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HEAT FLOW, RADIOACTIVITY, GRAVITY, AND GEOTHERMAL RESOURCES
IN NORTHERN COLORADO AND SOUTHERN WYOMING

by

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INTRODUCTION

Cooperative Agreement No. DE-FC07-791D1206 between the University of Wyoming and the U.S. Department of Energy involved combined heat flow and bedrock radioactivity studies in the Rocky Mountains in northern Colorado and southern Wyoming. The research was terminated in the summer and fall of 1980, and the results were incorporated into a M.Sc. thesis by K. L. Buelow (1980). This report summarizes the highlights of the studies and briefly alludes to their significance in the geothermal resource potential of the region.

Throughout this report, depths are in meters (m) or kilometers (km), temperatures are in degrees Celcius ($^{\circ}\text{C}$), and thermal gradients are in degrees Celcius per kilometer ($^{\circ}\text{C}/\text{km} = ^{\circ}\text{K}/\text{km}$). The thermal conductivity unit is abbreviated to CDU ($1 \text{ CDU} \times 10^{-3} \text{ cal}/\text{cm s } ^{\circ}\text{C} = 0.4184 \text{ W}/\text{m } ^{\circ}\text{K}$), the heat flow unit to HFU ($1 \text{ HFU} = 1 \times 10^{-6} \text{ cal}/\text{cm}^2 \text{ s} = 41.84 \text{ mW}/\text{m}^2$), and the radiogenic heat generation unit to HGU ($1 \text{ HGU} = 1 \times 10^{-13} \text{ cal}/\text{cm}^3 \text{ s} = 0.4184 \text{ W}/\text{m}^3$). Values of gravity are given in milligals and the density unit is gm/cm^3 . Standard errors ($\pm$) are shown to provide measures of the internal consistencies of the geothermal data.

DATA

Temperature-depth data are plotted in Figs. 1-10. Basic heat flow and radioactivity data for these stations are listed in Tables I and II, respectively. Basic temperature, conductivity and radioelement (U, Th, and K) data were collected and reduced using techniques and procedures described by Decker (1973). The observed heat flow values (q_{UNC}) refer to

the values obtained using uncorrected gradients and measured conductivities. The corrected values of flux (q_{CORR}) are the values that were obtained after the observed temperatures and/or gradients were corrected for the effects of three-dimensional terrain. Birch's (1950) method was used to correct for topography out to a lateral distance equal to twenty times the deepest temperature measurement in each hole. Buelow (1980) discusses details of data acquisition and reduction, and describes the generalized geology near each station. Temperature-depth plots for the holes also can be found in Buelow (1980), as can detailed tabulations of the temperature, conductivity, radioactivity and density data for each locality.

DISCUSSION

Heat flow values and generalized geology in the neighborhood of the Colorado-Wyoming border are shown in Fig. 11. Data are after Table I of this report, Decker (unpublished), Baker (1976), Blackwell (1969), Hallin (1973), Roy et al. (1968), Decker (1966, 1969) and Decker et al. (1980). Combined flux and radioactive heat production data along a north-south profile at 106°15' west longitude are plotted in Fig. 12; data are directly after Table II, Buelow (1980), and Decker et al. (1980).

Fig. 12 shows that the surface and reduced heat flow in the southern Rockies in Wyoming is low to normal, whereas that in the mountains in extreme northern Colorado is high. There is significant scatter in the values in the Park areas in the Colorado Rockies, but the averages of the most reliable surface and reduced heat flows in this region are unusually high (Fig. 12). As depicted in the figure, the transition of flux between the Wyoming Rockies and the Northgate (NGT), Colorado area is less than 50

km wide, as is the transition of flux between the Northgate area and the Park region (JC, PM2, PVM) in Colorado immediately to the south.

Steady-state interpretations of the regional geothermal data imply sub-solidus temperatures in the lower crust and upper mantle beneath the southern Rockies in Wyoming, and near-melting conditions near the crust-mantle boundary in the northern Front Range in Colorado (Fig. 13). In striking contrast, calculated equilibrium temperatures in the Park areas in Colorado imply massive amounts of melting of the lower crust and upper mantle (Fig. 13). There are at least two interpretations of the geothermal studies of the Park areas. First, the unrealistically high calculated temperatures (Fig. 13) suggests that the very flux may be explained by transient conductive or nonconductive heat sources in the subsurface.

Secondly, the heat sources that produce the excess flux must be in the crust because the depicted northern border of the anomaly is narrow (≤ 50 km). Decker et al. (1980) also suggested that this transition was narrow (≤ 75 km) and implied that the high flux could be due to nonsteady conductive or convective heat sources the crust or uppermost mantle.

Buelow (1980) synthesized regional gravity measurements and showed that the Bouguer gravity anomalies increase in a region of transition between Middle Park, Colorado, and the Medicine Bow Mountains in Wyoming. There is evidence also for a seismic low velocity zone in the upper crust in northern Colorado (Prodehl and Pakiser, (1980), and the Park areas and bordering parts of the Colorado Rockies experienced tectonism, igneous activity, uplift, and erosion in the late Cenozoic (Buelow, 1980, pp. 60-68). Thus, one reasonable speculation is that the regional gravity and heat flow anomalies are related to the same geologically-young masses in

the crust. A "preferred" interpretation of regional Bouguer gravity anomalies along 106° 15' longitude is shown in Fig. 14. As implied by the thermal parameters shown in Fig. 12, transient cooling of the low density bodies between 5 and 10 km in the upper crust also would explain the heat flow high in the Park areas, if large tabular masses were implaced about 2 million years ago at intrusion temperatures 600-700° C higher than those of the bordering units (also see Buelow, 1980, p. 76, Table III).

It is clear from the regional map (Fig. 11) that the geology in northern Colorado is complex, and that the associated thermal regime is not well determined because the number of heat flow and radioactivity stations is small. Additionally, the young (<2 million years) igneous rocks in the Basalt Mountain-Flat Top-State Bridge area, the late Miocene volcanics in the Elkhead Field, and the high reduced flux at Hahn's Peak suggests that the unusually high regional flux may not be confined to a simple north-south trending zone (Fig. 11; Larson et al., 1975; Buelow, 1980). Thus, the actual heat flow field could be complex and a likely interpretation is that the area is underlain by a three-dimensional distribution of young intrusions, bedrock radioactivity, and/or nonconductive heat sources. Although such models are appealing, it is desirable to better establish the regional heat flow regime in northern Colorado before pushing the interpretation much beyond the generalized two-dimensional conductive cooling model discussed above.

GEOTHERMAL RESOURCE POTENTIAL

The surface heat flow values in the Sierra Madre-Medicine Bow-Laramie Mountains region are in the range 0.6-1.5 HFU. When the heat from local bedrock radioactivity is considered, the reduced flux in these mountains

low to normal (0.6-1.2 HFU). These data and the low to normal gradients (10-25°C/km) in the studied drill holes strongly suggest that the resource potential of the Southern Rockies in Wyoming is low. The geothermal resource potential of the sedimentary basins in Wyoming that border these mountains also appears to be low because preliminary estimates for the flux in these areas are ≤ 1.5 HFU and the average gradients in analyzed drill holes are generally $\leq 30^\circ\text{C}/\text{km}$.

In contrast to southern Wyoming, the high surface and reduced heat flows strongly suggest that the Park areas and other parts of the Southern Rockies in northern Colorado are potentially valuable geothermal resource areas. The narrow northerly borders (≤ 50 km) of these positive anomalies suggest that some of the resources could be shallow, as does the evidence for regional igneous and tectonic activity in the late Cenozoic. The small number of combined heat flow and radioactivity stations precludes detailed site-specific evaluations in these regions, but the data permit a few generalizations. These generalizations are listed below, where the associated number is thought to provide a measure of the order of ranking of its credibility.

1. The Middle and North Park areas and bordering parts of the Southern Rockies in northern Colorado probably contain areas that are underlain by reservoirs with low-to-moderate temperature hydrothermal fluids adequate for uses in direct-heat applications. The high values of flux and the late Cenozoic igneous activity in the region provide the most compelling evidence for such resources areas. This view is also consistent with hot springs in the Rocky Peak, the Steamboat Springs, the Hot Sulphur Springs, and the Juniper Hot Springs quadrangles in the area (Berry et al.,

1980), and a 42-43°C flowing well at 40°42.1'N, 106°32.1'W near Walden, Colorado in North Park (Hail, 1965, p. 112).

Hail (1965) documents evidence for as much as 2 km of shale and/or shaley units at places in the sedimentary section in the northwestern part of North Park. The thermal conductivity of similar shales and shaley rocks can be low and so high gradients could occur in these units in the Park, if the undisturbed heat flow everywhere in the region is in the range 1.5-2.0 HFU. It is possible, therefore, that low to moderate temperature hydrothermal waters (70-100° C) could occur at the bottoms of the shales in areas where the pre-Quaternary sediments obtain their maximum thickness (approximately 5.1 km [after Hail, 1965]). One implication of this speculation is that future geothermal resource assessments of North Park should analyze heat flux, the subsurface thermal properties, and the configuration and structure of the sedimentary basin.

2. Reservoirs with moderate to high temperature waters adequate for the generation of electricity may exist in the subsurface in some parts of the north and middle Parks, if downward circulating ground waters have accumulated below impermeable rocks in some areas. The unusually high surface and reduced flux in the Park areas is consistent with this generalization, but the regional heat flow regime is not known in detail sufficient to permit location of potential resource areas or to delimit the reservoirs. Perhaps the most favorable areas are in the vicinity of the Basalt Mountain-Flat Top-State Bridge area (Fig. 11), where some of the basaltic volcanic rocks are <2 Myr old (Larson et al., 1975; Buelow, 1980).

3. Moderate-to-high temperature hydrothermal reservoirs could exist at depth in the Rockies in northern Colorado because the border of this

high flux region is narrow (<50 km), and the surface and reduced heat flows in this region exceed those in Wyoming to the north by about 0.8-1.0 HFU. We can not be more specific about this area without more data in the vicinity of the indicated heat flow transition.

4. The high surface and reduced flux in the Rockies in northern Colorado suggest that the Parks in these mountains could be underlain by hot dry rock (HDR) resource areas. The most favorable site for HDR resource development could be in the young volcanic terranes (<2 million years) in the State Bridge-Basalt Mountain-Flat Top regions (Fig. 11). The relatively low rank of this generalization is partly due to the current high risks and high costs of HDR resource development.

In summary, geologic, geothermal, and other geophysical data suggest that potentially valuable hydrothermal and HDR resource areas could exist in the Southern Rocky Mountains in northern Colorado. However, the locations and sizes of "possible" subsurface reservoirs are not known because the regional geology is complex and the heat flow and radioactivity data are sparse.

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Table 1. Summary of Basic Geothermal Data for Drill Holes

Locality	West Longitude	North Latitude	Collar Elev. (meters)	Depth Range	N	K CDU	Grad °C/km		Heat Flow HFU	
							UNC	CORR	qUNC	qCORR
Hahn's Peak (HP)										
DDH-7A	106° 55.4'	40° 50.3'	2987	50-280	66*	6.24* +.06	21.8 +.2	39.2 +.4	1.36 +.02	2.45 +.05
DDH-101			2851	50-330	18	6.09 +.05	37.1 +.2	42.4 +.3	2.29 +.03	2.56 +.04
				330-850	45	6.33 +.03	35.4 +.1	40.1 +.2	2.24 +.03	2.54 +.03
								Best Value		2.54 +.05
Poison Ridge (PR)										
DDH-105	106° 14.9'	40° 19.2'	2994	440-980	67*	5.91* +.09	30.3 +.3	30.1 +.04	1.78 +.04	1.78 +.04
DDH-105	106° 15.1'	40° 29.1'	2937	610-920	67	5.91 +.09	27.3 +.2	26.4 +.1	1.61 +.04	1.56 +.04
								Best Value		1.66 +.10
Parkview Mountain (PM2)										
PV-105	106° 08.0'	40° 19.9'	3475	380-680	26	6.28 +.25	30.3 +.16	36.8 +.6	1.90 +.09	2.32 +.13
Northgate (NGT)										
FS-105	106° 16.6'	40° 55.9'	2609	60-840	64	8.59 +.07	27.0 +.2	26.4 +.2	2.32 +.03	2.27 +.03
Medicine Bow Mountain										
MB-5 (MB1)	106° 13.8'	41° 28.7'	3072	100-330	51	13.26 +.22	7.2 +.1	8.1 +.1	.95 +.06	1.07 +.05
MB-13 (MB2)	106° 21.0'	41° 27.4'	1945	60-170	*	13.56 +.22	7.6 +.1	7.2 +.1	1.03 +.06	.98 +.05

Table 1. Continued

Locality	West Longitude	North Latitude	Collar Elev. (meters)	Depth Range	N	K CDU	Grad °C/km		Heat Flow HFU	
							UNC	CORR	qUNC	qCORR
Sierra Madre SM-11 (SM1)	107° 08.2'	41° 13.3'	2847	64-256	20	6.32	15.2	15.0	.96	.95
						<u>±.25</u>	<u>±.3</u>	<u>±.3</u>	<u>±.06</u>	<u>±.05</u>
SM-8 (SM2)	106° 53.8'	41° 10.7'	2676	60-200	12	8.64	8.3	9.2	.75	.80

Table 2. Radioactivity data for heat flow stations**

Locality	N	U ppm	Th ppm	K ₂ O %	A HGU	qCORR HFU
Hahn's Peak, Co. DDH-7A*	62	2.98 ±.07	7.31 ±.11	6.33 ±.13	4.07 ±.09	
DDH-101	7	8.18 ±.12	7.63 ±.20	3.66 ±.10	3.77 ±.05	2.59 ±.05
	22	2.88 ±.11	7.00 ±.35	7.31 ±.13	4.19 ±.13	
			Best Values		9.06 ±.10	2.54 ±.05
Northgate, Co. FS-105	14	9.89 ±.59	28.01 ±.55	4.22 ±.03	11.4 ±.5	2.27 ±.03
Poison Ridge, Co. AO-105	7	5.67 ±.67	17.79 ±.78	3.49 ±.10	7.07 ±.56	
AO-107	7	3.49 ±.26	15.89 ±1.22	3.39 ±.20	5.90 ±.10	
			Best Values		6.23 ±.45	1.7 ±.1
Parkview Mtn., Co. PV-105	28	3.87 ±.09	13.01 ±.31	3.57 ±.08	5.15	
PV-105	7	3.76 ±.18	12.82 ±.60	3.54 ±.15	5.09	
			Best Values		5.13 ±.20	2.27 ±.10
Medicine Bow Sierra Madre Mtns., WY*	75	1.59 ±1.41	10.0 ±7.8	1.66 ±.96	3.5	

* Radioactivity data are for samples from the same or nearby holes (Decker unpublished).

**Radioactivity data are for samples from the Archean granitic gneisses (Karlstrom and others, in press).

***After Table 2 in Buelow (1980).

Fig. 1. Temperature-depth profile for drill hole DDH-101 in Hahn's Peak, Colorado.

Fig. 2. Temperature-depth profile for drill hole DDH-7A in Hahn's Peak, Colorado.

Fig. 3. Temperature-depth profile for drill hole DDH-105 in Poison Ridge near Rand, Colorado.

Fig. 4. Temperature-depth profile for drill hole DDH-107 in Poison Ridge near Rand, Colorado.

Fig. 5. Temperature-depth profile for drill hole PV-5 in Parkview Mountain near Rand, Colorado.

Fig. 6. Temperature-depth profile for drill hole FS-105 in the Northgate fluorspar mining district, Northgate, Colorado.

Fig. 7. Temperature-depth profile for drill hole MB-5 of Sand Lake, Medicine Bow Mountains, Wyoming.

Fig. 8. Temperature-depth profile for drill hole MB-13 east of Sand Lake, Medicine Bow Mountains, Wyoming.

Fig. 9. Temperature-depth profile for drill hole SM-11 in the Sierra Madre Mountains, Wyoming.

Fig. 10. Temperature-depth profile for drill hole SM-8 in the Sierra Madre Mountains, Wyoming.

Fig. 12. Heat flow data along line A-A' in Fig. 11. Data from Tables I and II, Decker et al. (1980), and Decker (unpublished). Abbreviations: SL = Sand Lake, WY.; AL = Albany, WY.; KS = Keystone, WY.; JCK = Jack Creek, CO.; and NGT = Northgate, CO. (after Decker et al. (1980)). Other abbreviations shown in Table I. HP_p is Hahn's Peak data projected perpendicularly to profile; HP_g is Hahn's Peak data projected to profile according to geology; and CS means complicated geologic structure. Thermal parameters depicted in prisms are for transient cooling models that Buelow (1980) used to explain the heat flow anomalies. After Fig. 16 in Buelow (1980).

Fig. 13. Possible steady-state temperature-depth models for the Laramie Range-eastern Wyoming Basin area, the eastern Front Range, and the North Park region. Temperatures calculated for models depicted in the upper right hand corner of figure. Lined areas represent the range of temperatures using uniform (lower bound) and exponentially decreasing (upper bound) crustal radioactivity for the various models. Values of parameters directly follow surface values or commonly used values (see Roy et al., 1968a, 1972; Lachenbruch, 1968, 1970; Decker et al., 1980). Crustal thicknesses are indicated by hatching; thicknesses are from Prodehl and Pakiser (1980). Solidus and liquidus curves are for granite (rhyolite), tonalite (andesite), and gabbro (olivine tholeiite) from Lambert and Wyllie (1972, 1974), Stern and Wyllie (1973), and Stearn et al. (1975). After Fig. 14 in Buelow (1980).

Fig. 14. Interpretations of regional gravity profile (dashed lines) along line A-A in Fig. 11. The effect of generalized near-surface geology and structure was stripped from the Bouguer gravity anomaly (solid curve) to obtain the regional gravity. Figure and procedures after Buelow (1980, Fig. 19, p. 84-94).