of northern British Columbia and southern Yukon show heat flow of 63–100 mW/m^2 and heat generation, obtained from intrusive rocks at three of these sites, of 1.8–6.5 μW/m^3. These few data cannot define a linear relation between heat flow and heat generation for this region, but the plotted points lie between the lines of the stable crust of the eastern United States and of the Basin and Range Province. Conductive thermal models of the crust, assuming a basalt composition for the lower crust, predict at 35 km depth a heat flow of 30 mW/m^2 and temperatures between 645 and 775°C at most sites.

At two sites conductive models based on reasonable properties do not yield reasonable temperatures. The site on the axis of the Stikine Volcanic Belt shows a probable component of convectively enhanced heat flow or the presence of a young intrusion at depth. The site in the Bowser Basin shows the probable effect of water movement in the sediments.

Les mesures enregistrées à sept emplacements dans la région Intermontagneuse du nord de la Colombie-Britannique et du sud du Yukon indiquent un flux thermique de 63–100 mW/m^2 et une production de chaleur, obtenue pour les roches intrusives prélevées à trois de ces endroits, de 1,8–6,5 μW/m^3. Ces données peu nombreuses ne permettent pas d'établir une relation linéaire entre le flux thermique et la production de chaleur dans cette région, mais les valeurs portées en graphique se situent entre la courbe représentant la croûte stable de l'est des États-Unis et celle représentant la région de Bassins et Chaînes des Rocheuses. Les modèles thermiques de la croûte, lequels supposent un transfert de chaleur par conduction et une croûte inférieure composée de basalte, prévoient qu'à 35 km de profondeur le flux thermique est de 30 mW/m^2 et les températures sont entre 645 et 775°C, et ce pour la plupart des emplacements.

À deux emplacements donnés, ces modèles fondés sur des propriétés raisonnables ne fournissent pas des températures raisonnables. L'emplacement localisé sur l'axe de la ceinture volcanique Stikine est caractérisé par un rehaussement du flux thermique causé probablement par un phénomène de convection ou par la présence en profondeur d'une intrusion jeune. L'emplacement situé dans le bassin de Bowser est probablement perturbé par l'effet de la circulation de l'eau dans les sédiments.

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Introduction

Heat flow and heat generation measurements made in north-central British Columbia and southern Yukon provide new data on the thermal structure of the northern Intermontane Belt. The area is geologically complex, including both exotic terranes of accreted continental crust and subduction complexes of oceanic origin. It has undergone repeated episodes of magmatic activity of which the most recent result is manifest in the late Tertiary and Quaternary Stikine Volcanic Belt. This study was initiated with the aim of detecting thermal effects related to young volcanic activity. To this end three holes (3, 5, and 6 in Fig. 1) were drilled at varying distances from Mount Edziza, a volcanic complex on the axis of the Stikine Volcanic Belt. Subsequently measurements were made at four additional sites that were drilled in the course of mineral exploration and made available for study. The seven localities lie in a variety of geological environments and both heat flow and heat generation exhibit a correspondingly wide range of values. Although the data sample is small it has important implications with respect to the crustal structure of the region.

Geological setting

The seven heat flow values reported in this paper were measured within the northwest trending, Intermontane Physiographic Belt of the north-central Cordillera, as shown in Fig. 1. At the latitude of the measurements (57–61°N) the belt is about 150 km wide. It is flanked on the west by the Coast Plutonic Complex, which comprises mainly Mesozoic plutonic and metamorphic rocks but includes gneisses as old as late Precambrian and high-level plutons as young as mid-Tertiary. East of the Intermontane Belt and separated from it by major faults, the Omineca Crystalline Belt is underlain by late Paleozoic to early Mesozoic volcanic and sedimentary rocks cut by large plutons, batholiths, and penetratively deformed metamorphic complexes of mid-Cretaceous age. The northern

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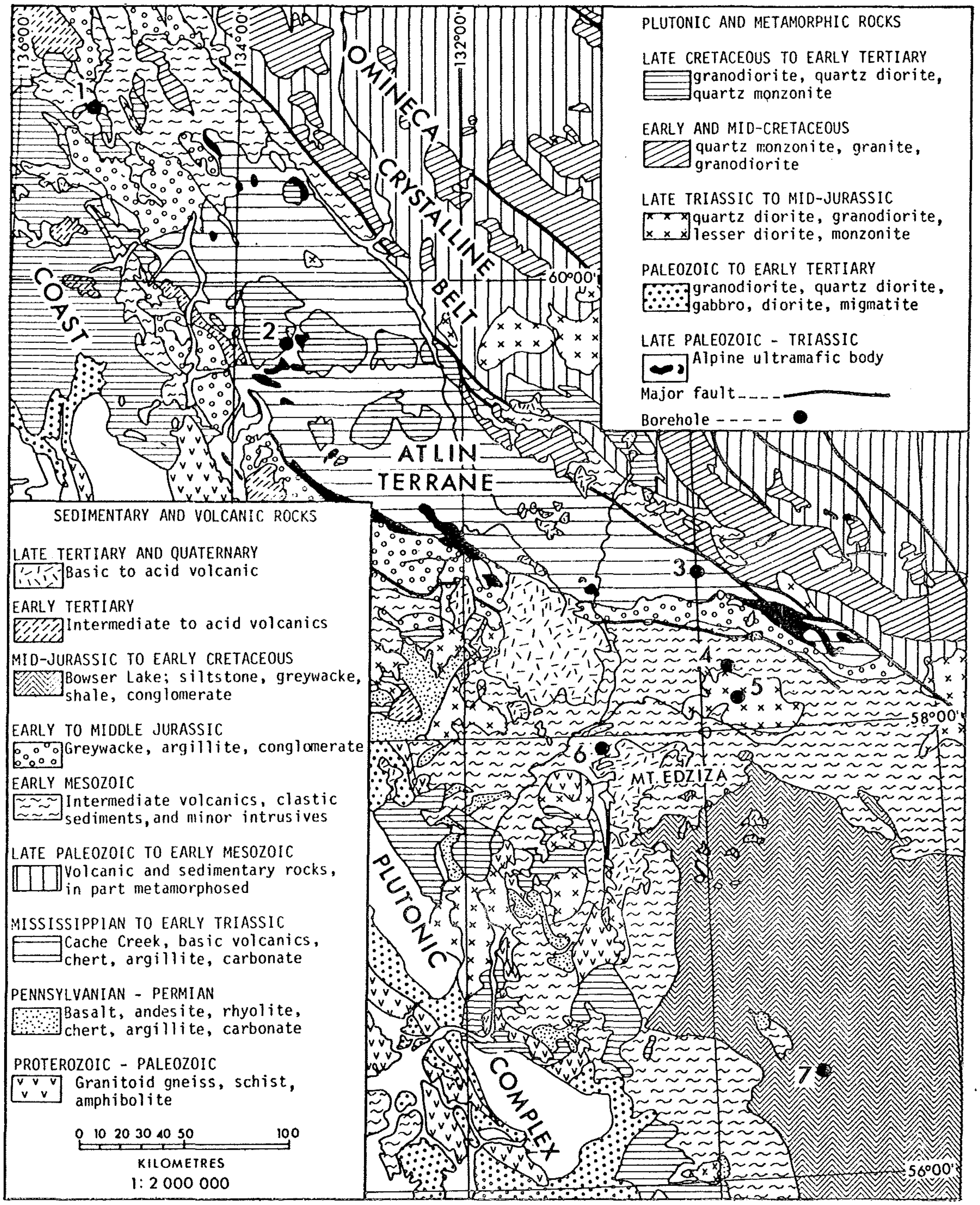

FIG. 1. The location and geological setting of the seven new heat flow sites, numbered 1–7 according to the list of Table 1.

Intermontane Belt is itself a composite of several tectonic assemblages. The early Mesozoic sedimentary and calc-alkaline volcanic rocks and associated plutons of the Stikine Terrane are considered to be part of an allochthonous, magmatic arc (Stikinia) that was accreted to the continental margin prior to mid-Jurassic time (Monger and Price 1979). It is separated from the continent by a subduction complex comprising basalt, peridotite, and oceanic sediments of the Carboniferous to late Triassic Cache Creek Group. These rocks underlie most of the Atlin Terrane within which two of the heat flow holes are located.

Clastic sediments of the late Triassic to middle Jurassic Whitehorse Trough and the middle to late Jurassic Bowser Basin rest unconformably on these older, allochthonous terranes. Provenance for the Whitehorse Trough lay to the west along the axis of the magmatic arc of Stikinia. However, it is uncertain whether the arc lay above a westerly or easterly sloping subduction zone and hence whether the trough formed as a back-arc basin (Davis *et al.* 1978) or as a fore-arc basin (Tempelman-Kluit 1979). Most of the sediment, at least in the northern part of the Bowser Basin, appears to have been derived from Cache Creek rocks, and is believed to have been shed from the uplifted Atlin Terrane during a period of late Jurassic compressive folding and southwesterly directed thrusting. Post-Jurassic uplift of the entire western Cordillera was accompanied by the emplacement of high-level quartz monzonite plutons mainly along the western margin of the Coast Plutonic Complex but also within the Atlin and Stikine terranes. Coeval continental volcanism produced locally thick piles of mainly acid pyroclastic rocks, flows, and volcaniclastic sediments of the upper Tertiary Sloko Group. These are commonly associated with normal faults, grabens, half grabens, and cauldron subsidence structures indicative of late Cretaceous to early Tertiary regional extension in the eastern Coast Plutonic Complex and along the western margin of the Stikine Terrane. Regional uplift and erosion continued throughout the mid-Tertiary. By late Miocene all but a few remnants of Sloko volcanics had been eroded away and extensive areas of early Tertiary plutonic rock were exposed.

Late Tertiary and Quaternary volcanic centres define a broad north-northwesterly trending belt, the Stikine Volcanic Belt (Souther 1977), which cuts across all the older terranes. The first lava poured out on the late Miocene erosion surface about 10 Ma ago to form the basal, basaltic shields of Mount Edziza and Level Mountain. Sporadic eruption of basalt and lesser amounts of trachyte and rhyolite continued at various places along the belt throughout late Tertiary and Quaternary time, the most recent cinder cones being only a few hundred years old.

Geological influences on thermal structure

The present thermal structure of the region is a function of the thickness, heat production, and thermal conductivity of the various crustal elements, heat flux from the underlying mantle, rates of uplift and erosion, and the mass movement of magma and groundwater. In general, basic subduction complexes such as the Atlin Terrane are deficient in uranium, thorium, and potassium and thus have lower rates of heat production than acid to intermediate magmatic rocks such as constitute the Stikine Terrane. Similarly, older tectonic terranes such as the pre-Jurassic Stikine block are relatively depleted in radioactive constituents and hence have lower rates of heat production than younger plutons such as those emplaced along the eastern Coast Plutonic Complex during the late Cretaceous and early Tertiary. The thermal imprint of local thermal events, such as must have accompanied the early Tertiary episode of volcanism and high-level plutonism, would decay in less than 10 Ma. Thus no residual heat of emplacement would be expected to remain from the 50 Ma old Sloko and older events. However, both local and regional thermal anomalies resulting from late Tertiary and Quaternary volcanism may persist along the Stikine Volcanic Belt. Residual heat due to the rise of magma to the surface or into shallow subvolcanic reservoirs would, if present, be confined to very small anomalies around the volcanoes themselves. However, the generation of magma within the Stikine Volcanic Belt during the past 10 Ma is probably the result of anomalously high temperatures in the underlying mantle, and this additional heat source at the base of the crust should add a measurable component of the conductive surface heat flow, probably with convective water-borne transport in at least part of the crust.

Measurement techniques

Heat flow and heat generation measurements were made using standard techniques. The temperatures in boreholes were measured using a portable winch with a thermistor sensor and Wheatstone bridge. Accuracy of measurement was 0.01 K absolutely and 0.002 K relatively and the resolution of depth of any point was 0.3 m. After corrections for cable stretch the maximum error in an average gradient of 10 mK/m was 3%. Standard corrections to the temperatures were made for the effects of topography (Jeffreys 1937) and for Pleistocene climatic perturbations (Jessop 1971). Thermal conductivity was measured on a divided bar (Jessop 1970) using discs cut from cores unless otherwise noted.

A gamma-ray spectrometer with a Ge(Li) detector (Lewis 1974) was used to determine the heat generation in representative rock samples. In general the heat generation of every rock sample was determined to a greater accuracy than the variations observed between different samples of the same rock.

Detailed comments on each site, numbered as in Fig. 1, follow, and a summary of data appears in Table 1.

1. Whitehorse

The measurement was made on a mineral exploration hole, drilled by Whitehorse Copper Mines Limited about 5 km west of the city of Whitehorse. This belt lies along the contact of a mid-Cretaceous, mainly granodioritic batholith within late Triassic sediments of the Laberge Group (Wheeler 1961). Mineralization is localized where calcareous Laberge sediments have been altered to skarn. The measured hole, which has an inclination of 60°, lies entirely within the granitic rock. Heat generation samples were taken both from drill core and surrounding outcrops. Close agreement between the two sets of data (Table 1) indicates that neither surface weathering nor mineralization has significantly affected the heat generation.

Pleistocene Miles Canyon basalt outcrops about 8 km south of the hole. However, the source of these flows is even farther away and, since residual heat from small basaltic eruptions of this type is commonly restricted to the actual conduit, there is little chance that the heat flow measurement is influenced by Miles Canyon volcanism.

2. Ruby Creek

The Ruby Creek data were obtained from two holes drilled by Adanac Mining and Exploration Limited on the Adera Group, about 27 km northeast of Atlin (Sutherland-Brown 1969). Molybdenum mineralization on this property occurs along the periphery of a small boss near the western end of the Surprise Lake batholith. Both the boss and batholith comprise similar leucocratic, two-feldspar granite and alaskite (and the two bodies are probably connected at shallow depth). The mid-Cretaceous Surprise Lake batholith (Aitken 1959), with an area of about 800 km^2, is one of the largest bodies of plutonic rock in the Atlin Terrane. It has the form of an ellipse with its long axis oriented east—west across the north-northwesterly structural trend of the enclosing Cache Creek rocks. Moreover the Ruby Creek site is only about 2 km from a centre of latest Tertiary and Pleistocene volcanism (Aitken 1959). Thus, although the site lies within the Atlin Terrane its thermal characteristics are completely dominated by the large, relatively young, and much more radioactive body of Surprise Lake alaskite and possibly by the presence of residual magmatic heat added during late Pleistocene volcanism.

The two Ruby Creek boreholes were logged to depths of 305 and 350 m. Unfortunately no core samples were available from the logged holes, and all conductivity measurements were made on samples from other holes on the property. All core was split for assay purposes, and so all conductivity measurements were made by the cell method (Sass *et al.* 1971). The site is in an area of severe topographic relief and there is evidence that the gradient in the upper part of the holes is disturbed by water movement. The gradient in the lower part of the holes has been accepted for heat flow calculations.

TABLE 1. Heat flow and heat generation data

Site	Lat. (N)	Long. (W)	Depth interval (m)	Temperature N	Temperature Grad. (mK/m)	Conductivity N	Conductivity Avg. (W/mK)	Heat flow (mW/m²) Meas.	Heat flow Corrected Topo.	Heat flow Corrected Clim.	Heat flow Prob. error	Heat generation N	Heat generation Mean (µW/m³)	Heat generation Std. error
1. Whitehorse	60°45.0′	135°11.0′	40–388	24	18	23	2.94	60		64	3			
Surface												23	1.75	0.12
Cores												13	1.85	0.14
Total												36	1.79	0.10
2. Ruby Creek A	59°42.8′	133°24.1′	76–350	19		*	3.5	109	103	104	10			
B	59°42.8′	133°24.1′	61–305	17		*	3.4	102	92	96	10			
Average										100	10	7	6.53	0.59
3. Dease Lake	58°38.9′	130°00.6′	100–292	26	21	30	4.73	91	84	88	8	10	1.10	0.13
4. Gnat Lake A	58°15.3′	129°49.0′	70–143	10	30	6	2.57	75		76	8			
B	58°15.3′	129°49.0′	65–150	12	31	6	2.55	76		77	8			
Average										76	8	3	1.07	0.05
5. Hotailuh	58°09.6′	129°51.9′	50–425	16	29	46	2.23	64	58	63	8	18	2.59	0.36
6. Buckley Lake	57°53.6′	130°51.3′	100–427	22	33	45	2.10	67	69	72	2	19	0.65	0.08
7. Ritchie	56°25.1′	129°0.92′	330–900	39	30	13	3.87	112	90	93	4			

*Conductivity derived from similar rocks from nearby holes.

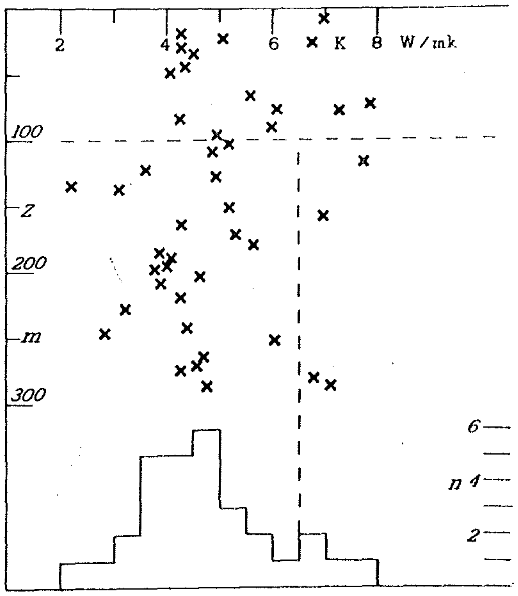

FIG. 2. Conductivity distribution of samples from the Dease Lake hole, plotted against depth and summarized in a histogram. Only data from below 100 m depth are used in the computation of heat flow and histogram. The vertical dashed line indicates a possible arbitrary cut-off of the data in order to correct for bias in sampling.

The heat generation measurements were made on one sample from the nearby adit, one sample from outcrop, and five composite samples from adjacent drill cores.

3. *Dease Lake*

The Dease Lake site was selected and drilled with the aim of gathering heat flow data from the Atlin Terrane, in a typical Cache Creek assemblage as far removed as possible from the influence of younger plutonic bodies. The borehole lies about midway between the bounding faults of the terrane and penetrates 291 m of Permian and Pennsylvanian Kedahda Formation (Monger 1969). The rock is predominantly quartzose phyllite with fine silver grey laminae of muscovite and variable amounts of graphite. Minor argillite and calcareous phyllite were also intersected. The apparent heat flow depends directly on the measured values of thermal conductivity, which show an average of 4.75 W/mK. However, the fissile, highly fractured cores from this hole were difficult to cut and grind to the tolerance required by the divided bar, and many discs were spoiled. There may thus be a bias in the measurements toward the less friable, quartz-rich samples, which would give preferentially high conductivity results. There is considerable scatter in the conductivity values as shown in Fig. 2. If we arbitrarily cut off the tail of the histogram, as shown, the average is reduced by 8% to 4.35 W/mK, which would cause a similar reduction in heat flow to 81 mW/m². This has been used to assign the limit of probable error, but since this reduction is somewhat speculative the original heat flow value is maintained. Heat generation samples were selected from the core, at depths from 37 to 267 m.

4. *Gnat Lake*

The data from this site were obtained from three holes drilled by Dease Lake Mines Limited on their exploration property near the northwestern contact of the Hotailuh batholith, where an older phase of the crystalline rock is overlain unconformably by volcanic and clastic rocks of the Stuhini Formation (Gabrielse 1980). The measured holes are entirely within the altered upper Triassic Stuhini Formation, comprising mainly augite porphyry breccia, conglomerate, and andesite flows. However, the thermal regime must certainly be influenced, if not completely dominated, by the large subjacent mass of late Triassic to early Jurassic age Hotailuh granodiorite (Anderson 1978).

Each of the three holes was blocked below a depth of about 150 m. While this is not generally regarded as deep enough for a reliable measurement of heat flow in mountainous terrain, the results from two of the holes indicate a uniform heat flow over the lower 70 m, with good agreement between the two. The third hole shows increasing heat flow with depth, characteristic of the upper portion of most holes, indicating that it is not deep enough to give an equilibrium result. Heat generation measurements were made on three composite samples of core fragments.

5. Hotailuh

At the time this site was selected and drilled the Hotailuh batholith was thought to be a fairly uniform body of late Mesozoic quartz monzonite and granodiorite (Gabrielse *et al.* 1962). Subsequent work (Gabrielse 1980; Anderson 1978, 1979, 1980; Wanless *et al.* 1972) has shown that the batholith is a complex of many separate phases that vary in composition from diorite through quartz diorite and granodiorite to quartz monzonite, syenodiorite, and syenite. The older phases give potassium–argon ages of 213–217 Ma and are overlain unconformably by late Triassic Stuhini Formation clastic sediments. Younger phases are clearly intrusive into both the Stuhini and older phases of the batholith itself.

The heat flow hole lies within one of these younger phases, a discrete, relatively potassic body, on the western edge of the batholith. It penetrates 427 m of mainly hornblende biotite granodiorite or monzonite cut by numerous andesite dykes and minor aplite (Souther 1971). Core samples of the granodiorite give potassium–argon ages of 147 Ma (hornblende) and 137 Ma (biotite) (Wanless *et al.* 1972).

The hole provided new paths for water flow between fractures, and artesian flow was generated. Flow to the surface was stopped by cementing, but the temperature profile in Fig. 3 shows disturbances at about 150 and 350 m. Between these points the temperature seems to be uniformly increased by about 1°C, suggesting an upward flow entering the hole at 350 m and leaving at 150 m. The best heat flow has been derived by accepting the temperatures above 150 m and below 350 m since these data lie in a straight line. However, heat flow in the region 200–300 m is very similar to the accepted value, a characteristic of slow, steady water flow in a borehole. Conductivity is very uniform. Distortion of the temperature field before drilling is impossible to estimate, and because of this uncertainty the limit of error has been arbitrarily set at 15%. Heat generation samples were selected from the drill core.

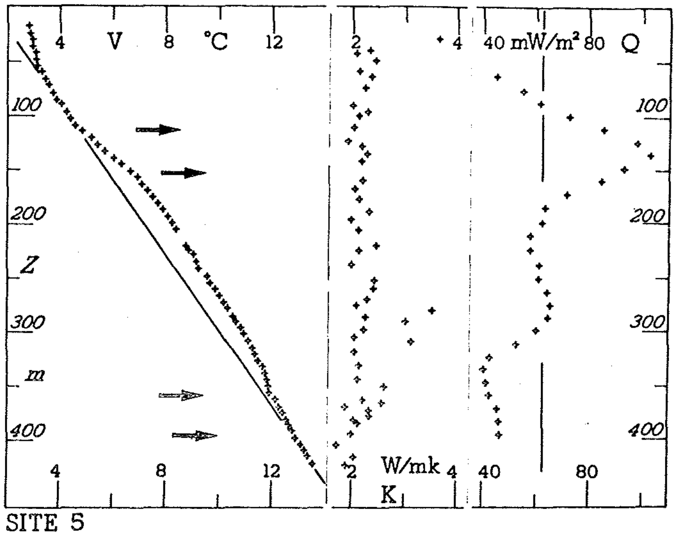

FIG. 3. Temperature, conductivity, and calculated heat flow from the Hotailuh well. The straight line temperature gradient shows the inferred gradient that existed before the hole allowed a change in water flow paths. Arrows indicate evidence of water entering the hole at 360–400 m and leaving at 120–160 m. Heat flow is calculated by overlapping sections of 10 temperature data, to give points, and by Bullard (1939) method using temperature data above 150 m and below 350 m, as shown by vertical line.

6. Buckley Lake

This site was drilled as close as possible to the axis of the Quaternary Stikine Volcanic Belt (Souther 1975). The hole penetrates 427 m of upper Triassic sedimentary and volcaniclastic rocks that are correlative with the Stuhini Formation of the Whitehorse and Atlin areas. These rocks are cut by late Mesozoic plutons and early Tertiary subvolcanic intrusions, both of which outcrop within a few kilometres of the drill hole. This entire Mesozoic and early Tertiary assemblage is overlain unconformably by flat-lying, late Tertiary and Quaternary lavas of the Stikine Volcanic Belt. The Mount Edziza Volcanic Complex, one of the largest and youngest volcanic assemblages in the belt, is a continuous volcanic terrane that extends south from the Buckley Lake site for about 60 km. It includes a complex of overlapping basaltic shields, composite trachyte volcanoes, and rhyolite domes. The youngest dated activity occurred about 1300 years ago, and four groups of thermal springs along the west side of the complex are believed to be related to an active hydrothermal system of volcanic origin.

Temperature gradient and conductivity are fairly uniform and heat flow calculation was routine. The heat generation samples are from several segments of core.

7. Ritchie

The measurement was made in a large diameter (121 mm) petroleum exploration hole drilled to a depth of 1890 m by Dome Petroleum Limited on a southwest flowing tributary of the Bell Irving River, 20 km east of Bowser Lake. The hole is located near the centre of the Bowser Basin, a successor basin in which at least 2000 m of mainly marine, Jurassic–Cretaceous siltstone, greywacke, shale, and conglomerate (Bowser Lake Group) was deposited. Around the margins of the basin Bowser Lake sediments rest unconformably on lower Jurassic and Triassic clastic sediments and volcanic rocks that probably underlie most of the basin. However, at Oweegee Peak, Bowser Lake sediments wedge out against an inlier of upper Paleozoic rocks. Strata in the Bowser Basin are highly folded and shortening in the sedimentary rocks may be transferred to a décollement separating them from the underlying, more competent rocks.

The borehole is collared in Bowser Lake sediments at an elevation of 1100 m. According to H. W. Tipper (personal communication, 1983) it penetrates 894 m of Bowser Lake sediments, the balance of the hole being in lower Jurassic grit, greywacke, and volcaniclastic rocks. The location of the hole, approximately 30 km east-southeast of the Oweegee structural high, suggests that it may lie above an easterly sloping décol-

TABLE 2. Heat generation from batholiths within the Intermontane Belt

Geological unit	Heat generation: N	Heat generation: μW/m³	Heat generation: SD	K/Ar age (Ma)	Rocks
Mt. Leonard boss (Surprise L. batholith)	8	6.48	1.54	71	Alaskite
Glundeberry batholith	3	4.82	1.92	76	Hornblende granite
Tuya batholith	2	1.80	0.02	78	Biotite granite and quartz monzonite
Klinkit batholith	5	1.77	1.28	87	Biotite quartz monzonite
Cassiar batholith	8	2.94	1.13	105	Biotite quartz monzonite and granodiorite
Whitehorse batholith	36	1.79	0.91	109	Granodiorite
Hotailuh batholith	18	2.59	0.68	142	Hornblende biotite granodiorite
Simpson Pk. and Nome L. batholiths	4	1.27	0.22	174	Biotite hornblende granodiorite
Christmas Crk. batholith	3	1.47	0.65	177	Hornblende quartz diorite
Eagle intrusive	1	0.56	—	180	Diorite

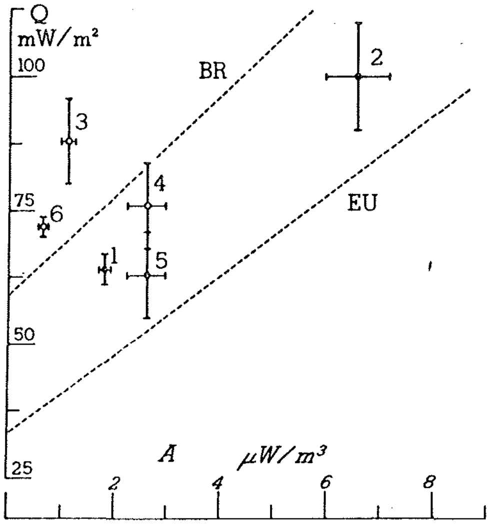

FIG. 4. The relation between heat flow and heat generation for sites 1–6. Solid circles represent those sites where measurements have been made in a batholith, and open circles represent sites in metamorphic or sedimentary rocks. Established lines for Basin and Range Province and eastern United States are labelled BR and EU, respectively.

lement surface. Water movement along such a deep major structure could influence the temperature gradient. The observed increase in gradient in the upper part of the Dome hole is consistent with the upward movement of relatively warm groundwater along lesser structures that may intercept the décollement at depth.

The well was logged to a depth of 900 m, and showed a temperature gradient of about 45 mK/m near the surface, reducing to 28 mK/m at the limit of logging. Correction for topographic relief and climatic history yields a gradient that is very uniform, varying only from 24 to 26 mK/m. Cores were available from only four intervals in the well, and only 13 samples were obtained for conductivity measurement. The samples were reasonably representative of the lithological log description for all intervals except the lowest, where the two samples are both coarse conglomerates in a zone of mixed sandstone and conglomerate. The four intervals give heat flows, corrected for topographic relief and climatic history, of 89, 96, 93, and 113 mW/m², for an average of 98 mW/m² and a standard deviation of 11 mW/m². Because the lowest interval has doubtful conductivity values and has heat flow more than one standard deviation removed from the mean it is rejected. The mean of the remaining three intervals is 93 ± 4 mW/m².

An estimate of the thermal resistance, calculated from an analysis of the proportions of various rock types as shown in the lithologic log and the available conductivity data, plotted against observed temperature yields a straight line relationship from a depth of 320 m to 900 m. The resulting heat flow is 94 mW/m², which supports the analysis presented above, and the accepted heat flow is 93 ± 4 mW/m².

Additional heat generation measurements

In an attempt to augment the few thermal data for this area, the heat generation was measured for rock samples representing other batholiths, mainly from the Jennings River map sheet (National Topographic System (NTS) 104 O). The average value for each geological unit, including the three batholiths below heat flow sites, is shown in Table 2, with the standard deviation and a potassium–argon age date from a nearby location. The general trend towards higher heat production in younger rocks as expected due to composition (Larsen and Gottfried 1961) is demonstrated by this data. The data from the three batholiths below heat flow sites conform to the general trend exhibited by the full data set.

Heat flow and heat flow generation

The heat flow – heat generation pairs of Table 1 are plotted in Fig. 4 and provide a basis for comparison with other regions. However, only three of the sites, Whitehorse (1), Ruby Creek (2), and Hotailuh (5), are drilled in large, relatively uniform bodies of plutonic rock in which the measured heat production from core and surface samples can be projected to depth with any degree of certainty. The close agreement in the plots for the Whitehorse and Hotailuh sites compared with the plot of the Ruby Creek site suggests that composition rather than age is a dominant control. Both the mid-Cretaceous Whitehorse batholith and the lower Triassic Hotailuh batholith are predominantly granodiorite with relatively low potassium content compared with the Ruby Creek alaskite, which contains about 50% potash feldspar. Although these three points do not provide sufficient data to define a line for the Stikine region, they fall roughly midway between the established lines (Roy *et al.* 1968) for the eastern United States and the Basin and Range Province. This suggests that the north-central Cordillera is too young to conform to the stable area of eastern North America but that it is not sufficiently thermally active to resemble the Basin and Range Province. This also places constraints on the northern extension of a corridor of anomalously high upper mantle and

TABLE 3. Rock properties used for calculation of temperature profiles

Rock	Origin	Symbol	Conductivity (W/mK)	Heat generation (μW/m^3)
Alaskite	Ruby Creek	L	3.5	6.53
Andesite	Buckley Lake	A	2.1	0.65
Granodiorite	Hotailuh	Gh	2.23	2.59
Granodiorite	Whitehorse	Gw	2.94	1.79
Phyllite	Dease Lake	P	4.73	1.10
Stuhini Fm.	Gnat Lake	S	2.56	1.07
Basaltic lower crust	All sites	B	(1.9)	(0.5)
Tertiary granite	Buckley Lake	Gb	(2.5)	(4.0)
Granite	Ritchie	Gr	(2.5)	(3.3)
Sediments	Ritchie	R	3.87	(5.0)

NOTES: Symbols are used in Figs. 5, 7, and 8. Quantities in parentheses are assumed values; all others are derived from measured data.

lower crustal temperatures inferred from magnetotelluric and magnetic depth soundings in the south-central Cordillera (Caner 1970; Gough *et al.* 1982). The aeromagnetic survey of Haines *et al.* (1971) supports the results of Caner.

Without implying any linear relationship between heat flow and heat generation for these three sites, it seems reasonable to adopt the median reduced heat flow at 46 mW/m^2. It is then possible to deduce a heat flow from the mantle of 30–35 mW/m^2 by subtraction of a further 25–30 km of basic crustal material of assumed heat generation of 0.5 W/m^3.

In contrast to the sites in intrusive rocks, the heat flow – heat generation pairs for the Dease Lake (3) and Buckley Lake (6) sites plot well above the Basin and Range line and thus appear to be anomalously high with respect to the broad zone defined by the three granitic sites. These apparent anomalies are probably due more to errors resulting from the use of surface samples of metamorphic and sedimentary rocks for measurement of heat generation than to real differences in the thermal structure of these sites. Correction of the possible overestimate of heat flow at Dease Lake due to conductivity bias does not significantly change the position of this point relative to the Basin and Range line, suggesting that the site is underlain at fairly shallow depth by rocks having a much higher heat production than the quartzose phyllites intersected by the drill. This supports the concept that the Atlin Terrane is a relatively thin allochthonous slice of Cache Creek rocks that has been thrust southwest onto granitic crust (Monger and Price 1979) and that it is not, as formerly thought, a block of oceanic crust resting directly on the mantle.

Both the Gnat Lake (4) and Buckley Lake (6) boreholes are confined to volcanic or closely related volcaniclastic sediments of the upper Triassic Stuhini Formation. At Buckley Lake the rock is unmetamorphosed, whereas similar rock at Gnat Lake has been intensely altered, probably during emplacement of a late phase of the Hotailuh batholith.

The Gnat Lake (4) site is plotted using the heat generation value for the Hotailuh hole (5), because the Hotailuh batholith is believed to control the thermal character of the site. The data from the Gnat Lake core show a lower mean heat generation than the Hotailuh granodiorites, as shown in Table 1, but these rocks are only a thin veneer on the flank of the batholith. As plotted, the Gnat Lake site lies somewhat below the Basin and Range line, but if the local surface heat generation were used it would be above this line and similar to the Dease Lake (3) and Buckley Lake (6) sites.

The anomalously high heat flow at Buckley Lake (6) is less readily explained. It may be due to a high mantle heat flux along the axis of the Stikine Volcanic Belt or it may simply be the result of a hidden body of granitic rock at relatively shallow depth beneath the borehole. The very fresh rock cut by the Buckley Lake hole indicates that a subjacent intrusion, if present, must lie at a depth greater than the aureole of contact metamorphism. However, subvolcanic plutons of early Tertiary Sloko affinity commonly have very narrow contact metamorphic selvages. Also, the presence of early Tertiary rhyolite domes, dike swarms, and flows a few kilometres east and west of the borehole suggests that a large subvolcanic body under Buckley Lake is not only possible but highly probable. Thus the present data do not offer unequivocal evidence of high heat flux along the axis of the Stikine Volcanic Belt. If thermal anomalies are present along this belt, as suggested by thermal springs, then they probably form a series of discrete, local hot spots rather than a broad thermal arch. There are no hot springs in the immediate vicinity of the Buckley Lake hole, but it is possible that the high heat flow is controlled by hydrothermal activity rather than by a deeper crustal source.

Crustal temperature and mantle heat flow

Each of the seven sites permits the construction of models of crustal thermal conductivity and heat generation, from which temperature profiles may be calculated. In each layer of conductivity K, heat generation A, upper boundary heat flow Q_0, and temperature v_0, the temperature and heat flow at a depth z below that upper boundary are given by

$$v = v_0 + (Q_0 z/K) - (Az^2/2K)$$

$$Q = Q_0 - Az$$

Calculation of temperature may thus proceed from the surface downwards, through any number of layers.

Models for each site have been constructed from the available data of Table 1, with the addition of plausible assumed values for lower crustal layers. Details of the values used are shown in Table 3. The lower crust is assumed to have the properties of basalt and to be uniform in all models, although the thickness is variable. The thickness of the crust is assumed to be 35 km, but there are no seismic or gravity data on which to base this figure.

It is found that plausible models can be constructed for the Whitehorse (1), Ruby Creek (2), Dease Lake (3), Gnat Lake

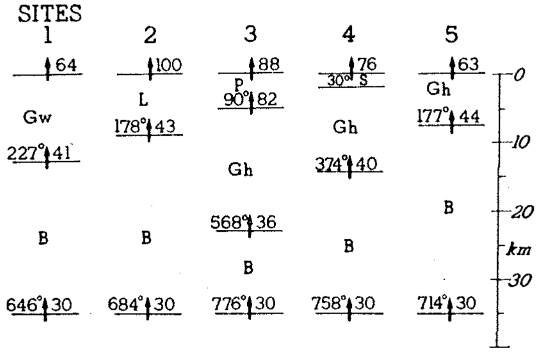

FIG. 5. Crustal models for five of the heat flow sites, numbered according to the list of Table 1. At each boundary a heat flow and temperature are shown. Symbols representing the rock type are defined in Table 3, where the associated conductivity and heat generation values are to be found.

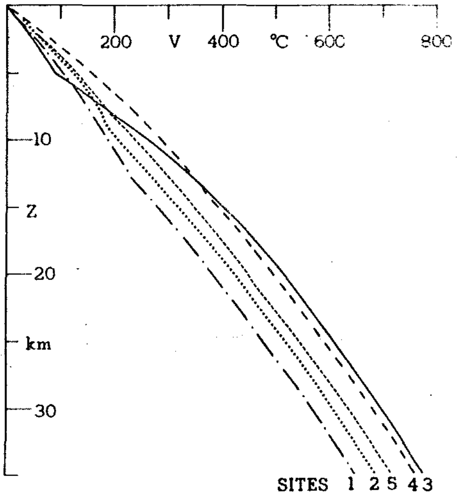

FIG. 6. Crustal temperature profiles derived from the models of Fig. 5. Curves are numbered according to the list of Table 1.

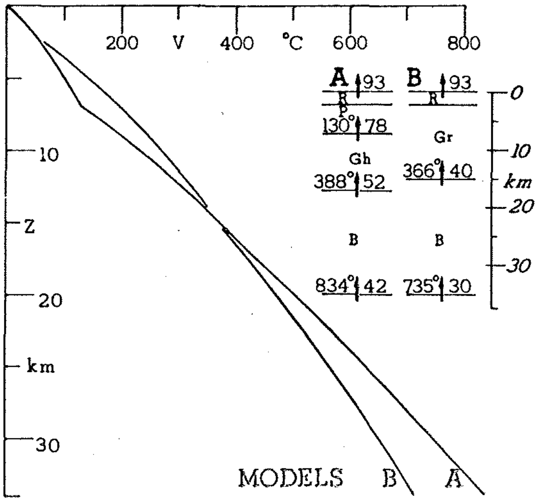

FIG. 7. Crustal models and derived temperature profiles for the Ritchie site.

(4), and Hotailuh (5) sites, each of which results in a heat flow of about 30 mW/m^2 and a temperature in the range 640–780°C at the assumed base of the crust. These temperatures give reasonable bounds to the temperature to be expected at the base of the crust within the study area, and the heat flow at that level is probably within the range 30 ± 5 mW/m^2. These temperatures are consistent with the general character of the Basin and Range Province, as calculated by Jessop and Lewis (1978), but they show a much lower heat flow at 35 km depth. Model temperatures might have been expected to be somewhat lower, but the earlier models were very generalized and the present models are probably a much more reliable guide for the sites under analysis. The models for these five sites are shown in Fig. 5.

Temperature profiles derived from these models, shown in Fig. 6, show strong similarity to each other. Only in the Dease Lake model is it necessary to invoke any layer that is not observed at the surface or known from geological evidence to underlie the site at a shallow depth. At Dease Lake it is necessary to assume a layer of granite or granodiorite equivalent to 18 km of the Hotailuh rock, or a lesser thickness of a material of higher radioactive content. Despite its proximity to a centre of Pleistocene volcanism, the heat flow at Ruby Creek is adequately explained by a reasonable thickness of the material of high heat generation that is observed at the surface. It is possible that some combination of lower heat generation and residual volcanic heat could provide the same heat flow, but the available data cannot provide such a distinction.

For the Ritchie (7) and Buckley Lake (6) sites reasonable models to provide similar crustal temperatures are not possible. Figure 7 shows two models and the resulting temperatures for Ritchie. The sediments are known to have a thickness of about 2 km, and by assuming 5 km of phyllites, similar to Dease Lake, and 10 km of granodiorite, similar to the Hotailuh batholith, a Mohorovičić (Moho) temperature of 834°C and a heat flow of 42 mW/m^2 are produced (model A). In order to achieve a temperature and heat flow at 35 km similar to those of Fig. 6, it is necessary to postulate the presence of 13 km of granitic material of a higher concentration of radiogenic elements than is found in the Hotailuh batholith, as shown in model B of Fig. 7. Alternatively, some correspondingly smaller thickness of material of high conductivity and heat generation could be substituted. It is more probable that the high measured heat flow is attributable to water movement in the deeper sedimentary formations. A potential recharge area is present at Oweegee Peak, and the well was drilled on the crest of an anticlinal structure, where migrating water would be forced to rise over the anticline, thus transporting heat upwards to augment the conducted heat flow at the Ritchie site.

For Buckley Lake three models have been analyzed, as shown in Fig. 8. Model A assumes 10 km of the andesitic greywacke that is observed at the surface above a basaltic lower crust, and leads to a temperature in excess of 1100°C and a heat flow of 53 mW/m^2 at the Moho. The insertion of 3 km of Tertiary granitic material, outcrops of which are observed within a few kilometres, as shown in model B, brings the temperature at the Moho down to 929°C, but 7 km of granite is needed to bring the temperature and heat flow down to levels similar to those of the other sites (model C). It seems improbable that this much granite is present beneath the Buckley Lake site. It is much more likely that the excess heat flow observed at the surface is derived from an abnormally high temperature at the Moho or from volcanic mass transport in the crust and long-term cooling of intrusive masses beneath the Mount Edziza Complex of the Stikine Volcanic Belt. It is worthy of note that this conclusion is based on a value of heat flow that is by no means the highest observed.

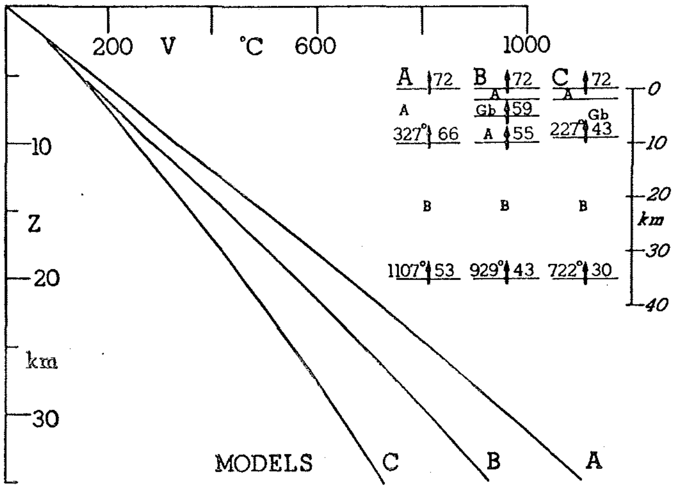

FIG. 8. Crustal models and derived temperature profiles for the Buckley Lake site.

Conclusions

(1) Heat flow at seven sites in northwestern British Columbia is at or above world average levels. Where heat flow can be related to the heat generation of intrusive rocks it shows a behaviour intermediate between that of the stable crust of the eastern United States and that of the young active crust of the Basin and Range heat flow province.

(2) Most of the sites show geothermal data and geological evidence to support a temperature of about 700°C and a heat flow of about 30 mW/m^2 at a Moho that is assumed to be at 35 km depth.

(3) The Ritchie (7) site in the Bowser Basin shows a high heat flow that is probably related to water migration over the anticline or to high levels of radiogenic heat production beneath the sediments.

(4) The Buckley Lake (6) site, although showing a modest heat flow of 72 mW/m^2, is probably explained by an accumulation of volcanically concentrated or transported heat or the presence of a large granitic body that is almost covered by later sediments or volcaniclastic rocks.

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