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HEAT FLOW AND THERMAL PROCESSES IN THE JORNADA DEL MUERTO, NEW MEXICO
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Most heat-flow data in rifts are uncertain largely because of hydrologic disturbances in regions of extensive fracturing. Estimates of heat flow in deep petroleum tests within a large basin of the Rio Grande rift, which has suffered little syn-rift fracturing, may begin to provide clearer insight into the relationships between high heat flow and crustal thinning processes. The Jornada del Muerto is a large basin located in the Rio Grande rift of south-central New Mexico. The region of interest within the Jornada del Muerto is centered about 30 km east of the town of Truth or Consequences, and is approximately 60 km north-south by 30 km east-west (Figures 1a, 1b). High heat flows are estimated for the region (1; Figure 1b). Values increase from about 90 mWm⁻² in the northern part of the study area to about 125 mWm⁻² in the southern part. These high heat flows are rather enigmatic because in the immediate vicinities of the sites there is little evidence of Cenozoic volcanism or syn-rift extensional tectonics.

Young basaltic volcanics (~2-3 Ma; 2) are present at distances of 10-20 km east of the high-flow sites. Even though geothermal anomalies are quite unlikely to be caused by magma conduits at such distances, it is possible that information obtained from the volcanics can be related to the heat-flow data. Although most of the basalts along the Rio Grande rift appear to have risen quickly through the crust (3), some of the basalts at the western edge of the Jornada del Muerto show a modest amount of differentiation (4). This is consistent with, but not definitive of, lower crustal holding chambers. The geochemical data from the basalts implies a moho depth of about 31 km, a geothermal gradient of about 31°C/km, and a temperature of ~900°C at 30 km (4). From these data one may estimate a steady-state heat flow of ~96 mWm⁻² (4; 5). This estimate assumes a crustal radiogenic layer having an exponentially decreasing radiogenic concentration with depth. The value of 96 mWm⁻² is in close agreement with the average heat flow at the four northern sites in the study area and with the average heat flow estimated over much of the southern Rio Grande rift in New Mexico (~95 mWm⁻²; 1; 5). Moho depths of ~31 km for the area (as estimated from the geochemical data) are in good agreement with estimates based upon seismic data (27-33 km; 6; 7; 8).

Figure 2 presents a geologic cross section through the Jornada del Muerto and adjoining areas. The location of the profile is shown by AA' in Figure 1b. The upper crustal section across the Jornada del Muerto is depicted as a synclinal structure, a remnant of pre-rift (probably Laramide) compression throughout the region (9). As such, there is little evidence of extensional tectonics which might be expected in a Cenozoic rift having a thin crust as discussed in the above paragraph. Consequently, the probable crustal thinning in the region is suggested to occur in the lower (non-elastic) crust.

Lachenbruch and Sass (10) examine in detail possible heat-flow increases resulting from the steady-state stretching, underplating, and intrusion of the lithosphere. Cook and co-workers (6) suggest several massive intrusions of the lower crust during rifting in the southern Rio Grande rift to explain the "regional" heat flow of ~95 mWm⁻². A somewhat different model relating to the high heat flow across the Jornada del Muerto will be discussed here. One may approximate the change in surface heat flow due to crustal thinning as,

$$\Delta Q_s = \Delta Q_m \quad (1)$$

where ΔQ_s is the change in surface heat flow and ΔQ_m is the change in mantle heat flow. Although a specific mechanism for crustal thinning is not proposed, the fact that the radiogenic crustal layer is not included in equation (1) implies that crustal thinning is occurring only in the lower crust (below

the radiogenic layer). This is consistent with the suggestion that crustal thinning has likely occurred below the elastic layer as concluded above from geologic data. If moho temperatures remain constant during crustal thinning then it follows that,

$$\Delta Q_s = \Delta Q_m = [(Z_i - Z_p)/Z_p] \times Q_{mi} \quad (2),$$

where Z_i is the initial crustal thickness, Z_p is the present crustal thickness, and Q_{mi} is the mantle heat flow before crustal thinning.

From equation (2) it may be noticed that estimates of crustal thicknesses both before crustal thinning, and at present, are required to calculate the resulting heat-flow increase. A pre-rift crustal thickness of 40-50 km may be a reasonable estimate based upon crustal thicknesses in nearby, less geologically disturbed areas; e.g. ~40 km in the Colorado Plateau and ~50 km in the Great Plains (11; 12). Present estimates of crustal thickness in the southern Rio Grande rift and in the Jornada del Muerto vary between 33 and 27 km, with the likelihood of a decrease in the depth of the moho going southward (6; 7; 8; 13). Therefore, one may estimate the regional crustal thinning across the Jornada del Muerto as ~33% ((45-30) km/45 km); although considerable uncertainty is present in this estimate.

Figure 3 shows the increase in heat flow with percent crustal thinning for the above model (using equation 2); 33% crustal thinning across the region would increase the heat flow ~24 mWm⁻². If a pre-rift heat flow of 67 mWm⁻² is hypothesized then crustal thinning of ~36% would generate the mean heat flow for the 4 northern sites in the Jornada del Muerto (95 mWm⁻², Figure 1b). (Note that 67 mWm⁻² is the approximate mean heat flow in the Colorado Plateau of New Mexico, a value that could be obtained by the thinning of a lithosphere initially similar to that in the Great Plains; 14; 15). The heat-flow anomaly resulting from a temperature increase maintained over time at 30 km is 84% realized after ~7 my. Therefore, if rifting started 32-27 Ma (16) one may anticipate that the heat-flow anomaly has been appreciably realized (even though the rifting is probably episodic). Recent volcanism in the western part of the Jornada del Muerto, at ~10-20 km distance from the heat-flow sites, is consistent with maintaining elevated mantle temperatures as required by the above model.

Consider now the pattern of heat flow in the Jornada del Muerto (Figure 1b). It would appear that in general the heat flow increases from north to south. This first order pattern is consistent with the suggestion that the moho becomes shallower going southward along the Rio Grande rift (13). The observed increase in heat flow could be generated by increased crustal thinning and/or by different levels of magma intrusion into the lower crust. We may separate the heat-flow data into 3 regions with values of ~90 mWm⁻² in the north, 98 mWm⁻² in the central area, and 125 mWm⁻² in the south of the Jornada del Muerto (Figure 1b). The crustal thinning required to generate the respective non-radiogenic anomalies would be 32%, 39%, and ~55% (Figure 3). This would require present day crustal thickness of ~31, 28, and 20 km if the pre-rift crustal thickness was ~45 km. Values for crustal thicknesses of 33-27 km would be consistent with seismic interpretations as discussed above; however, a crustal thickness of 20 km is beyond present expectations. As such, the crustal thinning model as presented is consistent with heat-flow data in the northern and central regions of the Jornada del Muerto, but does not fully explain the values of ~125 mWm⁻² in the southern region.

Morgan and co-workers (17) present a very interesting model in which southward ground-water flow along the Rio Grande rift is constrained between various basins to move upward, thereby elevating geothermal gradients. This model is likely to explain high heat flows at many areas along the Rio Grande rift; but in the southern part of the Jornada del Muerto it is suspected that

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non-hydrologic phenomena are causing the elevated heat flows. Firstly, the deepest BHT data at the southernmost site is at great depth (3,556 m; 1) and is near or within Precambrian rocks; therefore, very little temperature effect from upward ground-water movement might be expected. Secondly, the elevation of the Precambrian surface deepens N to S along the Jornada del Muerto, and further deepens south of the heat-flow sites (18; 19). Therefore, boundaries in the southern part of the study area which could cause deep ground-water flow to be directed toward the surface, and thereby elevate near surface heat flows, are unexpected.

As mentioned above, models of regional crustal thinning and/or massive lower crustal intrusions generate thermal anomalies that could cause a "regional" heat flow of $\sim 95 \text{ mWm}^{-2}$ for the area; however, one must look further to attempt to understand the heat-flow values of $\sim 125 \text{ mWm}^{-2}$. Consider the projection of the heat-flow estimates in the Jornada del Muerto on a N-S profile along 107° W long (Figures 1b, 4). The interpretation of the heat-flow change from ~ 90 to $\sim 124 \text{ mWm}^{-2}$ indicates a half width of ~ 6 km (determined from the $1/4$ and $3/4$ amplitude points of the anomaly). Alternative interpretations of the heat-flow increase (Figures 1b, 4) yield half widths of ~ 6 to ~ 11 km (although the distance between the sites having 98 and 127 mWm^{-2} implies a half width of $< \sim 5-6$ km; Figure 1b). If one assumes (only as an approximation) that a simple steady-state temperature step causes the increase in heat flow within the southern part of the study area, then a first-order estimate to the depth of the temperature step would be $\sim 5-11$ km. Temperature gradients at the heat-flow sites with higher values are $\sim 40^{\circ}\text{C}/\text{km}$ (1). These gradients are likely to become somewhat greater in the Precambrian upper crustal rocks because the high thermal conductivity of the largely limestone-dolomite sedimentary section would tend to create a lower gradient for a given heat flow. The mean gradient in the upper 10 km may be closer to $\sim 45^{\circ}\text{C}/\text{km}$ (this estimate considers the decrease in crustal radiogenic concentration with depth). Consequently, temperatures of $\sim 245^{\circ}\text{C}$ to $\sim 515^{\circ}\text{C}$ may be expected at depths of 5-11 km (including 20°C surface temperature). These temperatures are reasonable in terms of steady-state conduction or steady-state extensional models (e.g. 10; although the present estimates are slightly less, in part because of the upper ~ 3 km of high thermal conductivity material). The importance of the temperature estimates at 5-11 km is that they exceed, or are in the range of, temperatures suggested to demarcate elastic behavior in crustal rocks (i.e. beyond $250^{\circ}\text{C}-450^{\circ}\text{C}$ crustal materials no longer behave elastically; 20). It is therefore suggested that the geothermal anomaly in the southern Jornada del Muerto ($\sim 125-\sim 95 \text{ mWm}^{-2}$) results from some type of mass movement-heat transfer mechanism operating in the crust just below the elastic layer. This conclusion is consistent with the geologic and geophysical data which describe a thin crust, apparently devoid of features indicative of extensional-tectonics in the upper part of the elastic crust.

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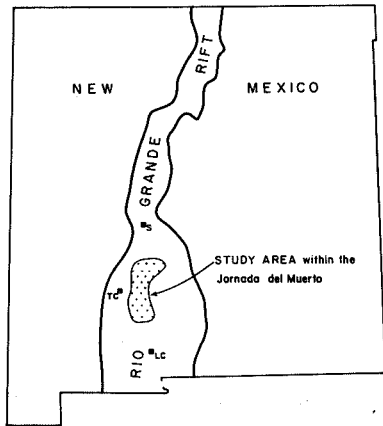


Figure 1a. Location map, S-Socorro, TC-Truth or Consequences, LC-Las Cruces.

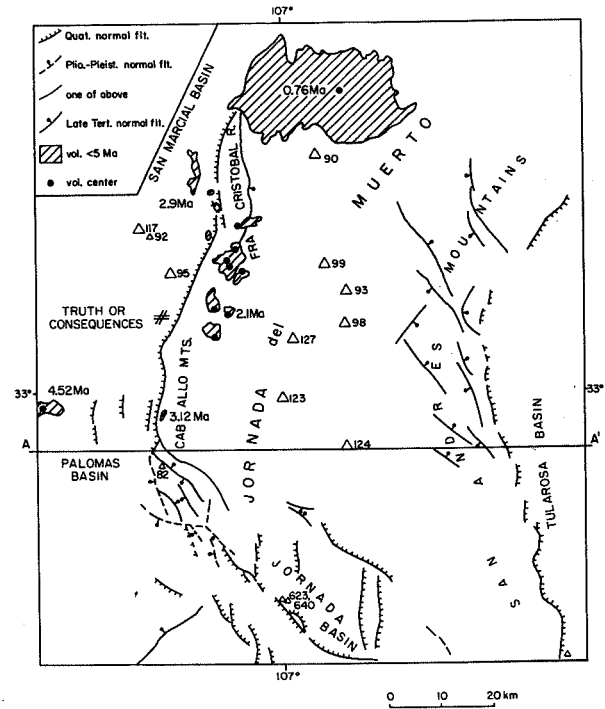


Figure 1b (right). Study area, map after (2). Heat-flow estimates and measurements (large and small triangles respectively) in mWm^{-2} (1).

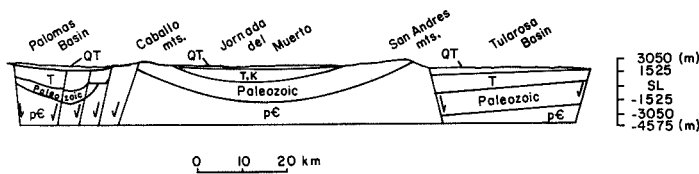


Figure 2 (left). Geologic cross section through the Jornada del Muerto, after (21).

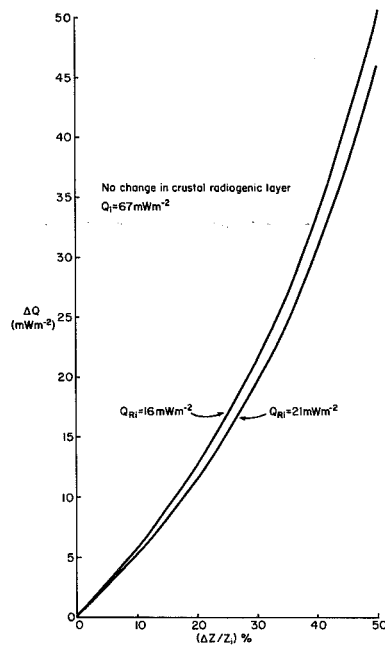


Figure 3. Heat-flow increase with % crustal thinning. Q_{Ri} is radiogenic.

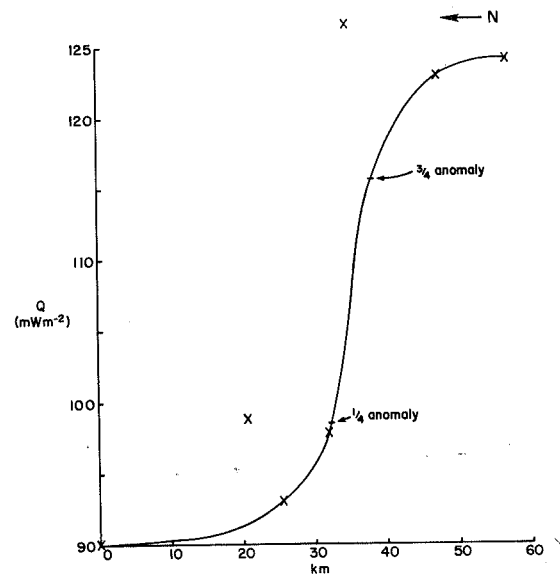


Figure 4. N-S heat-flow profile across area, x indicates data, solid line is interpretation.