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2011 Geothermal Map of Arizona and New Mexico

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ABSTRACT

As part of a large-scale update of the 2004 Geothermal Map of North America, Arizona and New Mexico were designated as a specific study area. An additional 932 published heat flow measurements from the study area were analyzed for the update. Of these measurements, 930, all but two, are from American Metals Climax (AMAX). The measurements were primarily located in the Rio Grande Rift and Basin and Range geologic provinces. The addition of the AMAX dataset infers lower heat flow in the Basin and Range in many places. Many of the wells were too shallow (less than 100 meters) to have been reliable indicators and, therefore, were excluded from the final contouring. 814 conventional heat flow measurements were added in the study area for the final contouring. Location quality of AMAX data in the Basin and Range is low because USGS quadrangles are the only location information. In contrast to the Basin and Range data, the AMAX data for the Rio Grande Rift confirmed high heat flow and even increased heat flow in areas, highlighting potential areas for further exploration. In addition to the conventional heat flow measurements, the 2011 update also included the addition of bottom-hole temperature (BHT) data from the AAPG Geothermal Survey of North America dataset. These BHT measurements were used to calculate heat flow for 370 wells. Primarily located in sedimentary basins, the addition of BHT values generally supported the conventional heat flow measurements in the area and resulted in increased data density of the map. New BHT calculations for the Colorado Plateau in Northeast Arizona were helpful in confirming lower heat flow where very little data were previously available. Temperature-depth data are a useful calibration tool for BHT data but were only available for the San Juan Basin. Temperature-at-depth maps produced for the study area highlight many areas containing high temperatures.

Introduction

The update of the Geothermal Map of North America (GMNA) (Blackwell and Richards, 2004) in 2011 (Blackwell et al., 2011) includes an update for the resources within the states of Arizona and New Mexico. The project to update the 2004 GMNA was primarily focused on increasing data density in the eastern United States because large portions of this area are devoid of any heat flow information; therefore, temperatures-at-depth cannot be calculated with high resolution (Frone and Blackwell, 2010; Batir et al., 2010; Sica et al., 2010). The addition of bottom-hole temperature (BHT) data from oil and gas exploration wells was the primary source of new information, focusing most of the data in sedimentary basins. These data were collected from the AAPG Geothermal Survey of North America (AAPG, 1994). The procedures developed to use BHT data in the Eastern US were then applied to data in Arizona and New Mexico. In addition, equilibrium temperature logs were used to calibrate BHT data where available. This process is outlined in further detail by Blackwell et al. (2010).

In the project study area, BHT data were added for two sedimentary basins: the San Juan Basin of northwestern New Mexico and the Black Mesa Basin of northeast Arizona. BHT data were already incorporated in the Permian Basin of eastern...
New Mexico in the 2004 GMNA, so no data were added in that region. In addition to the BHT data, a large dataset of gradient measurements from the late 1970s was obtained from American Metals Climax, Inc. (AMAX) (EGI, 2011a-d). In the original AMAX study, conductivities were estimated from well lithology and nearby outcrop. This data is primarily located in the Basin and Range and Rio Grande Rift geologic provinces. This paper presents the collection and manipulation of the data, the regional geology, and the results of the project.

**Data Sources, Manipulation, and Calibration**

The 2004 GMNA contained mostly conventional heat flow measurements throughout the region, while bottom-hole temperature (BHT) data were used to populate the Permian Basin and eastern New Mexico. Data density was fairly consistent throughout the Basin and Range and Rio Grande Rift provinces but was sparse on the Colorado Plateau, especially in Arizona. This lack of data caused much weight to be placed on the few existing heat flow measurements.

The 2011 update of the GMNA primarily focused on compiling BHT data and developing thermal conductivity models for calculating crustal heat flow. Necessary parameters for these calculations include: well depth, BHT, surface temperature, sediment thickness, thermal conductivity of the rocks, and heat production. The source of BHT data for this study was oil and gas well data collected in the AAPG Geothermal Survey of North America (GSNA) (AAPG, 1994). This dataset was selected because of its reasonable amount of data within regions of previously low data density and its prior use in the 2004 GMNA in other regions. In this study, 370 BHT values were analyzed, of which 356 were added to the map. Figure 1 shows the new and existing data for this study. The procedure for calculating heat flow from BHT data is discussed below and in further detail in Blackwell et al. (2010).

The BHT values are first corrected for the disturbance due to the drilling process in order to represent the equilibrium temperature at the bottom of the well using the Harrison correction (Harrison et al., 1983). This correction only applies to BHTs measured at depths from 600-4000 meters, so measurements less than 600 m and greater than 4000 m were individually examined. All wells less than 600 m were discarded due to the correction problem combined with other effects seen in shallow well BHT values. The corrected BHT value was then used to calculate the average geothermal gradient within the well.

Geologic sections from the Correlation of Stratigraphic Units of North America (COSUNA) were used to calculate average thermal conductivity within each well (AAPG, 1985). These sections were compiled as characteristic stratigraphic sections of the geologic basins of North America, and although variations in lithology occur throughout basins, these sections overall provide robust average conductivities. That being said, the conductivity estimations are the greatest source of error when using this method to calculate heat flow. In order to calculate average conductivity for a well, conductivities are applied to each formation based on available lithologic data, and a weighted average is taken based on formation thicknesses and total sediment thickness. Conductivities in this study were primarily based off of measurements by Reiter (2011) when they could be correlated to specific formations in COSUNA sections.

When calculating geothermal gradients from BHT data, equilibrium temperature-depth logs from nearby wells can be used to calibrate non-equilibrium BHT measurements. Unfortunately, equilibrium temperature-depth logs are sparse in many sedimentary basins and, in this study, were only available for the San Juan Basin (Reiter, 2011). Figure 2 illustrates how these logs are used to calibrate BHT data. In applying the Harrison correction, the BHT values approach the equilibrium temperature regime in the area.

![Figure 2. Uncorrected and corrected BHT data and equilibrium temperature-depth curves for the central San Juan Basin (Reiter, 2010).](image-url)

The equilibrium temperature-depth curves for the central San Juan Basin show relatively uniform gradients as a function of depth in the area. The Harrison corrected BHT values clearly lie closer to the curves than the uncorrected values, yet even the corrected temperatures are colder than the equilibrium temperatures. In the 2011 update of the GMNA, it was decided to consistently use the Harrison correction (Blackwell et al., 2010; 2011). In the future, a basin-specific correction could be determined based on equilibrium temperatures (Dingwall and Blackwell, 2011).

In addition to BHT data, a large dataset of conventional heat flow measurements from American Metals Climax, Inc. (AMAX) was available for analysis (EGI, 2011a-d). 930 measurements sites were analyzed, but many were not included in the final contouring due to poor quality. This dataset was collected in the late 1970s and early 1980s as a regional geothermal exploration project. Some wells in geothermal areas have temperature-depth data available, but most just have interval gradients specified. Thermal conductivities were estimated at the time of logging based on nearby outcrop and well lithology from a model derived by the SMU Geothermal Laboratory (Blackwell unpublished, 1979).
**Geology**

All of the BHT data added for this project are in the Colorado Plateau in the San Juan and Black Mesa basins. The San Juan Basin is the southernmost extent of the Colorado Plateau and is bounded on the north by the San Juan Mountains, on the south by the Zuni Uplift, on the east by the Nacimiento uplift, and on the west by the Four Corners Platform. The surface geology of the basin is mostly Cretaceous and Tertiary sandstone and shale units. The basin first developed in Pennsylvanian time when the area was a marine trough and maintained this shape through most of the Mesozoic era. The Cretaceous and Tertiary Laramide orogeny resulted in the folded shape of the basin seen today. The basin is asymmetric, deepening from southwest to northeast, with its deepest section in northern New Mexico and southern Colorado near the San Juan Mountains where it reaches depths greater than 4,500 m (Peterson et al., 1965). The Black Mesa Basin is located on the Colorado Plateau in northeastern Arizona. Through most of Paleozoic and Mesozoic time, the basin area was the shelf between the Cordillera and the Ancestral Rockies. Paleozoic sediments reflect periodic marine shelf sedimentation, while Mesozoic sediments reflect a shift from predominantly marine carbonates to red beds, suggesting a continental environment source (Elston, 1960).

The heat flow data for this project were added in the Basin and Range and Rio Grande Rift geologic provinces. The physiography of the Basin and Range province of the western US is the result of extension during late Cenozoic time, beginning approximately 18 Ma and continuing through the present. Crustal blocks of complexly deformed pre-Cenozoic rocks as well as relatively undeformed early and middle Cenozoic volcanic rocks have been uplifted, tilted, and dropped along normal faults in a large area including southern Arizona and New Mexico (Thompson and Burke, 1974). The Rio Grande Rift is a sub-region of Basin and Range extension trending North-South in central New Mexico and Southern Colorado. Rifting began approximately 30 Ma and occurred in two separate phases from 30 Ma to 18 Ma and from 10 Ma to 5 Ma with minor extension continuing to the present. The early phase extension was associated with major magmatism, resulting in high-strain extension, while the late phase was associated with high-angle faulting resulting in large vertical strains (Morgan et al., 1986).

**Discussion**

The resulting heat flow map from this study shows a refinement on the Colorado Plateau from the 2004 GMNA (Blackwell and Richards, 2004) with the addition of the BHT data (AAPG, 1994). The BHT data in the San Juan Basin document the general trend of increasing heat flow from the southern section towards the San Juan Mountains in the north as described previously by Reiter and Mansure (1983). As seen in Figure 2, the Harrison correction has not completely compensated for drilling disturbance in the wells. Therefore, heat flow in this basin may actually be underestimated by approximately 10%. In addition, the BHT data greatly increases data density in the Black Mesa Basin area and shows the same general trend as the 2004 GMNA, which is lower heat flow in the southern Black Mesa Basin with heat flow increasing towards the Four Corners area.

The addition of AMAX data (EGI, 2011a) shows a decrease of heat flow in some areas of the Basin and Range. This data set is different from the other AMAX data because only the BHT value is available for each well. These points were treated as conventional heat flow data because they were equilibrium measurements and were assigned quality values. Whether these values represent the conductive heat flow regime in the area has yet to be determined. The AMAX data in the Basin and Range presents a problem because many of the holes are fairly shallow “free holes”, mostly water wells, and temperature-depth logs are not available. The lower heat flow values observed in some wells by AMAX could be due to local groundwater flow, which could be better evaluated with temperature-depth logs. Wells shallower than 100 m were not included in contouring to minimize this problem.

In the Basin and Range the AMAX locations have a large error because the data are mostly presented by USGS 7.5’ or 15’ quadrangle. Additionally, multiple heat flow measurements were made in a single quadrangle. In these cases, the heat flow values were averaged in the center of the quadrangle simply because no better site location was available. An average of the wells in a single quadrangle was the most representative option for contouring because such a limited amount of data was available.

The heat flow in the Rio Grande Rift increased primarily along the western side with the addition of the AMAX data (EGI, 2011b; 2011c). The data density throughout the area has increased greatly, and many of these focused areas of higher heat flow should be further studied on a more site-specific basis. Through further collection and analysis of temperature-depth data, these sites may be identified as candidates for hydrothermal or EGS exploitation.

Temperatures at depth were calculated using the surface heat flow map with equations described in Blackwell et al. (2007) and Blackwell et al. (2010). The temperatures at 6.5 km depth
are shown in Figure 4. The highest temperatures on the map are found in the Valles Caldera and along the western Rio Grande Rift (EGI, 2011b; 2011c). Temperature maps produced in this project in the northern San Juan Basin (Fig. 4) display temperatures high enough for potential EGS exploitation. However, the bulk of the data used in this area are BHTs, which have underestimated true temperatures in the San Juan Basin (Fig. 2). True temperatures could be even more attractive for EGS development.

![Temperature Map](Figure 4. Temperatures at 6.5 km depth.)

### Conclusions and Future Work

BHT data are extremely useful in the study and mapping of heat flow, especially in the presence of equilibrium temperature logs for calibration. Other BHT databases (current oil and gas data) exist for the region that could be used to increase data density for a more in depth study of heat flow. The 2011 Geothermal Map of Arizona and New Mexico shows a more detailed heat flow pattern than the 2004 GMNA, which helps to better constrain heat flow anomalies. Much of the data in the Basin and Range could be improved through the collection and analysis of equilibrium temperature logs. In addition, equilibrium temperature logs should be collected in the Rio Grande Rift to explore the many areas of high heat flow.

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