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Edward R. Decker, Gerald J. Bucher, Kenneth L. Buelow, and H. P. Heasler

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PRELIMINARY INTERPRETATION OF HEAT FLOW AND RADIOACTIVITY IN THE RIO GRANDE RIFT ZONE IN CENTRAL AND NORTHERN COLORADO

EDWARD R. DECKER[1], GERALD J. BUCHER[1], KENNETH L. BUELOW, and H. P. HEASLER[2]
[1]Department of Geological Sciences, University of Maine at Orono, Orono, Maine 04469:
[2]Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071

INTRODUCTION

Several values of heat flow have been published for Colorado and adjacent states in the past 15-20 years (Spicer, 1964; Roy et al., 1968a; Decker, 1969; Decker and Birch, 1974; Costain and Wright, 1973; Reiter et al., 1975, 1979; Edwards et al., 1978; Bode11 and Chapman, 1982; Reiter and Mansure, 1983; Sass et al., 1971b), and, as a result, a more complete picture of regional thermal regimes is beginning to emerge. The most obvious feature of present data for the mountains in Colorado is that most of the values are high. There is evidence also for unusually high flux in parts of the Rio Grande rift within the southern Rocky Mountain complex, but interpretation of the thermal regime in the northern rift system is difficult because the number of control points is small. This paper summarizes new heat-flow and radioactivity data for the rift zone in central and northern Colorado, and presents a preliminary interpretation of the results.

Data acquisition, calculation methods, and correction procedures are not discussed herein because they directly followed well-established philosophies and techniques (e.g., Roy et al., 1968a; Sass et al., 1971a, b; Decker, 1973; Birch, 1950). Instead, summaries of completed results are emphasized. Details of unpublished data used in the present study are in an advanced stage of preparation for publication, and will be submitted to a journal in the second half of 1984.

GEOGRAPHY AND GENERALIZED GEOLOGY

Figure 1 shows geography and generalized geology of Colorado and nearby parts of adjacent states. Most of the ranges in the southern Rocky Mountains are elements of late Paleozoic highlands that experienced uplift and erosion during the Laramide orogeny (Tweto, 1975). The Colorado parks are Laramide structural and sedimentary basins that contain significant thicknesses of sediments, the Uncompahgre highland was uplifted in late Tertiary as well as Laramide time, and the La Plata Mountains were the site of Laramide intrusions into Paleozoic sediments (Tweto, 1975). The current physiography of the region is considered to have resulted from uplift and differential erosion in late Tertiary time. Chapin (1979) suggests that the southern Rockies experienced rapid uplift betwen 7 and 4 m.y. ago, and Larson et al.

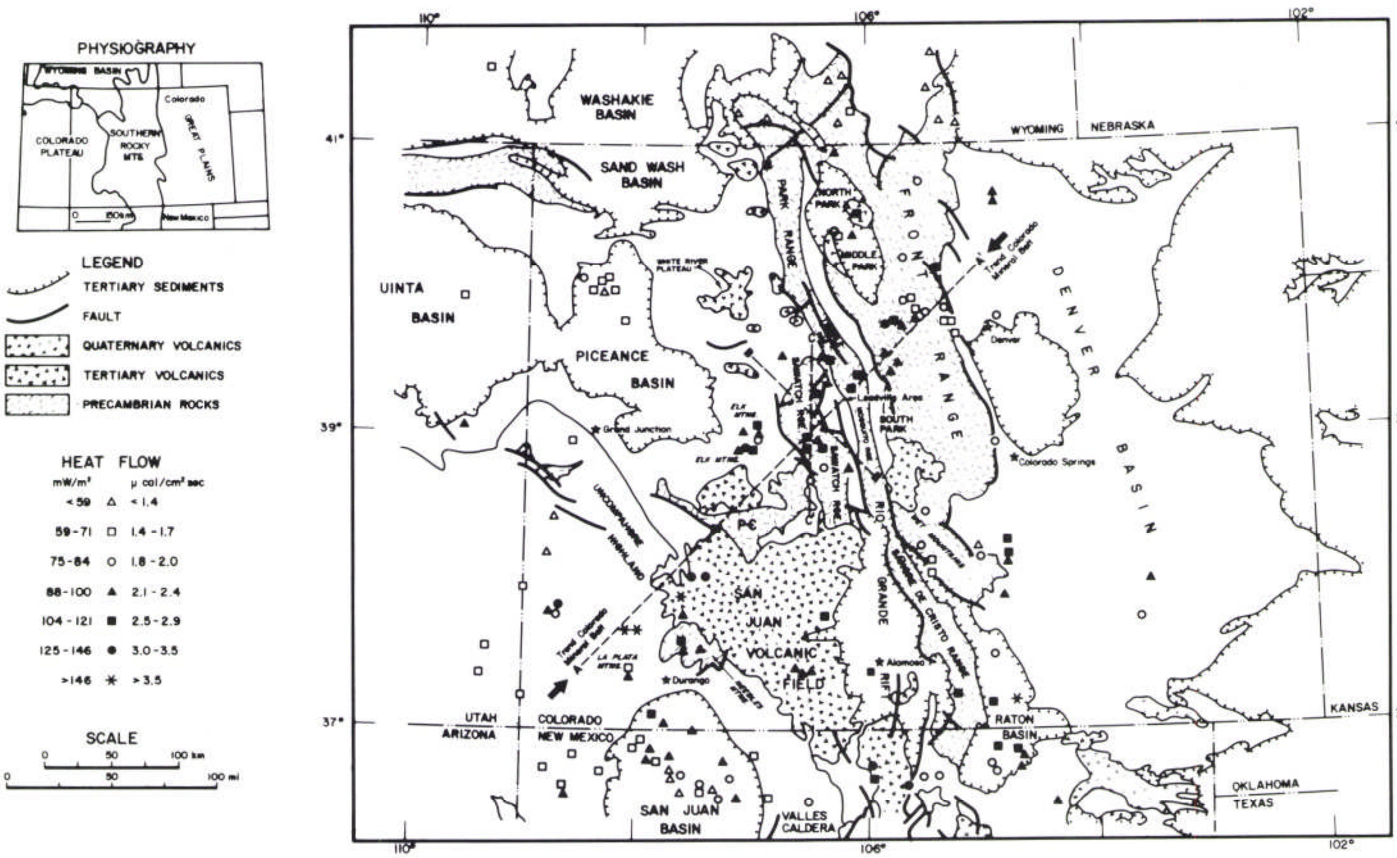

FIGURE 1. Map showing physiographic provinces, geography, generalized geology, and generalized heat flow in Colorado and nearby parts of adjacent states. Heat-flow values after Birch (1950), Spicer (1964), Roy et al. (1968a), Decker (1969), Costain and Wright (1973), Decker and Birch (1974), Sass et al. (1971b), Reiter et al. (1975, 1979), Edwards et al. (1978), Bodell and Chapman (1982), Decker et al. (1980), Buelow (1980), Reiter and Mansure (1983), and Decker et al. (in prep.). Geology after King and Beikman (1974). See Figure 3 for summarized thermal data along lines A–A′ and B–B′, and Figure 5 for summaries of gravity and thermal data near line C–C′.

(1975) find evidence for two periods of rapid uplift of the central and northern Colorado Rockies about 10 my. and 1.5 m.y. ago, respectively. Axelrod and Bailey (1976) suggest that late Tertiary uplift of the rift zone approached about 1.1 km.

Sizable masses of Laramide igneous rocks crop out in the environs of the Colorado Mineral Belt (Fig. I). In Oligocene time, a major volcanic field covered most of the Rockies in southern Colorado and northern New Mexico, and much of the Colorado park areas to the north (Steven, 1975). The youngest (30-25 m.y.) Oligocene volcanism created a large ash-flow field in the San Juan Mountains, and perhaps smaller fields near source areas in the Sawatch Range and the Never Summer Mountains near North Park (Steven, 1975). Miocene and Pliocene extrusive activity in the San Juan Mountains consisted of less voluminous bimodal volcanism (Lipman et al., 1978).

The Rio Grande rift in Colorado developed since latest Oligocene and/or earliest Miocene time (Lipman and Mehnert, 1975; Lipman et al., 1978; Chapin, 1979; Tweto, 1979). Although the main-graben zone ends about 20 km north of Leadville (Chapin, 1979), Tweto (1979) suggests that extension within the rift system reaches northward to areas near the Wyoming border. The rift between Alamosa and Leadville is notable for a near absence of Neogene volcanism in the axial basins (Chapin, 1979). In contrast, Neogene tholeiitic and alkali basalts occur in the environs of the rift south of Alamosa (Lipman and Mehnert, 1975), and Neogene basalts with alkali affinities crop out in the rift system north of Leadville (Larson et al., 1975).

HEAT-FLOW AND RADIOACTIVITY DATA

Generalized heat-flow data in Colorado and nearby parts of bordering states also are plotted in Figure 1. Fourteen of the values in the southern Rockies are from Reiter et al. (1975) and Edwards et al. (1978), and two are from Birch (1950). The other values in the mountains in Colorado and Wyoming were determined by Decker and co-workers (Decker, 1969; Decker and Birch, 1974; Roy et al., 1968a; Decker et al., 1980; Decker et al., in prep.). The new values by Decker and others directly follow basic data for more than 70 holes that were drilled for economic purposes. Ten of these holes are .200 m deep. The other holes are deeper than 250 m.

Several studies (Birch et al., 1968; Roy et al., 1968b, 1972; Lachenbruch, 1968) suggest that data on bedrock radiogenic-heat production are required for reliable regional heat-flow interpretations. Therefore, our research in Colorado and Wyoming focused on combined heat-flow (Q) and heat-production (A) studies in crystalline rocks. The relevant results for stations in the Colorado Rockies are shown in Figure 2. Figure 2 also shows Q—A bands for "normal" portions of the Basin and Range thermal province, and the Battle Mountain, Nevada, heat-flow high (after Lachenbruch and Sass, 1977). The data for two sites in the Front Range (the Adams and Moffat tunnels) are after Q values in Birch (1950); radioelement data for these stations are after analyses in Phair and Gottfried (1964) and Lovering and Goddard (1950). The other values of Q are our determinations (Fig. 1); A values for these stations are based on radioelement (U. Th, K) measurements using gamma-ray spectrometry (for instrumentation see Adams, 1964; Decker, 1973).

DISCUSSION

Figures 1 and 2 contain a large body of new data on heat-flow and radioactive-heat production for the Rio Grande rift system in Colorado. We call attention here to some of the implications of the now available data and briefly discuss their significance in regional thermal regimes.

Regional Heat Flow

Heat flows at seven localities in the Colorado Rockies are in the range 62-71 mW/m2. The much larger number of values that exceed 71 mW/m2confirms earlier suggestions (Decker, 1969; Roy et al., 1972; Reiter et al., 1975,1979; Edwards et al., 1978) that most of the southern Rockies in Colorado are characterized by high flux. From the data available, the mean flux in the Front Range is about 92 mW/m2. The mean of our values in the vicinity of the rift near Leadville is about 113 mW/m2, with a scatter of approximately 4 mW/m2.

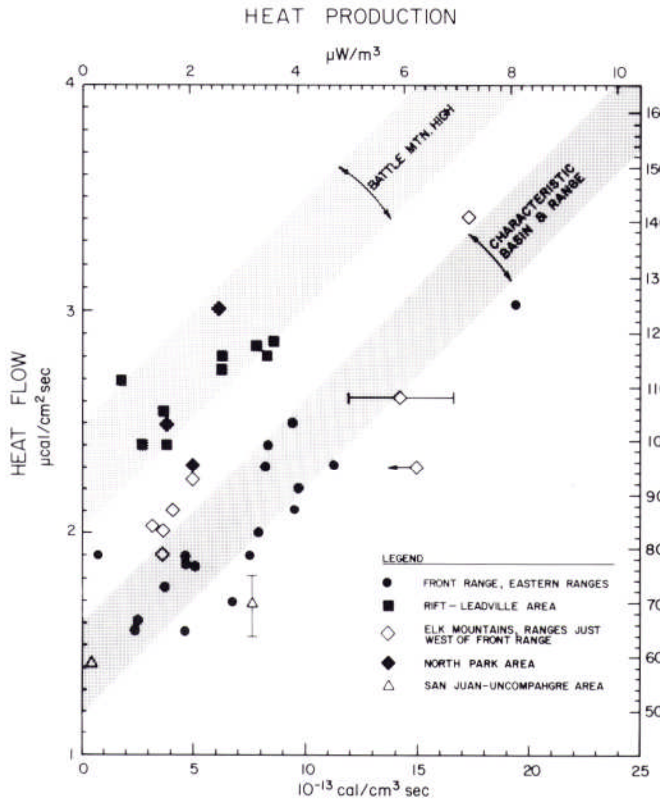

FIGURE 2. Heat flow as a function of near-surface radiogenic-heat production for the Colorado Rockies. See text for references. "Battle Mountain High" and "Characteristic Basin & Range" zones drawn from data in Lachenbruch and Sass (1977).

Heat Flow and Thermal Regime in the Rift near Leadville

The concomitant changes of Q and A in Figure 2 imply that near-surface radioactivity accounts for a substantial fraction of the lateral heat-flow variations in the Colorado Rockies. Additionally, the Q—A data for the Front Range plot near the heat-flow—heat-production band depicted for the Basin and Range thermal province, whereas the data for the rift—Leadville area and the North Park region plot in or near the zone shown for the Battle Mountain area in Nevada. The data therefore suggest that the rift—Leadville and North Park areas arc unusual thermal highs that are bordered by a high heat-flow zone in the Front Range to the east.

The Q—A values for the Front Range determine a line with an intercept of about 54-59 mW/m2, and that for a line through the rift—Leadville area data is about 88 mW/m2. The slopes of the lines are in the range of 7-11 km. The contrasting intercepts imply that the deep flux in the rift near Leadville is unusually high. Thus, profiles of surface and reduced heat flow 1 flux with the variable crustal component removed (after Roy et al., 1972)] were constructed to further investigate the indicated anomaly. The resulting profile parallel to the Mineral Belt shows that the reduced flux in the rift—Leadville area changes from 84—92 mW/m2 to 50-60 mW/m= in the Front Range (Fig. 3b). Similarly, a profile perpendicular to the Mineral Belt indicates a narrow, reduced heat-flow high in the rift zone near Leadville (Fig. 3a). The number of control points west of the Leadville area is small, but reduced values in discordant intrusions in the Elk Mountains (R, P, PI) are 25-21 mW/m= lower than those in the rift zone to the northeast (Fig. 3b). The borders of indicated anomaly near Leadville are only 30-50 km wide (Fig. 3). Therefore, the unusually high reduced flux is likely due to heat sources in the crust.

Crustal-heat sources are also suggested by steady-state geotherms for the rift—Leadville area. For example, calculated equilibrium tempera-

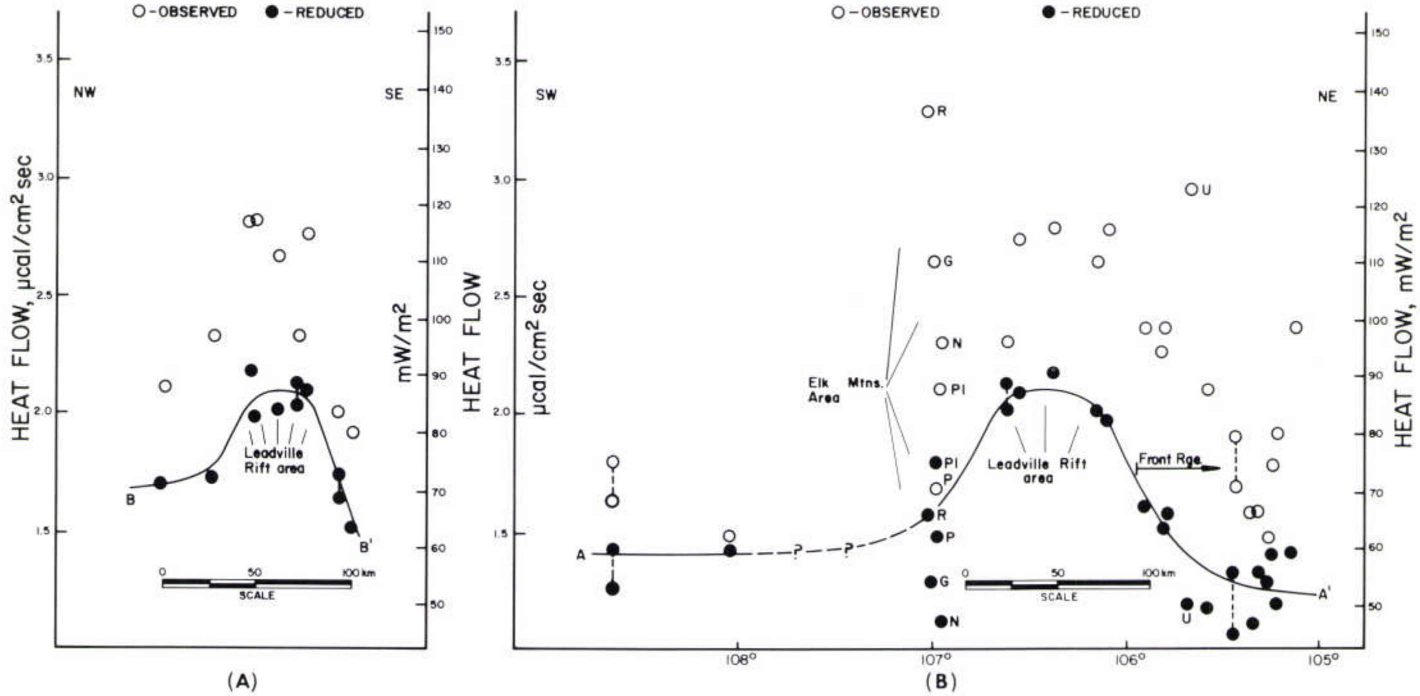

FIGURE 3. Surface and reduced heat-flow profiles parallel (A–A′) and perpendicular (B–B′) to the Colorado Mineral Belt. See Figure 1 for locations of profiles.

tures for the Leadville area exceed the liquidus of dry basalt in the lower 5-10 km of the crust (Fig. 4). Under such conditions there would be widespread melting in the lower crust and upper mantle, and large amounts of basaltic magma could be generated. However, the near absence of synrift volcanics in the Leadville area suggests that the large amounts of basaltic magma implied by the steady-state geotherm probably are not present in the crust. Similarly, P-wave velocities in the upper mantle should be lower than the observed values of 7.9-8.0 km/sec (Prodhel and Pakiser, 1980; Archambeau et al., 1969; Jackson and

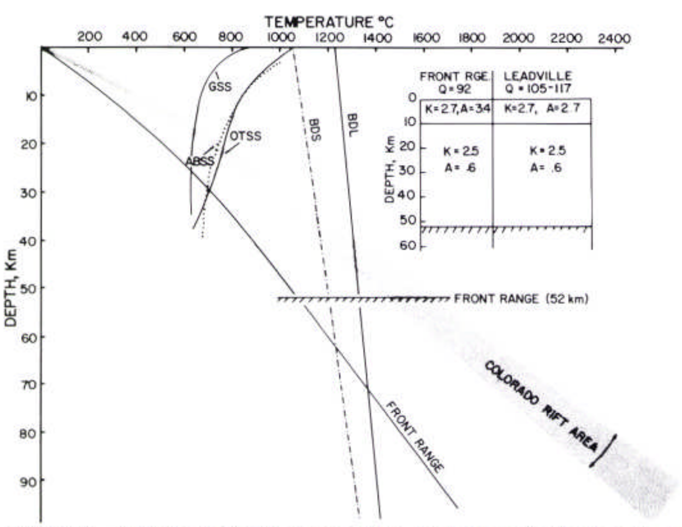

FIGURE 4. Possible steady-state temperature–depth curves for the Front Range and the rift–Leadville area. Crustal thicknesses after Prodhel and Pakiser (1980) indicated by hatching. Mean surface Q and shallow A values are after data summarized in this paper; other model parameters after accepted values used by Roy et al. (1968b), Blackwell (1971), Roy et al. (1972), and Smithson and Decker (1974). Melting curves after Yoder and Tilley (1962), Wyllie (1971), and Lambert and Wyllie (1972): GSS = granodiorite saturated solidus; ABSS = alkali-basalt saturated solidus; OTSS = olivine-tholeiite saturated solidus; BDS = basalt dry solidus; BDL = basalt dry liquidus. Units: heat flow (Q) in mW/m^2; thermal conductivity (K) in W/m°K; radiogenic heat production (A) in $\mu W/m^3$.

Pakiser, 1965), if large volumes of molten material exist near the crust—mantle boundary.

A major Bouguer gravity low is associated with the Mineral Belt—Arkansas Valley area near Leadville (Tweto and Case, 1972; Tweto, 1975, 1979). This anomaly, geologic mapping, and radiometric-age dates indicate that Laramide and Oligocene intrusive rocks are widespread in the underlying upper crust (Pearson et al., 1962; Tweto, 1968, 1975; Cunningham et al., 1977; Tweto and Case, 1972; Isaacson and Smithson, 1976). Additionally, post-Oligocene igneous units crop out as small bodies in the area, thin silicic-felsite and vitrophyre dikes are present in rift-related faults, and numerous rhyolitic pipes with post-Miocene ages(?) occur near Leadville (Tweto, 1979, pers. comm. 1980). Considered together, the Neogene igneous activity, the narrow borders of the thermal anomaly, and the unrealistic inferred equilibrium temperatures for the mantle suggest that the unusual reduced flux in the area arises from non-radiogenic time-dependent heat sources in the crust.

The gravity anomaly and the regional Neogene igneous activity permit speculation that the reduced heat-flow high could be due to temporal conductive effects of young, low-density intrusions in a buried batholith. This is evident from the gravimetrically constrained cooling-intrusion model depicted in Figure 5. From this figure, the surface flux produced by a 5-km-thick intrusion emplaced in the 15-20-km-depth interval between I and 2 m.y. ago closely approximates the heat-flow field based on reduced values projected to the gravity profile (line C—C'in Fig. 1). Buried intrusions with 1-2 my. ages may in turn be consistent with rapid uplift and erosion in central Colorado in the past 1.5 m.y. (Larson et al., 1975).

The model depicted in Figure 5 is artificial and others involving buried intrusions, anomalous radioactivity not indicated in surface rocks, or non-conductive heat sources could be designed. But the data available are not consistent with unusually high radioactivity below the Leadville area. Clearly, models with cooling late Neogene intrusions could be used to explain the gravity low, the heat-flow anomaly, and the uplift history. Alternatively, convective sources might be employed because Neogene faulting, rifting, and intrusions imply young extension in the area. Lachenbruch (1978) shows that steady convection in the lithosphere in tectonically extending regions (e.g., the Basin and Range) can produce very high flux without producing unrealistically high tem-

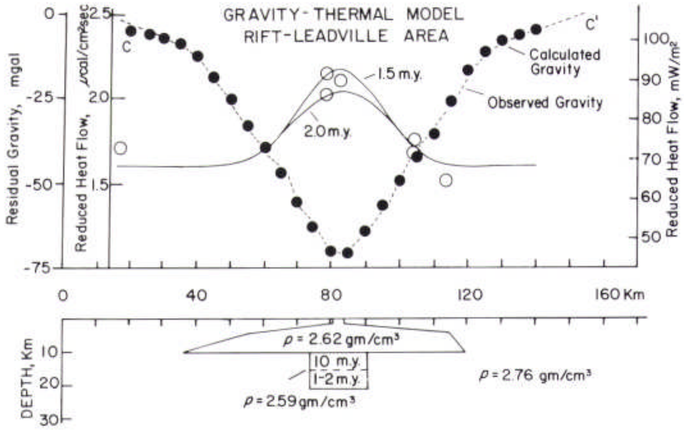

FIGURE 5. Gravimetrically constrained crustal structure—cooling-intrusion model for the rift area near Leadville. Profiles along line C–C′ shown in Figure 1. Gravity after Tweto and Case (1972); two-dimensional modeling used methods of Talwani et al. (1959). Conductive-cooling models with latent heat after Jaeger (1968) and Lachenbruch et al. (1976). Density values from Tweto and Case (1972): Neogene(?) rhyolites = 2.59 gm/cm³; Late Cretaceous–middle Tertiary porphyries = 2.62 gm/c³; Precambrian country rocks = 2.76 gm/cm³. Neogene(?) intrusions implaced in crusts with equilibrium temperatures like those calculated for the Front Range; therefore, the intrusions with latent heat initially were at temperatures of about 700°C (1100°C − 400°C) above those of bordering units in 10–20-km-depth intervals (see Fig. 4).

peratures in the crust or mantle. Although time-dependent, penetrative convection models involving uplift (e.g.. Bode11 and Chapman, 1982; Morgan, 1983) could be used to explain the Leadville area data, it is desirable to confirm the magnitude of the excess reduced flux and fix the widths of the western borders of the anomaly before presenting detailed interpretations.

Northern Rift Zone

Based on regional geology and a 120 mWim2 heat-flow value in the North Park area, Decker et al. (1980) speculated that very high flux occurs in parts of the mountains in northern Colorado, and implied that the northerly borders of the anomaly were narrow (70 km). Reiter et al. (1979) also implied high heat flow for northern Colorado, but their stations (4) in sediments in eastern Colorado and southeastern Wyoming were separated by distances that exceeded 90-100 km.

In Figure 6, available surface and reduced values for northern Colorado and southern Wyoming are projected to a profile along longitude 106°15'W. This plot shows that the surface and reduced heat flows increase from normal to high in a narrow transition zone (50 km) near the Colorado—Wyoming border, followed by very high reduced values in the park areas in the Colorado Rockies immediately to the south. The new evidence for unusually high reduced flux in Middle and North Parks is consistent with conjectures by Tweto (1979) and Decker et al. (1980) that the Rio Grande rift zone extends into extreme northern Colorado.

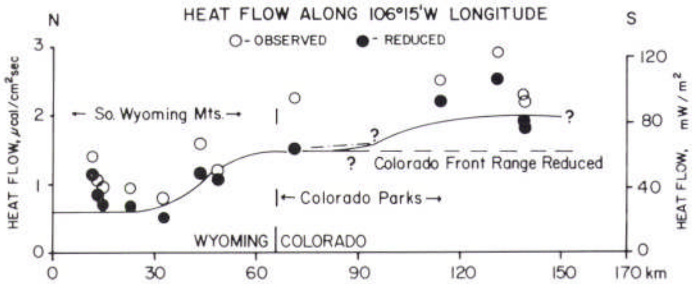

FIGURE 6. Surface and reduced heat flow projected along longitude 106°15′W in northern Colorado and southern Wyoming. Heat-flow values are after Q–A data in Decker et al. (1980) and Buelow (1980).

Buelow (1980) analyzed gravity, flux, and radioactivity data for the park areas in northern Colorado, and suggested that parts of the Bouguer gravity lows and reduced heat-flow highs could be explained by low-density, post-Miocene intrusions in the upper 10-15 km of the crust. Periods of late Cenozoic alkali-basalt volcanism during different time periods (24-20 m.y., 14-9 my., 8-10 m.y., m.y.) in northwestern Colorado (Larson et al., 1975) may be consistent with late Neogene intrusions in the northern park areas, as may be late Miocene (12-7 m.y.) intrusions and extrusions in the Park Range—Elkhead Mountains regions (Tweto, 1979). A low-velocity zone in the upper crust in the Park Range and other mountain areas east of the Front Range (Prodhel and Pakiser, 1980) also may imply low-density, young intrusions and elevated heat flow in the vicinity of Middle and North Parks.

CONCLUDING REMARKS

Combined heat-flow and heat-production data for the Colorado Rockies indicate a large positive heat-flow anomaly in the vicinity of the Rio Grande rift near Leadville, and perhaps in the rift zone in the Middle and North Park areas near the Colorado—Wyoming border. The borders of both anomalies are narrow (50 km) and inferred steady-state geotherms are unusually high; therefore, the excess flux in both areas is considered to be due to heat sources in the upper crust. Because negative Bouguer gravity anomalies and Neogene igneous rocks occur along the Mineral Belt near Leadville and in the park areas in northern Colorado, one reasonable hypothesis is that the unusually high heat-flow zones are partly caused by low-density, young intrusions (<5 m.y.) in the upper crust. This view is consistent with periods of rapid uplift and alkalic magmatism in central and northwestern Colorado in late Miocene and Pleistocene times. High reduced flux along the Colorado rift zone also could arise from convective-heat sources in a tectonically extending crust. However, the rift between Alamosa and Leadville is not characterized by extensive synrift volcanics (Chapin, 1979), alkali basalts in northwestern Colorado probably were derived from mantle below a thick crust (Tweto, 1979), and seismic data for the Leadville—northern park areas do not imply pronounced crustal thinning locally (Prodhel and Pakiser, 1980). Thus, questions arise about the likelihood of appreciable extension and lithospheric convection in the rift zone north of Alamosa. These views do not preclude other heat sources below the rift zone. However, we do not have concrete evidence for enriched crustal radioactivity below the thermally anomalous areas, and nothing in our deep measurements of flux unequivocally confirms widespread hydrothermal circulation in the upper crust in the rift zone in central and northern Colorado.

High regional heat flow in the Colorado Front Range implies near-liquidus equilibrium temperatures in the upper mantle (Fig. 4). Below a developing rift zone to the west, therefore, basaltic magmas from the mantle could rise into the lower crust and produce partial melting. Partial melting of parts of the lower crust might in turn produce rhyolitic magmas that could collect together and rise into the upper crust (Eichelberger, 1978; Eichelberger and Gooley, 1977). A two-stage melting process like this may account for extensive bimodal volcanism in rapidly extending parts of the southern Rio Grande rift and the western Great Basin (Chapin, 1979; Eaton, 1979; Christiansen and Lipman, 1972; Lipman et al., 1971,1972). In contrast, a relatively tight, less-extended rift zone in Colorado north of Alamosa would imply slower ascent of magmas and perhaps encourage solidification within the crust. Furthermore, large Oligocene and older intrusions below the Leadville—northern park areas could have hindered magma ascent. Hence, it does not seem unreasonable that these areas could be underlain by low-density plutons that were trapped in the crust during younger evolution of the rift zone in central and northern Colorado.

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