THERMAL STUDIES OF THE BOULDER BATHOLITH AND VICINITY, MONTANA

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INTRODUCTION

The Boulder batholith has been the subject of extensive and intensive geological, geochemical, and geophysical investigations. This paper presents additional data on heat flow, the uranium, thorium, and potassium contents of the plutonic rocks, the inter-relation of these two sets of data, and on geothermal features at Butte. An early conclusion of this study was that western Montana, including the Boulder batholith, is an area of abnormally high heat flow (Blackwell, 1969). The area of high heat flow includes the Basin and Range province in the southwestern United States, and the Columbia Plateau, northern Rocky Mountains, and Cascade provinces in the northwestern United States. These provinces together constitute a broad region of high heat flow (averaging about 2.2 μcal/cm^{2}sec) bordered on the east and west by regions of low to normal heat flow (averaging less than 1.5 μcal/cm^{2}sec). The region of high heat flow extends along the axis of the Cordilleran Mountain chain south into Mexico and north into Canada (Judge, 1973; Roy et al., 1973). The origin of this broad region of high heat flow has been attributed to the thermal effects of the subduction of the Farallon plate (Blackwell, 1971; Roy et al., 1972) which occurred during most of the Cenozoic off the west coast of North America (Atwater, 1970). The relationship of the Boulder batholith to this subduction will be considered below.

GEOLOGY AND GEOPHYSICS

The results of several geologic studies of the Boulder batholith by members of the U. S. Geological Survey have recently been published (Doe et al., 1968; Tilling et al., 1968; Robinson et al., 1968; Tilling and Gottfried, 1969; Tilling et al., 1970; Klepper et al., 1971). The Boulder batholith is a composite pluton consisting of several rock types; however, the predominant rock is the Butte Quartz Monzonite. The various phases of the Boulder batholith range in age from 78 to 68 m.y. The batholith intruded a suite of older rocks, from Precambrian to Cretaceous in age, including the Elkhorn Mountains Volcanics, which have an age of approximately 78 m.y. and which therefore may be contemporaneous with some of the earlier phases of the Boulder batholith. After the Cretaceous volcanic and plutonic activity, extensive volcanism in the Eocene resulted in deposition of the Lowland Creek Volcanics. These rocks are quartz latite and have been dated at approximately 50 m.y. (Smedes and Thomas, 1965). The thermal consequences of these earlier igneous events have long since been dissipated, however, and make no contribution to the present heat flow.

Many geophysical studies of the batholith have been made. Burfield (1967) and Biehler and Bonini (1969) have studied the gravity field of the batholith,

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TABLE D-A. Location, preliminary heat flow values, and geologic unit for heat flow localities. (K, thermal conductivity; numbers in parentheses in locality column indicate number of drill holes at each locality.)

Locality	Lat.	Long.	Depth range (m)	K 10^{-3} cal / cm sec °C	Gradient (°C/km)	Heat flow 10^{-6} cal / cm^2 sec	Geologic unit
Butte	46°03'	112°33'	200-1200	6.62 0.04	31.9 0.7	2.1	Butte Quartz Monzonite
Deer Lodge	46°23'	112°35'	110-210	7.4 0.2	24.2 0.3	1.93	Elkhorn Mountains Volcanics
Dillon	45°19'	112°53'	200-310	7.5	20.6	1.5	Paleozoic sediments and Precambrian metamorphic rocks
Elk Park	46°15'	112°27'	260-642	7.4 0.2	27.9 9.2	1.98	Lowland Creek Volcanics and Butte Quartz Monzonite
Jefferson City (4)	46°21'	112°05'	50-170	8.3	21.0	(1.7)	Butte Quartz Monzonite
Lincoln (2)	47°02'	112°23'	100-270			2.2*	Precambrian Belt Supergroup and quartz monzonite
Marysville (15)	46°44'	112°20'				3.2-19.5**	Precambrian Belt Supergroup and Cenozoic porphyries
Philipsburg	46°28'	113°25'	350-580	10.3 0.5	18.9 0.3	1.91	Precambrian Belt Supergroup
Silver Bow	45°57'	112°42'	20-155	(5.0)	38.9	(2.0)	Lowland Creek Volcanics and Butte Quartz Monzonite
Silver Star (2)	45°43'	112°20'	70-150	6.4 0.1	30.1 0.3	1.94	Rader Creek pluton
Unionville	46°29'	112°07'	75-145	7.3 0.1	26.3 0.5	1.92	Unionville Granodiorite and/or Butte Quartz Monzonite
Whitehall	45°55'	112°01'	220-260	7.8 0.3	19.8 0.1	1.8	Precambrian Belt Supergroup

* Blackwell (1969)
** Blackwell and Baag (1973)

and Johnson et al. (1965) and Zietz et al. (1971) have discussed the magnetic anomalies. Hanna (1969) has discussed some aspects of both the gravity and magnetic data.

HEAT FLOW

New measurements of heat flow are presented for 12 different localities (Table D-A, Fig. D-1). All of the heat flow determinations are from holes drilled for mineral exploration and cuttings or core samples from the holes have been made available to the authors for the thermal-conductivity measurements by companies doing exploration or by individual property owners.

The mechanical details of data acquisition and reduction have been summarized by Roy et al. (1968b). In Table D-A, the thermal gradients are least-squares straight lines fitted to the temperature-depth data in a given depth interval, and the conductivity values are mean harmonic averages of laboratory measurements; standard errors are shown beneath the entries. All of the heat flow values were calculated either as the product of the least-squares gradient and the average harmonic thermal conductivity, or by fitting a least-squares straight line to the summed thermal resistance and temperature data. Topographic corrections have been applied at all localities (Birch, 1950) and were carried to a distance of 20 km in most instances.

The most spectacular feature of the heat flow values listed in Table D-A are the high values of heat flow near Marysville. These drill holes are in Belt rocks near a small granodioritic stock, which is apparently an outlier of the Boulder batholith (Knopf, 1950). These values are in a geothermal area with no surface manifestation discovered during the course of the study. One interpretation of these data (Blackwell and Baag, 1973) is that the high heat flow values are due to a shallow pluton (with top at 1-3 km) emplaced about 10,000-50,000 years ago. This pluton is presumably still hot and the high heat flow is due to conductive heat loss from this buried magma chamber. It appears that the Boulder batholith area is still geologically active, as suggested by the earthquake data (Ryall et al., 1966; Smith and Sbar, 1973).

With the exception of the values near Marysville, the heat flow determinations in the Boulder batholith and vicinity range from 1.5 to 2.1 $\mu cal/cm^2 sec$. The lowest values of heat flow are the ones the farthest removed from the effects of Cenozoic and Mesozoic intrusive activity, i.e., the determinations at Philipsburg, Whitehall, and in basement rocks near Dillon. The rest of the determinations, all near 2.0 $\mu cal/cm^2 sec$, were made in drill holes which either are in rocks of the Boulder batholith or appear to be underlain at shallow depths by rocks of the Boulder batholith (Silver Bow, Elk Park, and Deer Lodge). The value of 1.7 $\mu cal/cm^2 sec$, obtained near Jefferson City, is not well determined as the holes are very shallow and on the top of a steep hill; more data are needed to verify this low value. The determinations at Butte, Elk Park, Jefferson City, and Silver Bow are in or just above rocks of the Butte Quartz Monzonite phase of the Boulder batholith. The drill hole at Deer Lodge is in rocks of the Elkhorn Mountains Volcanics; however, geologic mapping (Robinson et al., 1968) indicates that the Butte Quartz Monzonite may be present at depth there. The determination at Silver Star is in the Rader Creek pluton, which is one of the earlier, less felsic phases of the batholith. Similarly the determination near Unionville is near the contact between rocks of the Butte Quartz Monzonite and the more mafic Unionville Granodiorite.

Most of the heat-flow measurements were made in drill holes 150-600 m deep; however, the determination at Butte in the Butte Quartz Monzonite is for a drill hole 1.2 km deep. The heat flow in that hole varies systematically from 2.15 in the upper part of the hole to 1.9 $\mu cal/cm^2 sec$ in the bottom part. The cause of this variation is not certain; only part of the variation can be explained by the differences in the thermal properties of the rock and by possible penetration below the heat sources in the batholith; consequently, there is some uncertainty associated with this heat flow determination. The value listed is that measured in a shallow part of the drill hole to be consistent with the remainder of the data. This systematic variation with depth may occur elsewhere in the Boulder batholith, but no other deep holes have been measured.

TEMPERATURE DISTRIBUTION AT BUTTE

The drill hole at Butte is on the northwest edge of the district and does not intersect any water courses. As there is no running water in the hole, a good measurement of conducted heat could be made there; water is so effective in transferring heat by its mass movement that it can overwhelm conducted heat. Hot water has been found in all the mines in the Butte district, and its flow has markedly increased the wall rock temperatures underground; invariably the water temperature on a level when it is first opened up is higher than the rock temperature. This is shown in Figure D-2, in which selected rock and water temperatures are shown plotted against elevation; the thermal gradient of the Butte hole previously referred to is shown also. Rock and water temperatures have been measured during the last 50 years in most of the mines by geologists and engineers of The Anaconda Company, and it appears that the undisturbed, original rock temperature underground at Butte for a given elevation is approximately the same over the district, within 5°C. It is apparent that the water flowing from faults, veins, and joints must circulate to greater depth than the working in which it comes and that it heats the rock as it moves upward; note in Figure D-2 that the rock temperature in the mines is about 5°C above the drill hole temperature at the same elevation because of heating by the water.

In a study partly supported by The Anaconda Company (Robertson and Bossard, 1970), rock and water temperatures were measured in a crosscut on the 4600 level of the Kelley mine, the bottom level, where temperatures had not been disturbed by stoping. The measurements were made in holes drilled in the wall very soon after the advancing round was blasted in order to obtain undiminished original rock temperatures. The range of rock temperature observed in the crosscut is shown in Figure D-2; the highest water temperature encountered was 68°C (155°F), higher by 5°C than the hottest rock temperature. On the basis of the saline and silica content of one sample of the water, it is estimated that ground water in the Butte area probably circulates to a depth of 1-3 km, about that estimated for the top of the hypothesized shallow pluton at Marysville. In an analogous manner, ground water circulating to a deeply-buried pluton probably added to the hydrothermal solutions which produced the ore deposits at Butte.

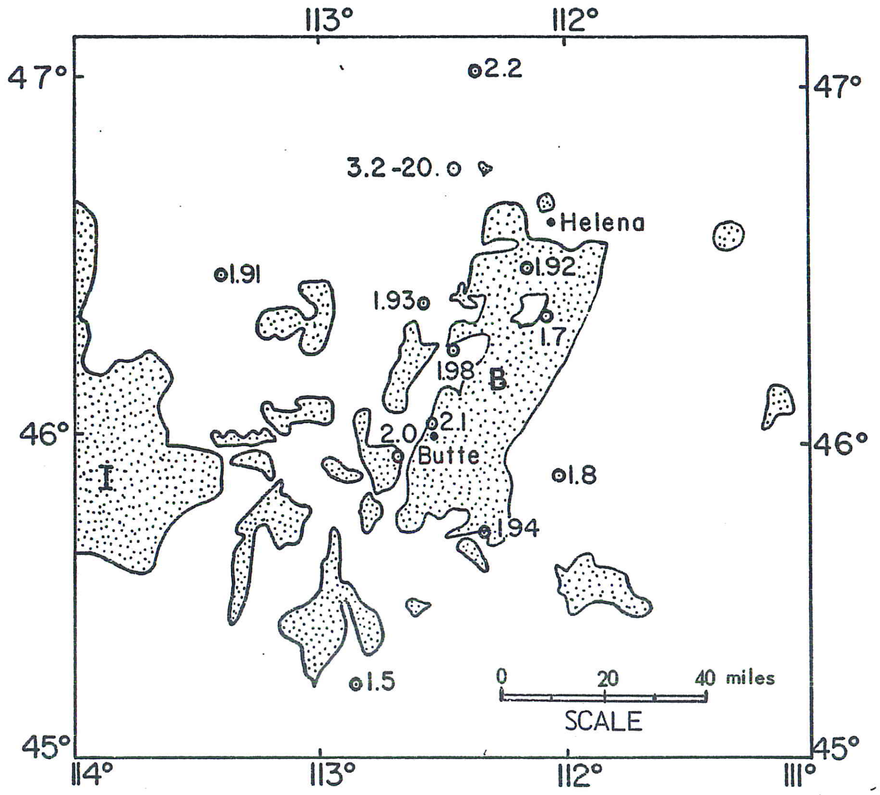

FIGURE D-1. Heat flow and granitic rocks of the Boulder batholith (B) and related plutons, as well as of the Idaho batholith (I). Granitic rocks indicated by dotted pattern. Heat flow values are in 10^{-6} cal/cm^2 sec.

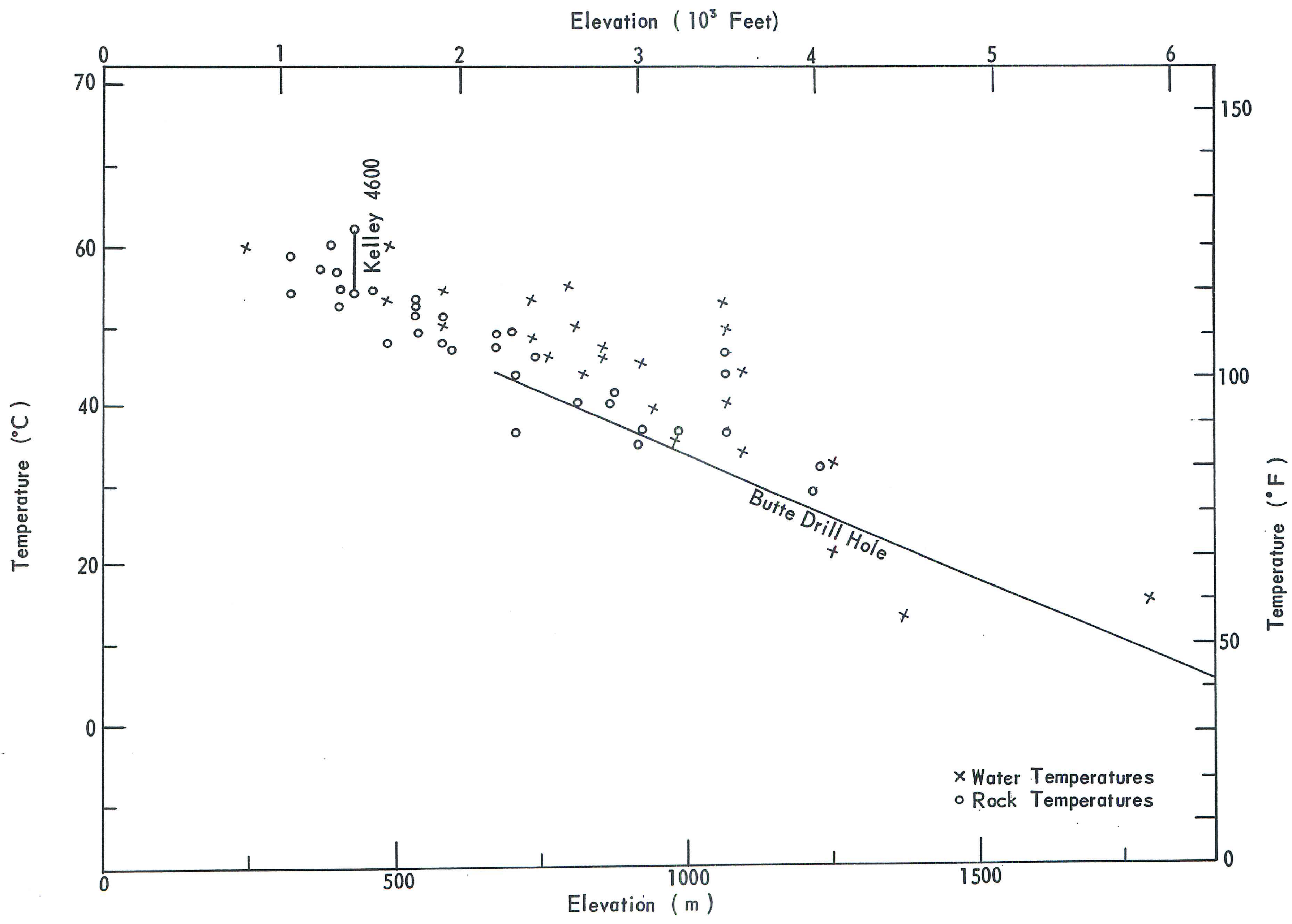

FIGURE D-2. Chart of selected rock and water temperatures vs elevation, Butte district, Montana.

HEAT PRODUCTION

The distribution of U, Th, and K in the different phases of the Boulder batholith has been studied by Tilling and Gottfried (1969). Additional measurements have been made by Swanberg and Blackwell (1973, and unpublished data), and a summary of the available information is presented in Table D-B. Averages of the different intrusive phases as separated by Tilling and Gottfried (1969) and the new data are given in the table, as well as the heat production data for the different heat flow localities.

There are several applications of the heat production information. Some of the petrological implications have been discussed (Tilling and Gottfried, 1969; Tilling et al., 1970), and Swanberg and Blackwell (1973) have pointed out that the trace element studies furnish an excellent method for discriminating between plutonic rocks allied with the Idaho and Boulder batholiths. The magnitudes and inter-relationships of U, K, and Th can also be used as a mapping tool in plutonic rocks; results from such a study of the Idaho batholith have implications for the tectonic setting of the Boulder batholith.

The radioactive elements generate heat in the earth as they decay, so their geographic variation has important implications for the heat flow distribution. Without going into the background studies, we will summarize the most important conclusions on the relationship of heat flow and heat production (for other references, see Roy et al., 1972). Over large areas of the earth's crust on continents, surface heat flow (Q) and surface heat production (A) in large bodies of plutonic rocks are given by the straight line

$$Q = Q_o + Ab$$

where Q_o and b are constants. In the northern Rocky Mountains, the values of Q_o and b may be taken as $1.4\mu cal/cm^2sec$ and 9.4 km, respectively (Blackwell, 1969), assuming they are the same as the values found for the Basin and Range province (Roy et al., 1968a). If this relationship holds for the Boulder batholith with the same constants as in the Basin and Range province, the areal weighted average heat generation value for the Boulder batholith can be used to predict the expected average heat flow. The average heat generation value was determined, using the areal weights of Tilling and Gottfried (1969, Table 2) for the various intrusive phases (excluding the satellite plutons), and the data were listed in Table D-B (Tilling and Gottfried, 1969; Swanberg and Blackwell, 1973, and new determinations). The overall average is 6.4×10^{-13} cal/cm^3sec, which corresponds to a predicted heat flow of $2.00\mu cal/cm^2sec$. The average measured heat flow is $1.98 \pm 0.06\mu cal/cm^2sec$ (omitting the Jefferson City determination). Thus the heat flow values in the Boulder batholith can be explained by assuming a heat flow-heat production relationship similar to that observed in the Basin and Range province.

MONTANA LINEAMENT

Many linear features in the northwestern United States have attracted attention at various times. In particular the "Columbia Arc" (Taubeneck, 1966), the "Montana lineament" (Weidman, 1965), the "Olympic-Wallowa lineament" (Raisz, 1945), and the "trans-Idaho discontinuity" (Yates, 1968) have been

TABLE D-B. Heat production measurements of the Boulder batholith

	No. of Samples	K %	U ppm	Th ppm	A 10^{-13} cal/cm^3 sec
A. Plutonic phases*					
Mafic	4	2.7	1.5	6.2	2.6
Granodiorite					
Mafic	5	2.8	3.4	11.0	4.6
Felsic	7	2.5	1.5	7.3	2.7
Butte Quartz Monzonite	30				6.6
Silicic Butte Quartz Monzonite	6	3.6	5.9	22.3	8.3
Alaskites	5	4.5	9.2	36.3	12.9
Leucocratic	12	2.9	4.1	15.7	5.9
B. Heat-flow localities					
Butte	19	3.4	6.3	22.8	8.5
Elk Park	12	2.8	5.6	16.4	7.0
Silver Bow	1	2.5	2.7	15.3	4.8
Silver Star	5	1.7	4.4	12.3	5.2
C. Areal average					
Boulder batholith					6.4

* After Tilling and Gottfried (1969, Table 2) except for addition of more samples to Butte Quartz Monzonite average.

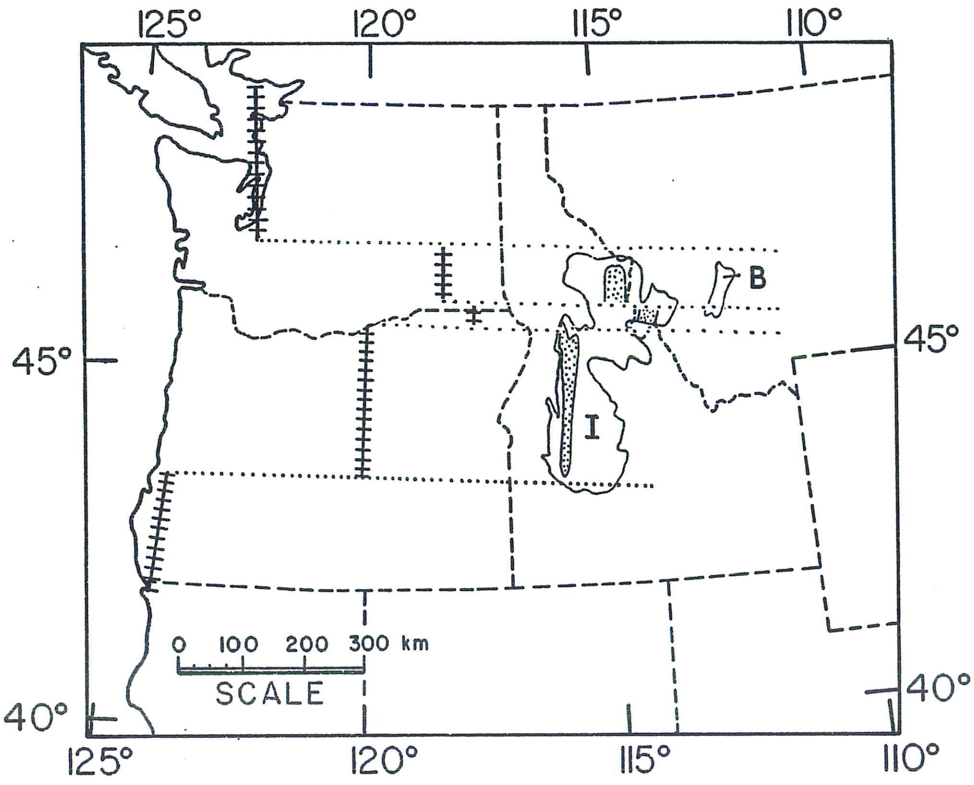

FIGURE D-3. Hypothetical position of trench-transform fault segments during the Mesozoic. Hachured lines show trenches, and dotted lines show transform faults. Solid lines show the position of the Idaho (I) and Boulder (B) batholiths. Dotted pattern indicates the muscovite quartz monzonite unit of the Idaho batholith which may be offset by the transform faults as shown (Swanberg and Blackwell, 1973). The offset, if as shown, would be primary and related to the position of the subducting slab during magma generation.

described and their significance has been discussed. Hypothesizing from various lines of geophysical and geochemical evidence, including seismic (Hill, 1972) and heat-flow data (Blackwell, 1973), and a geochemical study of the Idaho batholith (Swanberg and Blackwell, 1973), an alternative explanation is suggested for these lineaments in the northwestern United States (see Fig. D-3). It is inferred that the extreme southern part of the basalt of the Columbia Plateau in the state of Washington lacks a granitic crust and is merely a pile of basalt sitting on top of gabbro (for age of the basalt, see Brown, 1970). Heat flow data also suggest the absence of a granitic crust in the southern part of the Columbia Plateau basalt basin. On the basis of the geochemical evidence, a discontinuity is inferred in north-south trending units of the Idaho batholith at approximately the latitude corresponding with the southern edge of the Boulder batholith and the Washington-Oregon border (Swanberg and Blackwell, 1973; see also Zeitz, et al., 1971).

As summarized in Figure D-3, it is suggested that many of the lineament features and the data previously outlined could be explained by inland positions of a series of Mesozoic trench segments separated by transform faults. According to this hypothesis, the trench would have existed at approximately the site of the Puget Sound area in northern Washington and near the edge of the Klamath Mountains in southern Oregon; however, in southern Washington and northern Oregon the trench would have been offset inland several hundred kilometers, with subsidiary offset of another 100-200 km inland between the Washington-Oregon borders and approximately 47° N. If the granitic rocks were formed by melting along the subduction zone (for example, see Dickinson, 1970), the offset in the granitic rocks, including the Boulder batholith, far to the east of the rest of the Mesozoic batholiths, could be explained by primary offsets in the trench and in the consequent position of the magma generation and would not require subsequent strike-slip faulting. If the emplacement of the batholith led to local spreading because of space problems, then some of the contradictory evidence for offsets along these lineaments could also be explained. Subsequently, near the beginning of the Cenozoic the trench moved to its present position off the Washington and Oregon coast, and the small ocean basin that was left in northwestern Oregon and southwestern Washington was filled by flood basalts. At that time, the Cascade Range was formed at approximately its present position and has been the magmatic front and intrusive focus during the Cenozoic.

THICKNESS OF BATHOLITH

A topic of recent interest with respect to the Boulder batholith is its thickness. Hamilton and Myers (1967) have suggested that the Boulder batholith is rather thin, whereas Klepper et al. (1971) and others have suggested that it is rather thick. Some of our heat-flow data has been used to argue both for a thin and for a thick batholith. We believe that our results presented here cannot be decisive in the argument because, as is discussed in other papers (Roy et al., 1968a; Lachenbruch, 1968, 1970), several explanations relating heat production and depth satisfy the straight line relationship between heat flow and heat production. Using different models of heat production, either thick or thin batholiths could be justified. The ambiguity of depth with respect to the heat flow and heat production data prevent a close determination of the thickness of the batholith.

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