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ANALYSIS OF TERRESTRIAL HEAT-FLOW PROFILES ACROSS THE RIO GRANDE RIFT AND SOUTHERN ROCKY MOUNTAINS IN NORTHERN NEW MEXICO

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INTRODUCTION

The Rio Grande rift within the southern Rocky Mountains complex of northern New Mexico is a tectonically and volcanically active region. The southern Rocky Mountains have been uplifted —1.1 km since middle Miocene time (Axelrod and Bailey, 1976), with most of the uplift occurring between 7 and 4 m.y ago (Chapin, 1979). Within the Rio Grande rift recent bimodal volcanism has been extensive; the Jemez lineament and Taos Plateau have been especially active in the last 5 m.y. (Chapin, 1979; Lipman and Mehnert, 1979). On the eastern periphery of the southern Rocky Mountains in northeastern New Mexico extensive late Tertiary and Quaternary magmatic activity has occurred in the Raton and Las Vegas Basins and in the Capulin and Clayton volcanic fields (Baltz and Bachman, 1956; Gabelman, 1956; Baltz, 1965; Dane and Bachman, 1965; Johnson, 1968; Lipman and others, 1973).

The tectonic and volcanic activity in the rift is often associated with a thinned crust, upwarped mantle, and extensive subsurface magma bodies (e.g. Cordell, 1978; Baldridge, 1979; Keller and others, 1979; Lipman and Mehnert, 1979; Olsen and others, 1979; Rinehart and others, 1979). Based on heat flow, electrical conductivity, gravity, and the elevation profile across the Rio Grande rift, Cordell (1978) suggested the presence of a symmetrical anomalous crustal and upper mantle structure along the axis of the rift. Bridwell (1976) interpreted gravity anomalies in northern New Mexico along 36°N latitude in terms of an intrusion of low-velocity mantle material into an overlying thinned lithosphere across an area 400 km wide (E—W). Thermal models consistent with the gravity data also suggest that anomalous heat sources occur in the crust from 10 to 40 km depth (Bridwell, 1976). The presence of shallow magma bodies, 15-30 km deep, within the rift has been proposed on geochemical, seismic, heat-flow, and gravity data (Lipman, 1969; Sanford and others, 1973; Decker and Smithson, 1975; Cordell, 1976; Reiter and others, 1978). Cook and others (1979) suggested partial melting, or the intrusion of mantle material, at the base of the crust in the southern Rio Grande rift.

As would be expected in a region of tectonic and volcanic activity, the Rio Grande rift—southern Rocky Mountains region has high heat flow (Decker, 1969; Reiter and others, 1975; Edwards and others, 1978; Reiter and others, 1979). Edwards and others (1978) state that the heat-flow pattern across the southern Rocky Mountains suggests more widely distributed and perhaps deeper heat sources than along the Rio Grande rift itself. High heat flow in the rift can be related to elevated geotherms associated with a thinned crust and to crustal magmatic activity. High heat flow in the surrounding uplifted regions may not be as obviously related to magmatic processes. Heat-flow values in the region could also be elevated by ground-water circulation (Reiter and others, 1979; Swanberg, 1979). High radiogenic-heat production can contribute to elevated heat flow, but this does not seem to be a significant anomalous heat source in the Rio Grande rift (Decker and Smithson, 1975; Edwards and others, 1978).

The purpose of this study is to consider heat-flow data across northern New Mexico, and to discuss possible trends in the data and the subsequent implications concerning heat sources in the Rio Grande rift—southern Rocky Mountains region. Heat-flow data are considered in terms of steady-state, finite-difference, Isothermal-step models similar to those models presented by Reiter and Clarkson (1983) and Clarkson (1984). Fundamental parameters in the finite-difference models used to analyze the data are the mean heat flow within regions and the variation in heat flow with distance between regions of different mean heat flows. Isothermal-step models are surely a geometrical and phenomenological simplification of actual subsurface thermal sources; however, such models do allow basic appreciation of subsurface temperature discontinuities which may generate observed heat-flow variations between regions. The time constant for isothermal sources at depths ..30 km is relatively short, and, therefore, steady-state models may be reasonable first-order approximations to "relatively deep" subsurface heat sources. For the models to be considered in association with the northern Rio Grande rift and the San Juan volcanic field, heat-flow values and profile characteristics (half widths) reach about 3/4 of steady-state values 10 m.y. after step initiation, and approximate steady-state values after 20 m.y. (Clarkson and Reiter, unpubl.). As such, steady-state models may be generally consistent with the repeated volcanism in the Espaliola Basin (Manley, 1979), and may suggest heat replenishment in the San Juan volcanic field (Reiter and Clarkson, 1983).

DISCUSSION OF DATA

Heat-flow data across northern New Mexico are shown in Figure 1 along with the geologic localities in which they occur. Possible trends in the data are indicated in Figure 2. Using the data, one may consider various aspects of the heat sources associated with the Rio Grande rift and southern Rocky Mountains in northern New Mexico. If the rift is associated with a relatively deep heat source, such as an unwarping in the mantle, one may expect to see a heat-flow anomaly across the rift having a relatively broad half width (although such an anomaly may be obscured by shallow effects related to ground-water circulation or transient heating associated with shallow magmatic activity). Alternatively, shallow thermal sources will produce heat-flow anomalies having a relatively narrow half width (or high spacial variability).

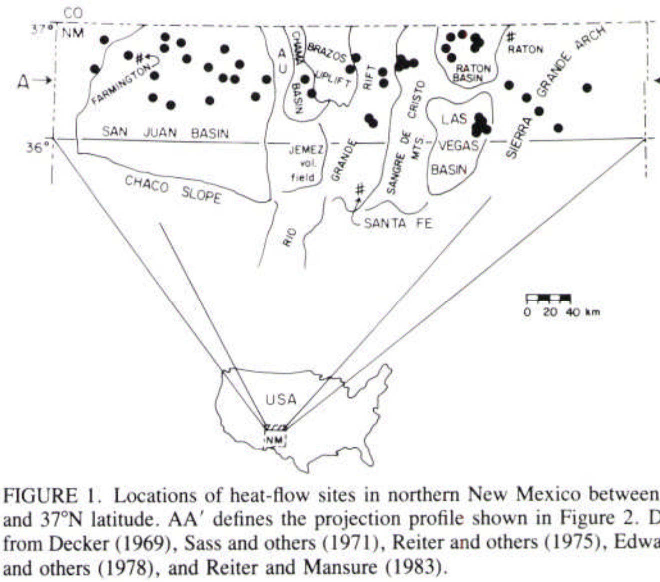

FIGURE 1. Locations of heat-flow sites in northern New Mexico between 36 and 37°N latitude. AA' defines the projection profile shown in Figure 2. Data from Decker (1969), Sass and others (1971), Reiter and others (1975), Edwards and others (1978), and Reiter and Mansure (1983).

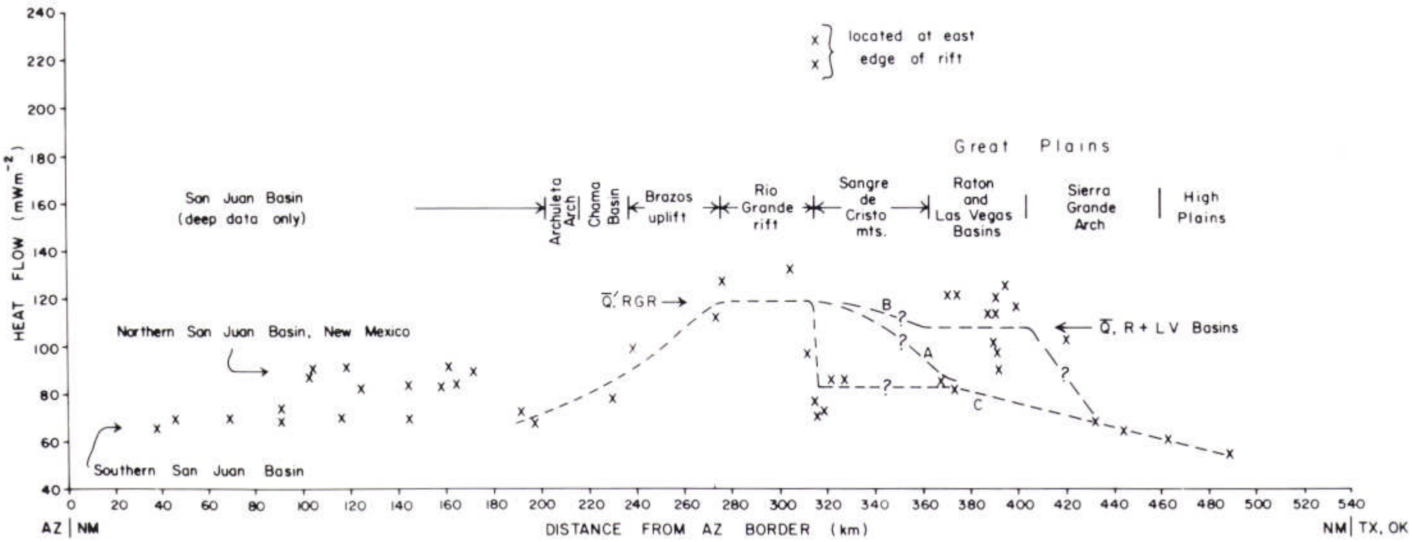

FIGURE 2. Heat-flow data and possible heat-flow trends across northern New Mexico (see Figure 1 for profile projection). Trends A, B, and C, east of the Rio Grande rift, represent various interpretations of the data (see text).

An example of a heat-flow trend in northern New Mexico which is likely to be associated with a relatively deep thermal source is shown in Figure 3a (data and profile locations are shown in Fig. 3b). The data are from heat-flow measurements in the San Juan Mountains and from deep heat-flow measurements in the San Juan Basin. The trend of increasing heat flow toward the San Juan Mountains can be modeled from a steady-state isothermal step rising from —100 km to —30 km depth (Fig. 4) beneath the northern San Juan Basin with the shallow isotherm extending underneath the San Juan Mountains (Reiter and Clarkson, 1983). More complicated models could be employed to explain the observed heat-flow trend; however, the isothermal-step model provides a good fit to the experimental data and allows a basic appreciation of a subsurface-temperature discontinuity which would produce the heat-flow increase approaching the San Juan volcanic field. Although ground-water movement can surely abstract heat-flow profiles by advecting heat from one region to another, the trend of increasing heat flow toward the San Juan volcanic field is believed to represent a basic change in the deep thermal state of the region, i.e. greater mantle and/or magmatic heat. Ground-water movement into the San Juan Basin from the northern and northeastern uplifted regions near the San Juan volcanic field (Stone and others, 1983) may influence the half width of the heat-flow profile; however, such water movement would serve to diminish the magnitude of the heat-flow contrast between the two areas by advecting heat from a warmer to cooler location. If the endpoint heat flows and the profile half width in Figure 4 are representative of conductive heat flow, then the temperature discontinuity or anomaly should be relatively deep as shown (i.e. in the lower crust or upper mantle). This suggestion would be consistent with the crustal low-velocity zone predicted by Prodehl and Pakiser (1980) for the San Juan Mountains region.

The isothermal-step model is not directed toward understanding the phenomena producing the subsurface-temperature discontinuity consistent with observed heat flow, and a discussion of the causes of elevated heat flow in major volcanic fields, rifts, and mountains is not the purpose of this study. The step model may, however, allow some limited speculation concerning the causes of upwarped isotherms. The temperature step shown in Figure 4 could be interpreted as a type of plume or advecting mechanism bringing heat from depth to nearer the surface. This basic idea may be consistent with the geochemical data presented by Lipman and others (1978), who suggest subduction processes may ultimately be involved with the production of the San Juan volcanics. The —1200°C isotherm at —30 km depth (Fig. 4) is approximately consistent with diffusion models, but is about 200-250°C higher than temperatures predicted from models incorporating convective-heat transfer at depth (Lachenbruch and Sass, 1978). Although it would seem quite reasonable that some type of mass-transport process is occurring in association with the elevated isotherm shown in Figure 4, the essence of the heat-flow contrast between the San Juan Basin and the San Juan volcanic field (and the subsurface temperature distribution) is approximated by the isothermal-step model.

A trend similar to that associated with the San Juan Basin—San Juan Mountains trend may be seen in the heat-flow data along a profile from the Rio Grande rift westward to the San Juan Basin (Fig. 2). This trend also appears to reflect a relatively deep heat source. The average heat flow from three values in the northern Rio Grande rift (excluding the two extremely high values at the eastern edge of the rift) is 118 mWm -=. The heat flow decreases to about 70 mWm -2 at the eastern edge of the San Juan Basin, approximately 100 km away from the edge of the Rio Grande rift. The similarity between the San Juan Basin—San Juan Mountains profile and the Rio Grande rift—San Juan Basin profile suggests that the heat-flow data west of the rift in northern New Mexico would also be consistent with a relatively deep heat source (an isothermal step from --86 to —32 km depth; Fig. 5). It must be kept in mind, however, that only a few data points have been used to define this trend and that the data outside the San Juan Basin are from relatively shallow wells where the temperature gradients may be perturbed.

Locally high heat-flow values within the northern Rio Grande rift could certainly be induced by ground-water convection, and should be complemented within the hydrologic framework of the northern rift by low heat-flow values. Regionally high heat flow in the northern rift, complemented by convective heat transport, still reflects anomalous sources of heat such as magmas, a shallow asthenosphere, etc. Although the broad half width of the heat-flow profile from the Rio Grande rift into the San Juan Basin may be influenced by ground-water movement into the basin (which would lower heat flows in the uplifts on the western edge of the rift), the suggested isothermal discontinuity near the northern Rio Grande rift (Fig. 5) is generally consistent with other studies (discussed above) proposing magma sources at rather similar depths. If the 1200°C temperature at 30 km depth, as predicted by the diffusion model, is somewhat high, then mass transport of heat may be occurring in the lower crust and upper mantle along the northern Rio Grande rift.

The heat-flow data from the Rio Grande rift east to the Great Plains are characterized by high spatial variability. Such variability must be due to relatively shallow causes. For example, heat-flow values along the eastern edge of the rift vary from 239 to 71 mWm' (Fig. 2). This variability may well result from ground-water circulation or near-surface magma emplacement along major rift faults (Reiter and others, 1979; Swanberg, 1979). The variability within the Raton and Las Vegas Basins

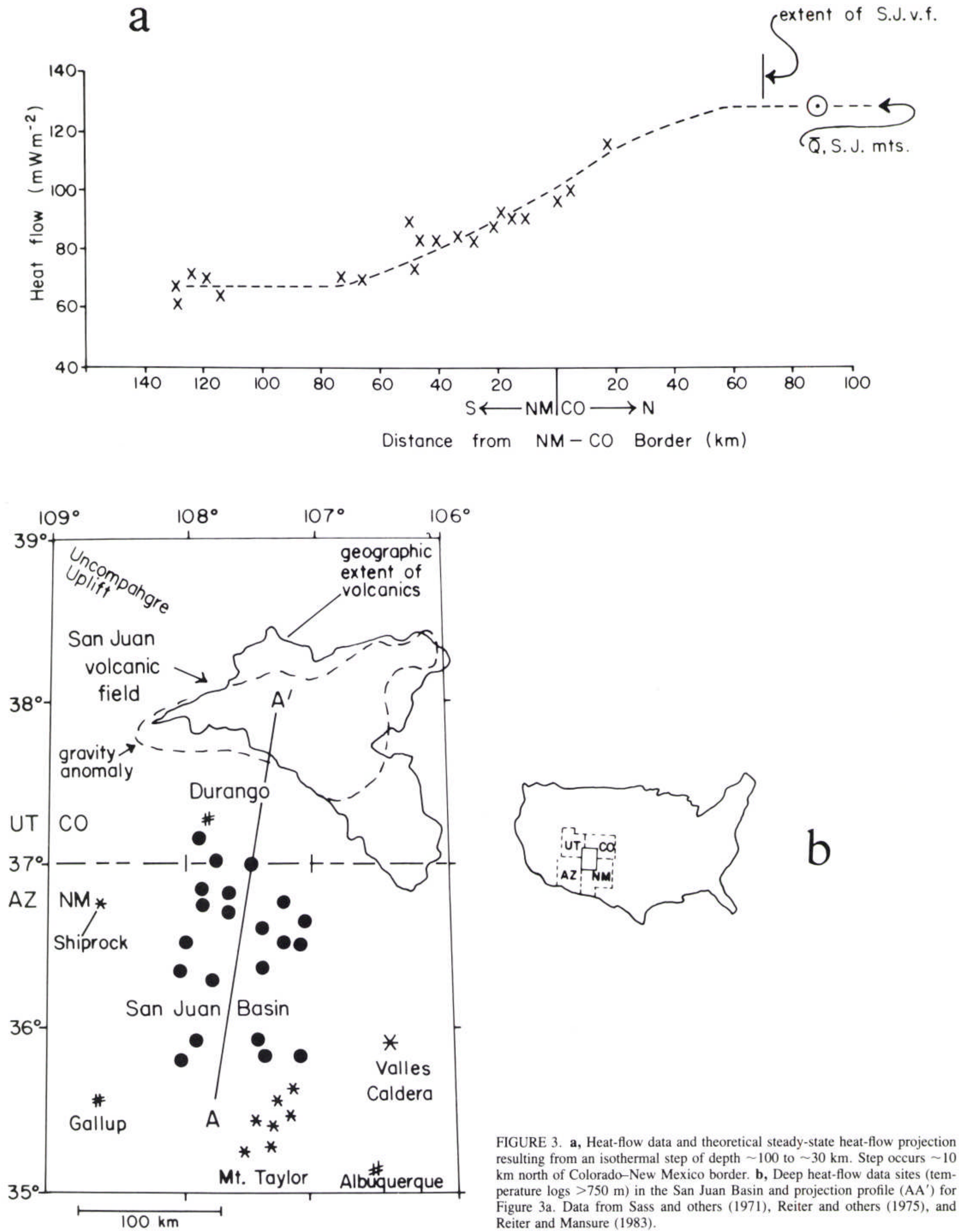

FIGURE 3. **a,** Heat-flow data and theoretical steady-state heat-flow projection resulting from an isothermal step of depth ~100 to ~30 km. Step occurs ~10 km north of Colorado–New Mexico border. **b,** Deep heat-flow data sites (temperature logs >750 m) in the San Juan Basin and projection profile (AA′) for Figure 3a. Data from Sass and others (1971), Reiter and others (1975), and Reiter and Mansure (1983).

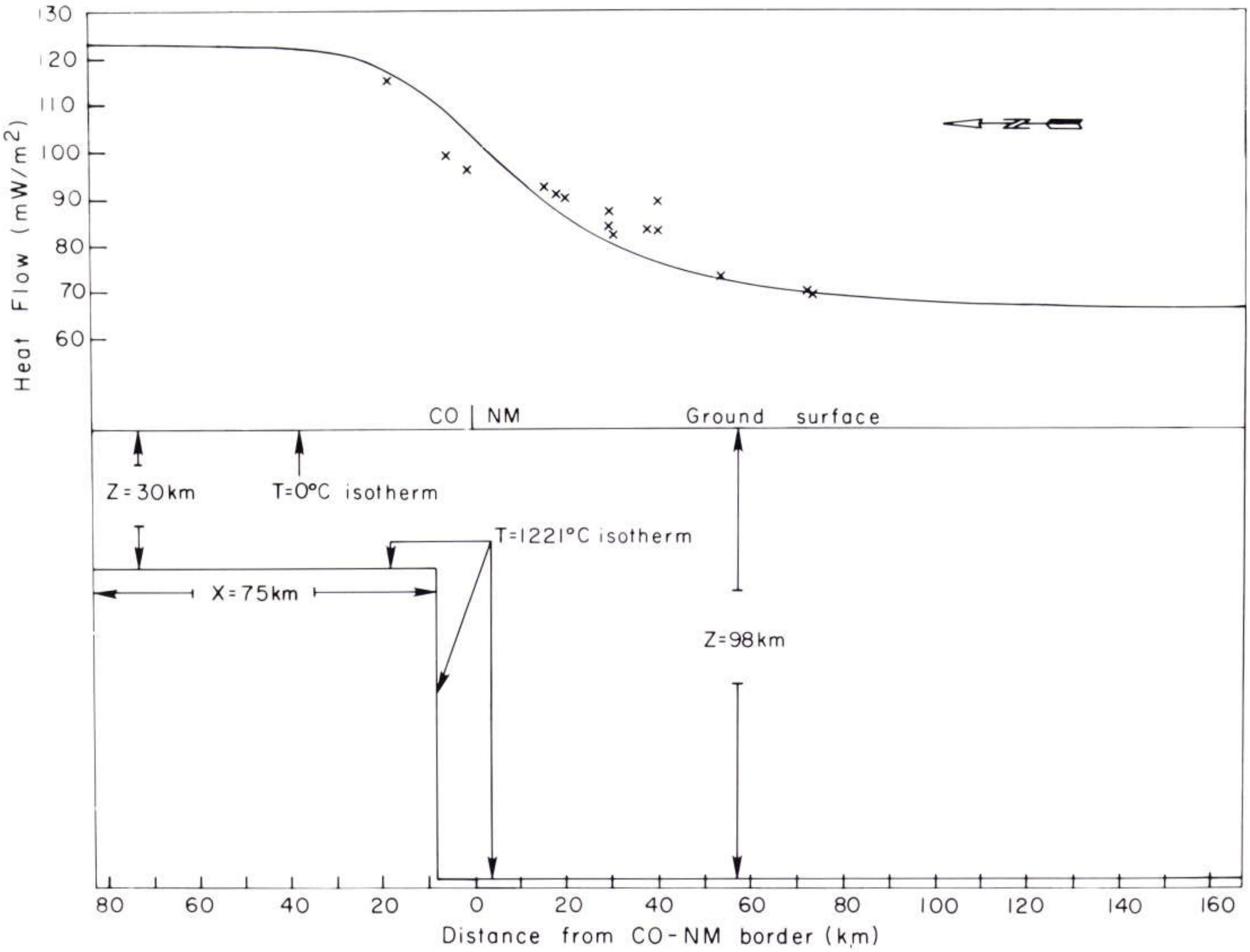

FIGURE 4. Steady-state isothermal-step model for the heat-flow profile approaching the San Juan volcanic field. Experimental data projected onto profile AA' (Fig. 3b) indicated by x, solid line is the calculated heat flow resulting from step isotherm. Endpoint heat flows determined by averaging data in San Juan volcanic field and southern San Juan Basin. Note comments in text concerning 1,221°C isotherm.

could also be associated with similar shallow phenomena. The Raton and Las Vegas Basins have experienced late Tertiary and Quaternary magmatic activity (Baltz and Bachman, 1956; Gabelman, 1956; Baltz, 1965; Johnson, 1968). In addition, the Las Vegas Basin contains a geothermal area, the Montezuma Hot Springs.

Even though the heat-flow data from northeastern New Mexico are highly variable, it may still be possible to discern a broader trend. Two such possibilities are illustrated in Figure 2. Trend A results by considering the two deepest heat-flow measurements (thermal gradients measured to >0.5 km) in the Raton Basin to be representative of the regional heat flux. With this assumption it is possible to suggest a heat-flow profile which may be similar to the Rio Grande rift—San Juan Basin profile, although the eastern profile eventually approaches a lower value of 50 mWm' in the High Plains (as opposed to the 70 mWm' value approached in the San Juan Basin). Taken together, the Rio Grande rift—San Juan Basin and Rio Grande rift—Great Plains heat-flow trends may suggest a fundamental, relatively deep (-30 km) thermal source which underlies the Rio Grande rift and possibly the western part of the Sange de Cristo Mountains and the eastern part of the Brazos uplift (Figs. 1, 2, 5).

A different trend in the heat-flow data across northeastern New Mexico may result if the average of all heat-flow data in the Raton and Las Vegas Basins is representative of the regional heat flux between the southern Rocky Mountains and the High Plains (trend B, Fig. 2). With this assumption a much broader high heat-flow region emerges. This profile would suggest a heat source underlying much of the southern Rocky Mountains, and the Las Vegas and Raton Basins, i.e. the Rio Grande rift, Sangre de Cristo Mountains, and the Raton and Las Vegas Basins. As Edwards and others (1978) stated, the heat-flow pattern across the southern Rocky Mountains suggests more broadly distributed, perhaps deeper sources than along the Rio Grande rift.

CONCLUSIONS

As previously noted by many authors, the Rio Grande rift—southern Rocky Mountains is a region of high heat flow. In particular, very high heat-flow values are found within the rift and within the Raton and Las Vegas Basins. The large variability of values within the rift and the basins suggests that much of the anomalously high heat flow is due to shallow heat sources such as crustal magmatic intrusion and/or ground-water circulation.

Possible trends in the heat-flow data across northern New Mexico suggest some constraints on relatively deep thermal sources; however, it should be noted that the scarcity of data and the potential effects of shallow heat sources and ground-water convection in the region result in ambiguous interpretation of the data. The heat-flow trend between the Rio Grande rift and the San Juan Basin is consistent with an iso-

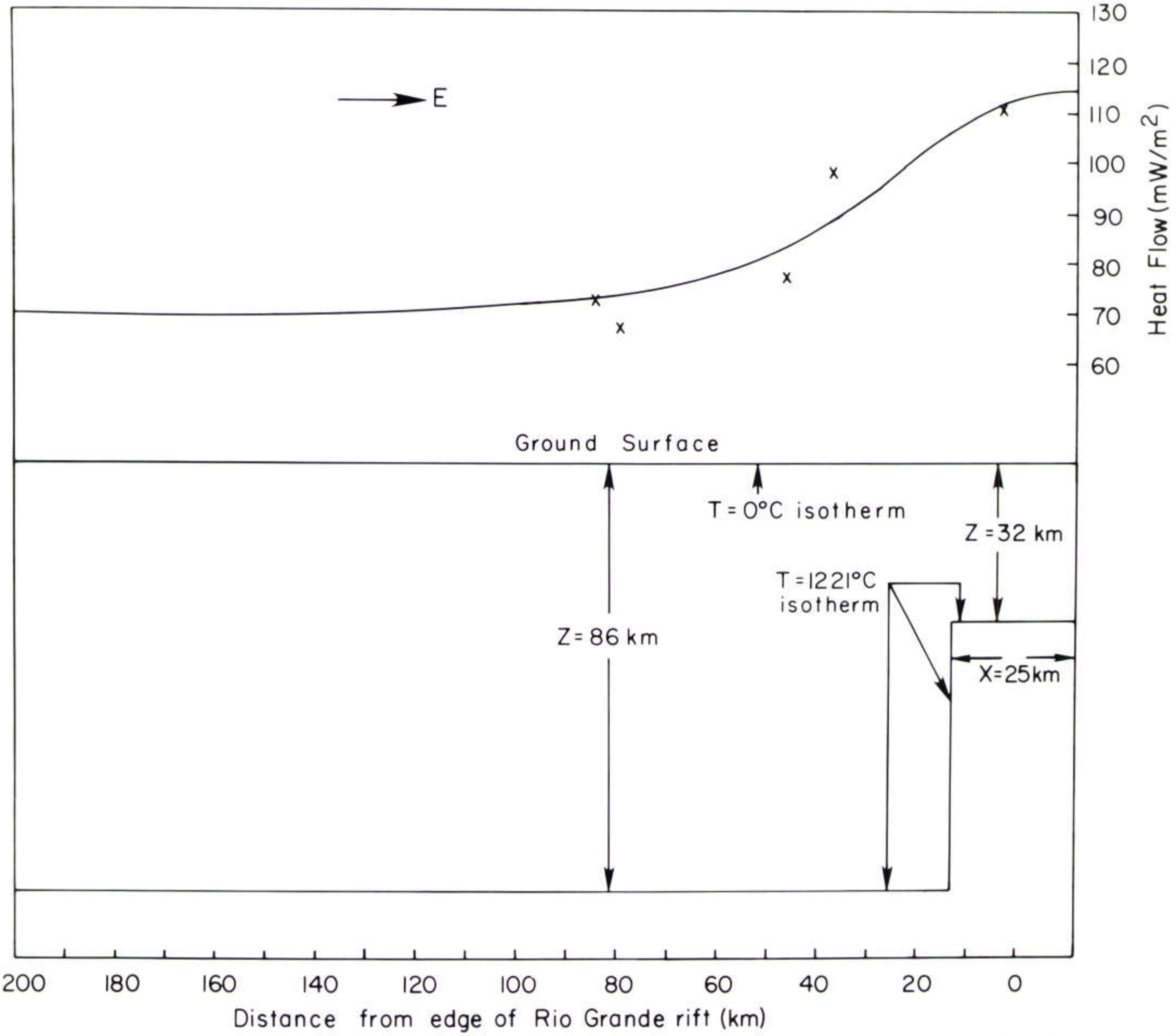

FIGURE 5. Steady-state isothermal-step model for heat-flow profile from northern Rio Grande rift into the San Juan Basin. Experimental data projected onto profile AA′ (Fig. 1) indicated by x, solid line is the calculated heat flow resulting from isothermal step. Rio Grande rift heat flow (endpoint) determined by averaging data (see text). Note comments in text concerning 1,221°C isotherm.

thermal step rising from depths of —90 km to —30 km (Fig. 5) beneath the Rio Grande rift and the eastern part of the Brazos uplift. If such a relatively deep heat source underlies the rift, then its effects may also be present east of the rift, e.g. under the Sangre de Cristo Mountains. A profile of the Rio Grande rift—Great Plains heat flow, which is very similar to the Rio Grande rift—San Juan Basin heat-flow profile, is possible (trend A, Fig. 2); however, a clear trend in the heat-flow data east of the rift is not observed, possibly due to the obscuring effects of shallow thermal phenomena. The heat-flow profile from the San Juan Basin across the rift and into the Great Plains (profile A, Fig. 2, east of the rift) would be consistent with a relatively deep heat source underlying the Rio Grande rift and parts of the uplifts on either side, i.e. the Brazos uplift and the Sangre de Cristo Mountains (Fig. 5).

Another possible trend of the heat-flow data in northeastern New Mexico (trend B, Fig. 2) may suggest a more geographically extensive heat source which reaches beneath the region of the Raton and Las Vegas Basins as well as the Rio Grande rift and Sangre de Cristo Mountains. However, the sharp drop-off in the observed heat-flow profile between the Raton and Las Vegas Basins and the High Plains—Sierra Grande arch (--25 km) is inconsistent with a relatively deep steady-state heat source in this region. A gradual increase of heat flow from the High Plains—Sierra Grande arch to the Raton and Las Vegas Basins (trend C, Fig. 2) suggests a thinning of the lithosphere approaching the southern Rocky Mountains. Caner and others (1967) and Reitzel and others (1970) have suggested increased electrical conductivity in the mantle going from the Great Plains to the southern Rockies; this would complement the observed heat-flow trend.

In summary, the observed heat flow across northern New Mexico is consistent with the existence of both relatively shallow (crustal) heat sources within the Rio Grande rift (which may result from magmatic intrusion and/or ground-water circulation) and with a relatively deep heat source underlying the Rio Grande rift and part of the surrounding uplifts (Figs. 2, 5). As such the heat-flow profile in northern New Mexico may reflect the effects associated with both the Rio Grande rift and the southern Rocky Mountains. However, additional heat-flow data will be needed in order to accurately define trends associated with relatively deep heat sources.

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