GEOTHERMAL CHARACTERISTICS OF THE COLORADO PLATEAU

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ABSTRACT

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New heat-flow measurements in the Colorado Plateau varying in depth from 400 to 1900 m suggest that the heat flux throughout the region is 1.5 HFU and greater (1 HFU = 41.8 mW/m^2). Along the eastern and southern boundaries of the Plateau, near the San Juan volcanic field and the Mogollon Slope respectively, high heat flows (>2.2 HFU) are observed to intrude 50—100 km into the Plateau. It is believed that the high heat flows are associated with the sources of the volcanics in those areas. In the interior areas of the Plateau, away from the major volcanic phenomena along its boundary (e.g., the Black Mesa—Kaiparowits synclinorium, the Four Corners area, and the Piceance and Uinta basins) heat flows are generally between 1.5 and 1.8 HFU, and appear to be rather uniform over large areas. This uniform heat-flow characteristic over large areas of the interior Plateau suggests the lack of large-scale, widespread, crustal thermal sources as in the Basin and Range or along the Rio Grande rift. It is possible that lithospheric temperatures within the Colorado Plateau were once similar to lithospheric temperatures within the Stable Interior. Present heat-flow differences between the two provinces (~0.4 HFU) may define the temperature change occurring in the lithosphere of the Colorado Plateau over the past 200 m.y. This temperature change may have contributed significantly to the uplifting of the Colorado Plateau by the process of thermal expansion.

REGIONAL GEOLOGY AND GEOPHYSICS

The Colorado Plateau is bordered on the east by the southern Rocky Mountains, on the south by the Datil and White Mountains volcanic fields, on the southwest and the west by the Basin and Range province, and on the north by the Uinta uplift. The Plateau is an elevated block demonstrating regional lithologic continuity and structural stability as compared with other areas of the western United States. Although the principal structures of the Colorado Plateau were defined in Laramide time, the major uplifting of the

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Plateau (1500 m) has occurred since Eocene time (King, 1959; Eardley, 1962).

The landscape of the Colorado Plateau is dominated by flat-lying sedimentary formations, disrupted by a number of monoclinal structures which are commonly the boundaries between the major uplifts and the major basins (Eardley, 1962; Kelley, 1955). The major basins within the Plateau are the Black Mesa, the San Juan, the Piceance, the Uinta, the Kaiparowits, and the Paradox (Fig. 1). The uplifts separating these basins are tectonic in origin, their length generally two to five times their width (Kelley, 1955). Mid-Tertiary laccoliths such as the Henry, La Sal and Abajo mountains are randomly distributed with respect to basins and uplifts (Eardley, 1962; Steven, 1975).

Extensive volcanic fields exist around the periphery of the Plateau. Along

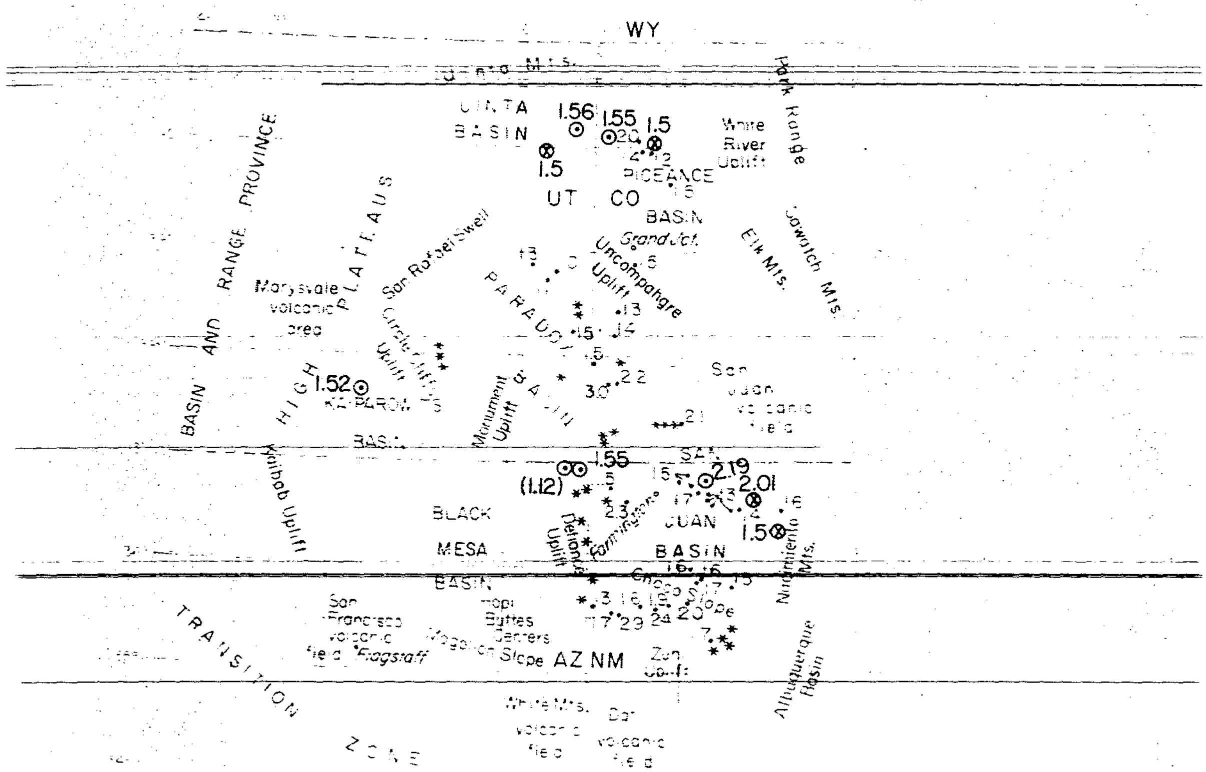

Fig. 1. Major geologic features of the Colorado Plateau, and heat-flow sites. Circled X's indicate heat-flow data sites previously reported where temperature logs were taken to depths greater than 900 m (Monroe and Sass, 1974; Reiter et al., 1975). Circled dots indicate new heat-flow data sites reported in this study. Dots indicate heat-flow data sites previously reported where temperature logs were taken to depths less than 900 m. * indicates volcanic centers.

the southern boundary, volcanic eruptions occurred throughout the Oligocene and in the Pliocene within the Datil and White Mountains volcanic fields (Elston et al., 1970; Ratté et al., 1969). Quaternary basalt flows are widespread along the Mogollon Slope (Hunt, 1956; Wilson et al., 1960). Pliocene to Holocene eruptions are present in the San Francisco centers (Kelley, 1955; Moore and Wolfe, 1976). The Hopi Buttes, a cluster of Pliocene diatremes in the southern part of the Black Mesa Basin, cover about 2000 km^2 (Williams, 1936). To the northeast, on the northern boundary of the San Juan Basin, the immense San Juan volcanic field was active in Oligocene and Miocene—Pliocene times (Lipman et al., 1978). On the eastern edge of the San Juan Basin the immense Valles Caldera has been active in Pleistocene and Holocene times (Doell et al., 1968). Geothermal energy development is proceeding in the Valles Caldera and also on the western side of the Colorado Plateau within the Marysvale volcanic area.

The volcanic activity along the southern part of the Colorado Plateau may explain heat-flow and geomagnetic data. Byerley and Stolt (1977) show a shallow Curie point isotherm for the Mogollon Slope (2—3 km below sea level). High heat flows along the Mogollon Slope are believed to be caused by the sources of the extensive Quaternary basalt flows (Reiter and Shearer, in press). Similarly in the northern part of the San Juan Basin higher heat flows may relate to the sources of the Oligocene and Miocene—Pliocene volcanics in the San Juan field to the north (Lipman et al., 1978; this study). In the interior of the Plateau heat-flow values are generally about 1.6 HFU which suggests a lithospheric thickness in a steady-state conductive regime of about 80—130 km (Reiter et al., 1975; Crough and Thompson, 1976; Chapman and Pollack, 1977).

Seismic studies have been made of the crustal thickness and the P_n velocity of the Colorado Plateau. Refraction data indicate a flat M-discontinuity beneath the Mogollon Slope at a depth of 40 km with an associated P_n velocity of 7.85 km/sec (Warren, 1969). Roller (1965) reported a crustal thickness of 43 km at Chinle, Ariz., and 40 km at Hanksville, Utah, with an associated P_n velocity of 7.8 km/sec. A crustal model for the northern Colorado Plateau based on surface wave dispersion data suggests a crustal thickness of 40 km (Bucher and Smith, 1971).

Gough (1974) reported a high electrical conductivity mantle under the Basin and Range and the Southern Rockies, and a more resistive sub-shield type mantle under the Great Plains. Under the Colorado Plateau he reported the electrical conductivity in the mantle as being of the Great Plains type or between the Great Plains and Basin and Range types.

ANALYSIS OF HEAT-FLOW DATA IN THE COLORADO PLATEAU

There are about 47 previously reported heat-flow measurements in the Colorado Plateau; 42 of these are shown on Fig. 1 in areas discussed in this study. Of these data four measurements have been obtained at sites where

TABLE I

New heat flow data in the Colorado Plateau (experimental procedure for these measurements is presented in Reiter et al., 1975).

Site name	Location	Surface elevation (m)	Depth interval (m)	Temperature gradient (value ± st. dev. in °C/km)
Rangely	14-2N-103W, Colo. 40° 14′N lat 108° 56′W long	1681	1189—1220	34.9 One 30m zone
				Average value for six 30m zones is 15.6 ± 3.1
			1740—1768	15.3 One 28m zone
Red Wash	28-7S-23E Utah 40° 10′N lat 109° 18′W long	1680	1006—1280	Average value for nine 30m zones is 28.2 ± 5.1
Upper Valley	24-36S-1E, Utah 37° 41′N lat 111° 44′W long	2178	660— 820	Average value for eight 20m zones is 27.3 ± 1.4
			820—1380	Average value for twenty-eight 20m zones is 16.1 ± 3.8
Navajo-2	16-41N-30E, Ariz. 36° 58′N lat 109° 09′W long	1556	1280—1402	Average value for four 30m zones is 25.4 ± 2.1
MB 23-11	11-41N-28E, Ariz. 34° 59′N lat 109° 09′W long	1654	1220—1372	Average value for five 30m zones is 19.8 ± 1.3
Com 8	32-31N-8W, N.M. 36° 51′N lat 107° 42′W long	1984	1107—1479	Varies between 54.9 and 27.8 over sixteen 30m zones
			1729—1878	Varies between 39.6 and 37.5 over five 30m zones

* Based on agreement of heat flow between Lewis and Menefee for six test measurements in the San Juan Basin.

Thermal conductivity (value ± st. dev. in mcal/cm-sec-°C)	Formation	Porosity	Anisotropy	Heat flow (HFU)	Best heat flow estimate (HFU)
Average value, two fragment samples is 4.54	Morrison	2% — lab data	24% — Powder vs. cuttings	1.58	1.55
Average value, three core measurements is 10.0 (cores from several hundred km)	Navajo	Core vacuum flooded	Core parallel to heat flow	1.56 ± 0.31	
One core sample — 9.86	Moenkopi	Core vacuum flooded	Core parallel to heat flow	1.51	
Average value, eight composite cuttings samples — 30m each sample — is 5.53 ± 0.60	Green River	6% — from logs	No correction	1.56 ± 0.45	1.56
Average value, three composite cuttings samples — 30m each sample — is 5.22 ± 0.08	Carmel	5% — from logs	No correction	1.43 ± 0.10	1.52
Average value, three core measurements is 10.0 (core from about a hundred km)	Navajo	Core vacuum flooded	Core parallel to heat flow	1.61 ± 0.36	
Average value, four composite cuttings samples — 30m each sample — is 6.09 ± 0.43	Hermosa	6% — from logs in area	No correction	1.55 ± 0.23	1.55
Average value, five cuttings samples — 30m each — is 5.64 ± 0.38	Hermosa	5% — from logs	No correction	1.12 ± 0.15	
Varies between 8.22 and [illegible].75 over sixteen cuttings samples — 30m each sample	Lewis	7% — from logs	14.5% to 3.6%, lab determination	2.15 ± 0.30	2.19
Varies between 6.20 and [illegible].70 over five cuttings samples — 30m each sample	Menefee	15% correction for both porosity and anisotropy *		2.22 ± 0.20	

geothermal gradients were logged to depths greater than 900 m. There are certain locations where deep wells (several km) will be necessary to measure geothermal gradients which are not influenced by ground waters convecting heat. Alternatively, there are also areas where regionally averaged data appear to agree with the deeper data, although gradient measurements to Precambrian would add considerable confidence to the heat-flow data. Precambrian well-bore samples from the Colorado Plateau would allow an estimate of upper crustal radiogenic heat production for the region, data which would relate to a belt of high uranium concentration in northeastern Arizona and southwestern Colorado reported by Silver (1976).

Figure 1 shows the major geologic features of the Colorado Plateau and the heat-flow sites where temperature logs have been made to depths greater than 900 m. In the northern part of the Plateau, the Piceance and Uinta basins may be characterized by heat flows of 1.5—1.6 HFU. New data in the eastern Uinta Basin at Red Wash, and just north of the Piceance Basin at Rangely (Table I, Figs. 1, 2a and 2b), agree with previously reported heat-flow values estimated from temperature logs taken at depths greater than 900 m (Fig. 1). The average of previously reported heat-flow data in the Piceance Basin is 1.54 ± 0.33 HFU (Table II) and agrees with the deeper data. The variation in the data within the Piceance Basin (1.4—2.0 HFU, Table II) doesn't appear to be geologically or volcanically related (Fig. 1); i.e., the variation may result from ground-water or well-bore problems. With the exception of Rangely, all of the data in this region of the Plateau have been estimated from logs taken in Tertiary sediments (Monroe and Sass, 1974; Table I). Although the value at Rangely is consistent with the heat-flow average of 1.5—1.6 HFU for the area, data taken in deeper lithologies at several locations would add confidence to the present analysis.

In the northern part of the Kaiparowits Basin a new site has a heat flow of 1.52 HFU (Table I, Figs. 1 and 2c). The heat-flow estimate was made from temperature logs in the Carmel Formation and Navajo Sandstone (Table I). This value agrees with the data in the northern part of the Colorado Plateau

TABLE II

Heat-flow averages in different basins within the Colorado Plateau. (Data from Spicer, 1964; Costain and Wright, 1973; Decker and Birch, 1974; Monroe and Sass, 1974; Reiter et al., 1975)

Name	No. of sites	Ave. heat flow + st. dev. (HFU)	Variation (HFU)
Piceance	5	1.54 ± 0.33	1.40—2.00
Paradox	9	1.58 ± 0.62	1.01—2.99
Uinta	1	1.5	
N. San Juan	14	1.54 ± 0.29	1.26—2.30
S. San Juan	12	1.82 ± 0.45	1.27—2.94

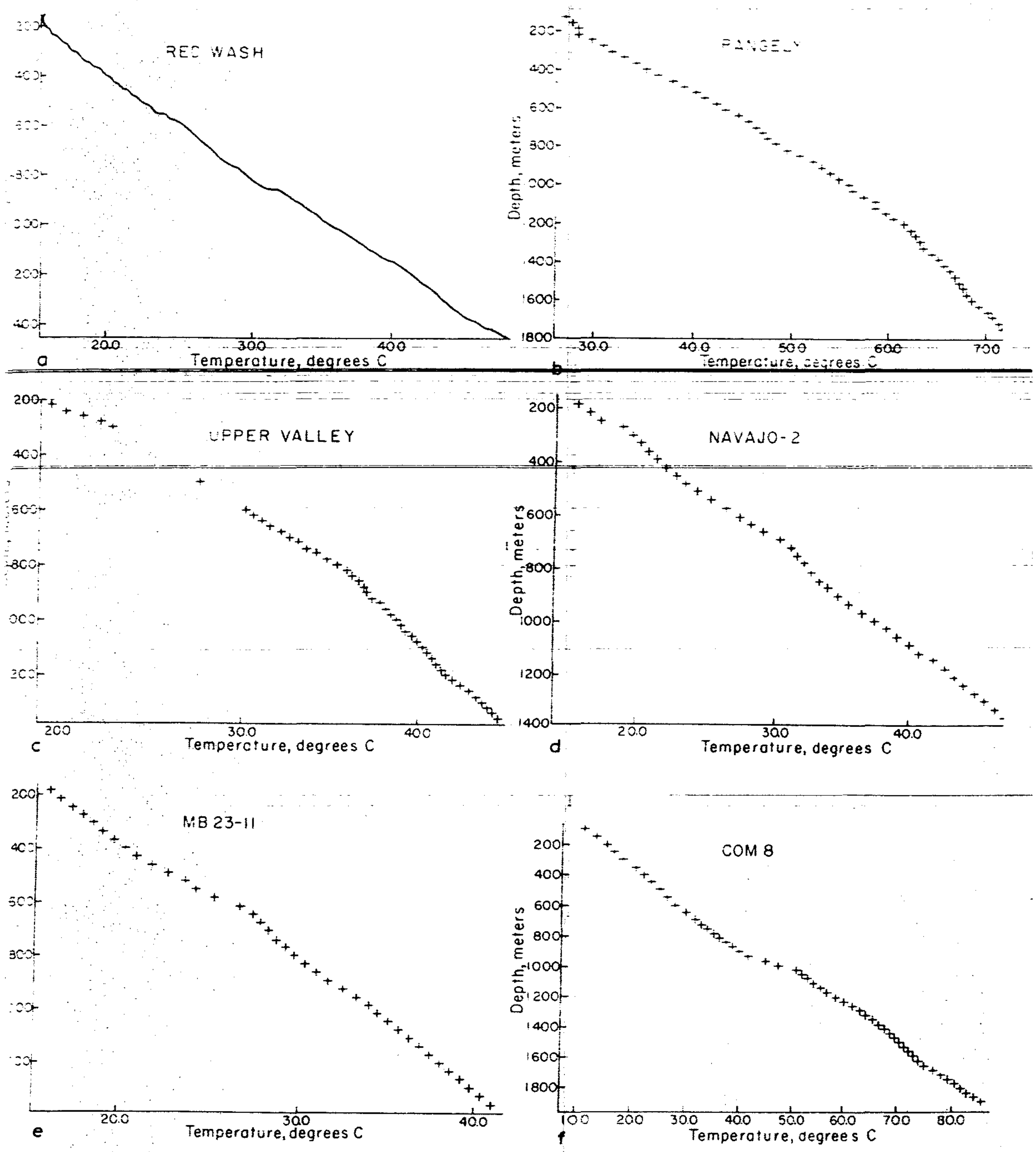

Fig. 2. Depth—temperature profiles measured for heat-flow data sites, this paper. a. Red Wash (continuous line indicates data taken as temperature probe was continuously lowered down well). b. Rangely. c. Upper Valley. d. Navajo-2. e. MB 23-11. f. Com 8.

(above) and with three measurements taken north to south in the Black Mesa Basin which show that the heat flow in that Basin is 1.5—1.8 HFU (Reiter and Shearer, in press).

West of the Four Corners, in the southern part of the Paradox Basin, two new heat-flow measurements have been made (Table I, Figs. 1, 2d and 2e). One of the values is believed geologically representative of the region (1.55 HFU at Navajo-2); the second value (1.12 HFU at MB 23-11) is believed unrepresentative based on present geologic and geophysical data along with new heat-flow measurements in the region (Table I; Reiter and Mansure, in prep.). The measurement (MB 23-11) is an excellent example of data which appear undisturbed but yet provide a heat-flow estimate which is geologically unreasonable (Fig. 2e). The value is estimated from temperature logs in the Hermosa Formation between 1220 and 1372 m, and oil production from the Hermosa Formation over many years is believed to have lowered the conductive thermal gradient in that zone and contributed to the low heat-flow estimate.

In the rest of the Paradox Basin previously reported heat-flow data have an average of 1.58 ± 0.62 HFU (Table II). The average heat flow agrees with the new value of 1.55 HFU in the southernmost part of the Paradox Basin. The variation of previously reported data in this basin (1.0—3.0 HFU, Table II) does not however appear to be geologically or volcanically related (Fig. 1).

In the northern part of the San Juan Basin a new heat-flow estimate at Com 8 from geothermal gradient measurements to 1878 m is 2.19 HFU, and is in approximate agreement with the value of 2.01 HFU at Gobernador (Table I, Figs. 1 and 2f; Sass et al., 1971). A previously reported value at the eastern edge of the Basin (1.5 HFU at Gavilon East; Reiter et al., 1975) may be 0.1—0.3 HFU too low. A trend that heat flows increase northward in the Basin is being demonstrated by detailed heat-flow studies in progress. Heat flows increasing northward in the San Juan Basin may result from thermal sources associated with the widespread Oligocene and Miocene—Pliocene volcanics in the San Juan volcanic field to the north (Lipman et al., 1978). The average of previously reported data in the northern end of the San Juan Basin (1.54 ± 0.29 HFU, Table II) is believed to be too low. The previously reported values are probably influenced by reduced gradients resulting from local recharge and discharge in the temperature-logged Tertiary section, and low thermal conductivity measurements resulting from friable Tertiary lithologic fragments. The new heat-flow data are generally estimated from temperature logs in the Lewis Shale (Table I), believed to be undisturbed by vertical ground-water movement, and from conductivity measurements on samples less friable than those obtained in the Tertiary section. These new data in the northern San Juan Basin suggest the potential for erroneous heat-flow estimates in other areas where data were taken in the Tertiary formations, e.g., the northern Colorado Plateau. The average of reported heat-flow data in the southern part of the San Juan Basin needs to be substantiated with deeper measurements (Table II).

Along the southern boundary of the Colorado Plateau high heat flows are observed in proximity to volcanic activity as they are along the northern part of the San Juan Basin. New data within the Mogollon Slope indicate an extension of high heat-flow values from west-central New Mexico into east-central Arizona which appear to be associated with the sources of the extensive Quaternary basalts along the Mogollon Slope. Values greater than 2.5 HFU in this region suggest partial melting at perhaps 40 km or shallower (Reiter et al., 1975; Chapman and Pollack, 1977; Reiter and Shearer, in press).

Although heat-flow measurements near Flagstaff, Ariz., would be very interesting in light of the extensive Pliocene to Holocene eruptions in the area, it seems improbable that good heat-flow estimates will be possible unless drill tests deeper than ground-water movement are available for temperature gradient measurements. Data taken in the vicinity of Flagstaff suggest almost total elimination of the conductive thermal gradient by ground-water movement (Shearer and Reiter, in prep.). The large amount of precipitation in the area supports the concept of ground water convecting heat vertically with subsequent reduction of conductive geothermal gradients. Drill tests at least several km deep will be necessary for accurate measurements of conductive geothermal gradients.

DISCUSSION

New heat-flow data taken at depths greater than 1 km indicate that large areas of the interior of the Colorado Plateau have heat flows of 1.5—1.6 HFU (this study, excluding data from the northern San Juan Basin). The value of 1.6 HFU is in close agreement with heat-flow data recently obtained in the Black Mesa Basin (1.5—1.8 HFU; Reiter and Shearer, in press) and in the southern part of the Paradox Basin (1.7 HFU; Reiter and Mansure, in prep.). It is also in agreement with previously reported heat-flow data estimated from measurements at depths greater than 900 m for areas in the Colorado Plateau excluding the northern San Juan Basin. The average values of shallow data (measurements from less than 900 m) also agree with the deep data values (greater than 900 m); however, the variation in the shallow data is large and probably geologically and volcanically unrelated. The total variation of deep data in the interior of the Colorado Plateau is about 0.2 HFU. This apparent uniformity of heat flow in the interior of the Colorado Plateau suggests the lack of significant crustal thermal sources such as within the Basin and Range and the Rio Grande rift, and may also suggest a relative uniformity of lithospheric temperatures, asthenospheric thermal properties, and radioactive concentration in the crust. It should be noted that with the deep data coverage, it is difficult as yet to further evaluate the possible variation of heat flows within or between basins, and from basin to uplift (Reiter et al., 1975).

Areas of high heat flow in the Colorado Plateau presently appear to be confined to bordering regions. The high heat flows observed in the northern part of the San Juan Basin are probably related to the sources of the extensive Oligocene and Miocene—Pliocene volcanism within the San Juan volcanic field (Lipman et al., 1978), as are the high heat flows along the Mogollon Slope (Reiter and Shearer, in press).

The present difference between heat-flow values characterizing the Stable Interior of the United States and the Colorado Plateau (~0.4 HFU) indicates different lithospheric temperature distributions in the two regions. (Measurements of crustal radioactivity in both regions are needed to better define lithospheric temperature distributions.) If in the past the temperature distribution in the lithosphere under the Colorado Plateau was the same as that predicted for the present Stable Interior, then subsequent change in lithospheric temperatures may have contributed to the uplift of the Colorado Plateau by means of thermal expansion. One may suggest that higher heat flows over much of the western United States have resulted from over-riding a higher temperature asthenosphere. From the Jurassic (170 m.y. B.P.) to the Cretaceous (100 m.y. B.P.) the movement of the North American continent and lithosphere over this potentially hotter asthenosphere was confined to the tectonically active western United States (Smith et al., 1973). From the Cretaceous to the Tertiary (50 m.y. B.P.) this relative movement involved most of the North American continent and lithosphere. Consideration that the lithosphere of the Plateau has had more time to warm up and to alter asthenospheric thermal phenomena, as well as to encounter new asthenospheric anomalies, may contribute to an understanding of present heat-flow differences between the Colorado Plateau and the Stable Interior. The structural integrity of the Colorado Plateau appears to have prevented significant crustal intrusion of magma as in the Basin and Range and along the Rio Grande rift. Therefore the Colorado Plateau may be an excellent region in which to consider primary thermal phenomena at depth under the western United States.

Assuming a heat flow of 1.2 HFU for the Colorado Plateau 200 m.y. B.P. we may use predicted present steady-state lithospheric temperatures, $T(Z)$, for both the Northern Plains of the Stable Interior and the Colorado Plateau to estimate the temperature change occurring under the Plateau during the past 200 m.y. (Crough and Thompson, 1976; Chapman and Pollack, 1977). Table III gives predicted present temperatures at depth for given depth intervals under the Northern Plains and the Colorado Plateau. Assuming an initial lithospheric thickness for the Colorado Plateau of 140 km (the approximate lower limit predicted for the Northern Plains or the Colorado Plateau; Chapman and Pollack, 1977), and a volumetric thermal expansion confined to the vertical so that the volumetric coefficient of thermal expansion ($\alpha = 3 \cdot 10^{-5}/°C$) may be used to calculate uplift, an uplift of 0.9 km appears possible from thermal expansion (Table III). This uplift may be considered as resulting either from the thermal expansion of a column supported at 140 km, or the isostatic adjustment of a column resulting from density

TABLE III

Comparison of subsurface steady-state temperatures between the Northern Plains (NP) of the Stable Interior and the Colorado Plateau (CP). (Data from Chapman and Pollack, 1977.)

Depth interval (km)	Mid-interval depth (km)	Temperature at mid-interval depth		ΔT (°C)	Interval thickness (km)
		NP (°C)	CP (°C)		
0— 40	20	240	350	110	40
40— 80	60	675	900	225	40
80—140	110	1060	1350	290	60

If an expansion caused by lithospheric reheating under the Colorado Plateau (CP) is volumetrically vertical we may use the coefficient of thermal expansion, $\alpha = 3 \cdot 10^{-5}/°C$, and the above estimated temperature differences between the Northern Plains (NP), and the Colorado Plateau (CP), ΔT, to calculate an uplift. The expansion or uplift for each depth interval is equal to the interval thickness (cm) $\cdot$ ΔT(°C) $\cdot$ $3 \cdot 10^{-5}/°C$, and is:

$40 \cdot 10^5 \cdot 110 \cdot 3 \cdot 10^{-5} = 13{,}200$ cm (first depth interval),

$40 \cdot 10^5 \cdot 225 \cdot 3 \cdot 10^{-5} = 27{,}000$ cm (second depth interval),

$60 \cdot 10^5 \cdot 290 \cdot 3 \cdot 10^{-5} = 52{,}200$ cm (third depth interval).

The total uplift = 92,400 cm = 0.92 km.

changes due to thermal expansion above 140 km; i.e., the expression for isostatic adjustment due to density changes caused by temperature changes is to the first order in $\alpha \cdot T(Z)$ the same as the expression for thermal expansion. Our estimate of the coefficient of thermal expansion may be too large and the expansion may not be completely vertical as suggested. It would appear however, that thermal expansion of the lithosphere should be included with other possible causes of the uplift of the Colorado Plateau. Pratt in the nineteenth century suggested that elevated regions are caused by columns of relatively low density material.

If heat flows have changed from 1.2 to 1.6 HFU over the past 200 m.y., one may wish to consider whether the lithospheric thickness of the Colorado Plateau remained at the postulated 140 km. Surface wave studies have indicated the uncertainty involved in estimating depth to the low velocity zone under the Northern Plains and the Colorado Plateau (Biswas and Knopoff, 1974). Lithospheric temperature models and solidus curves would suggest that the observed difference in heat flow between the Northern Plains and the Colorado Plateau implies a considerably shallower depth to partial melting under the Plateau. Partial melting of the initial lower lithosphere under the Plateau seems reasonable as temperatures increased in time. Uncertainties in the present lithospheric thickness and the boundary conditions at the base of the lithosphere (constant temperature or constant flux or the variation of temperature or flux with time) allow a variety of thermal models.

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