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2015, pp. 261-275. https://doi.org/10.56577/FFC-66.261
Supplemental data: https://nmgs.nmt.edu/repository/index.cfml?rid=2015003

in:

Guidebook 66 - Geology of the Las Vegas Area, Lindline, Jennifer; Petronis, Michael; Zebrowski, Joseph, New Mexico Geological Society 66th Annual Fall Field Conference Guidebook, 312 p. https://doi.org/10.56577/FFC-66

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GEOTHERMAL POTENTIAL OF THE RATON BASIN, NEW MEXICO

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ABSTRACT—The geothermal potential of the southern Raton basin and the adjoining Las Vegas basin/Tucumcari basin, Cimarron arch, and Sierra Grande uplift in northeastern New Mexico was evaluated using equilibrium, bottom hole, and wireline temperature data. Equilibrium logs are generally from shallow wells (<600 m); interval geothermal gradients frequently correspond to lithology, which is indicative of conductive heat flow. Interval geothermal gradients in the Paleogene Raton and Poison Canyon Formations and in Cretaceous shales (Pierre, Carlile, Graneros) are on the order of 40–75°C/km. In contrast, interval gradients in the Cretaceous Trinidad Sandstone and in other sandy units are 20–30°C/km. Bottom-hole temperature (BHT) data constrain the deeper thermal structure of the basin. High BHTs were measured in the southern Raton basin near the Colorado state line (Stubblefield Canyon gas field); the maximum uncorrected BHT is 135°C at a depth of 2160 m and associated geothermal gradients are 50–68°C/km. BHTs in the Las Vegas basin/Tucumcari basin to the south are cooler (85°C at 3091 m) compared to those in the southern Raton basin at similar depths. Four wells with multiple BHTs in the Castle Rock Park gas field show a distinct decrease in temperature between measurements in the Trinidad Sandstone and measurements in the underlying Pierre Shale. This pattern implies lateral flow of warm (~45°C) water in the Trinidad Sandstone in this area. Wireline temperature logs can provide good thermal data if used with caution. Wireline logs are obtained by petroleum companies to look for zones of fluid flow or to gauge the quality of a cement job. Wireline temperature logs measured in air-drilled holes that are filled with formation water prior to measurement yield thermal data of a quality similar to equilibrium logs.

Temperatures of 150°C at depths of ~2 km are present in the Colorado part of the Raton basin just north of the state border. Equilibrium data from the Stubblefield Canyon area just south of the state line yield published heat flow values of 89–120 mW/m^2. If the elevated gradients derived from thermal data from Stubblefield Canyon are extrapolated to depth, then a temperature of 150°C is reached at 2.6–2.7 km: this depth range is greater than the depths to 150°C on the Colorado side of the border (1.6–2.5 km). The difference in temperature between the southern Raton basin and the Las Vegas basin/Tucumcari basin is attributed to erosion of low thermal conductivity Cretaceous shales from the Las Vegas basin.

INTRODUCTION

A prospective power-generating geothermal resource has recently been identified in the Raton basin just west of Trinidad, Colorado (Morgan, 2009; Macartney, 2010; Bohlen, 2012). Economic, commercial-scale geothermal power, using binary technology, requires temperatures approaching 150°C and water production rates of 1000 gpm (Tester et al., 2006; Holbrook et al., 2014). Based on data from shallow (<2 km) wells in the central Raton basin of Colorado, >150°C temperatures are projected to be at a depth of 1.6 to 2.5 km (Morgan, 2009). The purpose of this investigation was to use available equilibrium, bottom-hole, and wireline temperature data to determine if this resource potential extends into New Mexico. Such a resource could impact economic development of the communities of Raton and Cimarron in the northeastern part of the state (Fig. 1).

Geologic Setting

The geology of northeastern New Mexico was shaped by three important tectonic events. First, faulting associated with Ancestral Rockies deformation created the Cimarron arch, Sierra Grande uplift, and the central Colorado, Taos, and Rainsville troughs (see Baltz and Myers, 1999 for locations); Pennsylvanian to Lower Permian strata, including the arkosic Sangre de Cristo Formation (Fig. 2), are thick in the troughs and are thin or absent across the arch and on the uplifts (Baltz and Myers, 1999). The Tucumcari basin also formed during this time frame (Broadhead et al., 2001). East-directed thrust and reverse faults with an Ancestral Rockies history have been recognized by Baltz and Myers (1999).

Epeirogenic subsidence of the Western Interior related to far-field Sevier deformation and nearby Laramide deformation during middle to late Cretaceous time culminated in the deposition of thick low-thermal-conductivity Late Cretaceous shales, including the Graneros, Carlile, and Pierre shales, and coals in the Vermejo Formation (Fig. 2). The Cretaceous shales and coals have had a profound impact on the thermal structure of northeastern New Mexico. Heat has a tendency to build up under these “thermal blankets,” causing the temperature of the rock section below the shales and coals to be high compared to areas where the shales and coals are absent (Kelley and Blackwell, 2002).

Laramide deformation caused many Ancestral Rockies faults to be reactivated during east-vergent compression (Baltz and Myers, 1999). This late Mesozoic-early Cenozoic compressional event led to the formation of the Raton and Las Vegas foreland basins and the Sangre de Cristo uplift. The basal conglomerate of the synorogenic Raton Formation and sandstone-dominated intervals in the middle Raton and Poison Canyon Formations indicate pulses of tectonism during Laramide deformation (Flores, 1987). The Late Cretaceous shales were downwarped and preserved in the Laramide basins of northeastern New Mexico. Also of note, the eastern part of the late Paleozoic Rainsville trough is preserved in the subsurface of the Laramide Las Vegas basin and the central Colorado Trough underlies portions of the Laramide Raton basin (Baltz and Myers, 1999).

Appendix data for this paper can be accessed at:
http://nmgs.nmt.edu/repository/index.cfm?rid=2015003

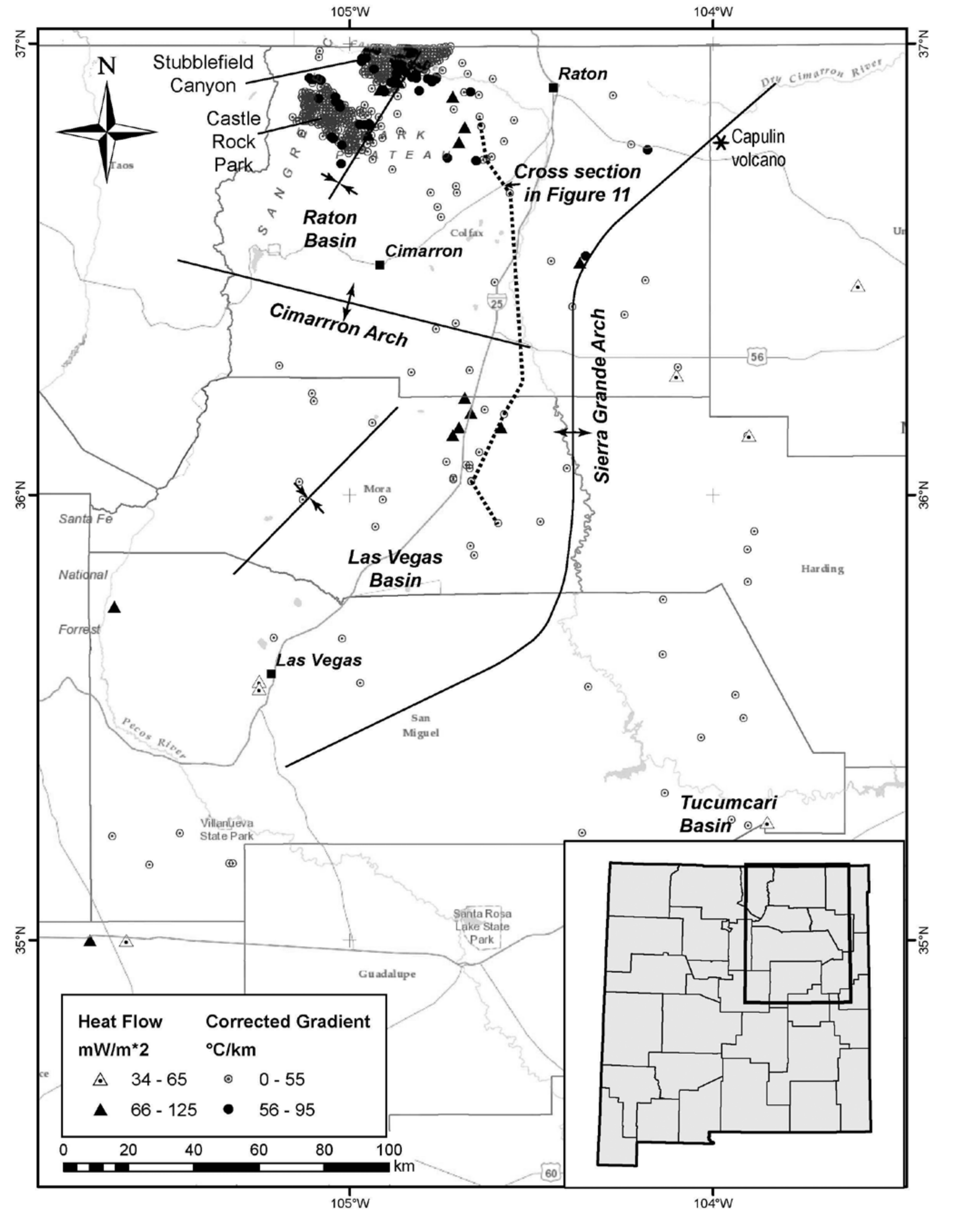


FIGURE 1. Location of petroleum wells with BHT data (circles; this study) and heat flow (triangles) data measured by Reiter et al. (1975) and Edwards et al. (1978) in and near the Raton and Las Vegas Basin/Tucumcari Basins in northeastern New Mexico. The location of the cross section in Figure 11 and Pennsylvanian and Laramide structural features are also shown.

The third event to affect the area was intrusion of the Chico sill complex and laccoliths at Turkey Mountain and the Vermejo Park anticline at 37 to 29 Ma, followed after a long interval of time by eruption of the Ocate and Raton-Clayton volcanic fields. These volcanic fields are associated with a NE-trending regional alignment of volcanic centers extending into Arizona called the Jemez zone or lineament (Mayo, 1958; Laughlin et al., 1972). The Ocate volcanic field was active 8.2 to 0.82 Ma (Olmstead and McIntosh, 2004; O'Neill and Mehnert, 1988). The Raton-Clayton volcanic field has been active since ~9 Ma (Stroud, 1997), but the youngest phase of volcanism in this area started at ~1.7 Ma. Many flows are <500 ka. The well-preserved Capulin cinder cone in Capulin National Monument is 56 ±8 ka based on $^{40}Ar/^{39}Ar$ dating by Stroud (1997). More recent $^{40}Ar/^{39}Ar$ dating by Zimmerer et al. (2014) indicates little volcanic activity 200 to 500 ka, activity in two centers at ~100 ka, and an episode of volcanism ~32 to 55 ka, including three eruptions that are younger than Capulin volcano.

The Raton basin is adjacent to the southern Rocky Mountain-southern High Plains physiographic province boundary. Recent seismic images of the mantle beneath southern Colorado and northern New Mexico show a finger of low velocity mantle at 75 km beneath the Raton basin that has been associated with volcanism along the Jemez lineament (Schmandt and Humphreys, 2010; Schmandt and Lin, 2014).

Petroleum Exploration in Northeastern New Mexico

About 2300 oil, gas, and CO_2 wells have been drilled in Colfax, Mora, San Miguel, Harding, Quay, and Union counties in northeastern New Mexico, based on records on file at the Oil Conservation Division (OCD) of the New Mexico Energy Minerals and Natural Resources Department (NMEMNRD). Most of the deep wells in the area were drilled during the 1960s to 1970s. The more recent activity, starting in the late 1990s, has focused on the development of coalbed methane from coals in the Late Cretaceous Vermejo Formation. More than 850 wells that are generally <900 m deep have been drilled into the Late Cretaceous–Paleogene Raton and Vermejo Formations in the New Mexico portion of the Raton basin, and many of these wells have also penetrated the Cretaceous Trinidad Sandstone and the top of the Cretaceous Pierre Shale. The coalbed methane wells are concentrated in two areas, the Castle Rock Park area to the southwest and the Stubblefield Canyon area along the New Mexico-Colorado state line (Fig. 1). Water that is produced in association with the coalbed methane development is injected in seven deeper and currently active disposal wells that are drilled into the Jurassic Entrada Sandstone or the Permian Glorieta Sandstone. The injection is gravity-driven.

Previous Thermal Studies

Reiter et al. (1975) and Edwards et al. (1978) were the first to document elevated heat flow in the Raton (84–197 mW/m^2) and the Las Vegas (100–125 mW/m^2) basins. These authors attributed the high heat flow to anomalous heat coming from the mantle,

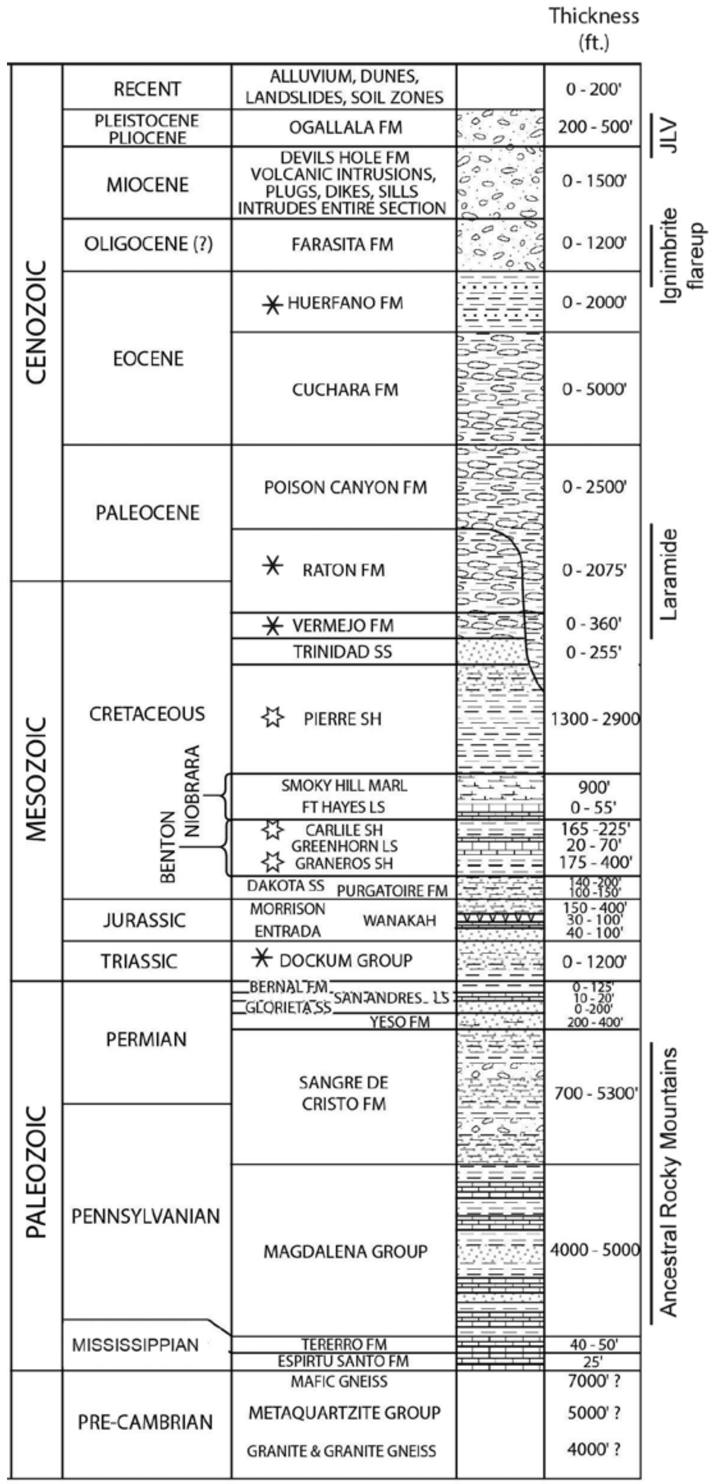


FIGURE 2. Stratigraphy of the Raton basin (modified from Dolly and Meissner, 1977). The rock units with low thermal conductivity are marked with stars and the units with intermediate conductivity are marked with asterisks. The remaining formations have high thermal conductivity. JLV=Jemez lineament volcanic activity.

partially related to activity in the Jemez lineament volcanic fields and partially related to deep heat sources beneath the southern Rocky Mountains. Equilibrium temperature logs measured by Reiter and his students are generally from shallow oil and water wells (<600 m). The linear geothermal gradient intervals in several instances correspond to lithology (Appendix 1), which is indicative of conductive heat flow. The interval geothermal gradients calculated from the equilibrium logs in the low-thermal-conductivity Late Cretaceous to Paleogene Vermejo, Raton, and Poison Canyon formations and in Cretaceous shales (Pierre, Carlile, Graneros) are on the order of 40–75°C/km. In contrast, interval gradients in the Cretaceous Trinidad Sandstone and in other high conductivity sandy units from wells on the Sierra Grande arch are 20–35°C/km.

More recently, Morgan (2009) and Macartney (2010) compiled and analyzed >1900 bottom hole temperature (BHT) points from coal bed methane, oil and gas, and injection wells in the Raton basin of Colorado. These authors report a mean geothermal gradient of 49.2 ±11.9°C/km and a surface intercept of 12.5°C for the Colorado portion of the using BHT values that have been corrected for drilling disturbance. Geothermal gradients for both shallow and deep wells generally increase west to east across the Raton basin; this trend is attributed to regional-scale groundwater flow from recharge areas in the Sangre de Cristo Mountains to the west and discharge on the east side of the basin along the Pugatoire River. Gradients derived from corrected BHTs from deep wells along the Purgatoire River exceed 90°C/km. Projection of the gradients in deep wells predicts temperature of 150°C at depths 1600–2500 m (Morgan, 2009).

METHODS

BHT Corrections and Background Geothermal Gradient Calculations

BHT and industry temperature log data were gathered for the National Geothermal Database System (NGDS). BHT data were collected from well headers from a variety of geophysical logs on file at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) petroleum records library or from the web page of the NMEMNRD-OCD. In some cases, BHT was measured in association with the installation of intermediate casings, so a few of the deeper wells have measurements at multiple depths. In addition, continuous temperature logs were run in two dozen wells in northeastern New Mexico to identify permeable zones or to evaluate the quality of a cement job. The paper temperature logs, which are available at the NMBGMR petroleum library, were scanned, digitized, and placed into the NGDS. Temperature-depth data from equilibrium logs measured by Reiter et al. (1975) and Edwards et al. (1978) were also digitized and put in the NGDS. The equilibrium logs with good lithologic control are plotted in Appendix 1.

BHT and industry wireline temperature logs are usually measured within a few hours to a few days after fluid circulation related to drilling ends. The drilling fluids usually cool the ambient temperature of the rock surrounding the drill hole; thus, these measurements do not accurately record the true temperature. Shallow coalbed methane wells that are drilled with air in two or three days are generally not as strongly disturbed as deeper wells drilled over the course of many weeks with mud. Equilibrium temperature logs (Reiter et al., 1975; Edwards et al. 1978) were usually measured months to years after drilling.

A variety of methods have been developed to correct BHT data (e.g., Majorowicz et al., 1990; Blackwell and Richards, 2004). Since the data from New Mexico are being compared to earlier work from Colorado, the measured BHT values were corrected to near-equilibrium values following the methods outlined by Morgan (2009). Morgan (2009) first applied a correction developed using BHT and measured temperatures in Oklahoma (Harrison et al., 1983). This correction is used to gauge the background gradient in the area. Morgan (2009) then used a formulation proposed by Blackwell and Richards (2004) to apply a second correction to account for differences between basins in Oklahoma and basins in Mid-Continent. Morgan (personal commun., 2015) has recently questioned the applicability of these corrections to Rocky Mountain foreland basins and has updated the BHT corrections for the Colorado portion of the of the Raton basin:

$$BHTcorrected\ (°C) = BHTuncorrected\ (°C) + 0.0056125 * Depth\ (m) + 3.369$$

The ambient surface air temperature lapse rate derived from 34 climate stations in northeastern New Mexico, adjusted to include a +3°C factor that accounts for the difference between mean air and mean ground temperature (Morgan, 2009), is similar to that derived by Morgan for south-central Colorado (Fig. 3). The temperature difference based on the two data sets is <2°C.

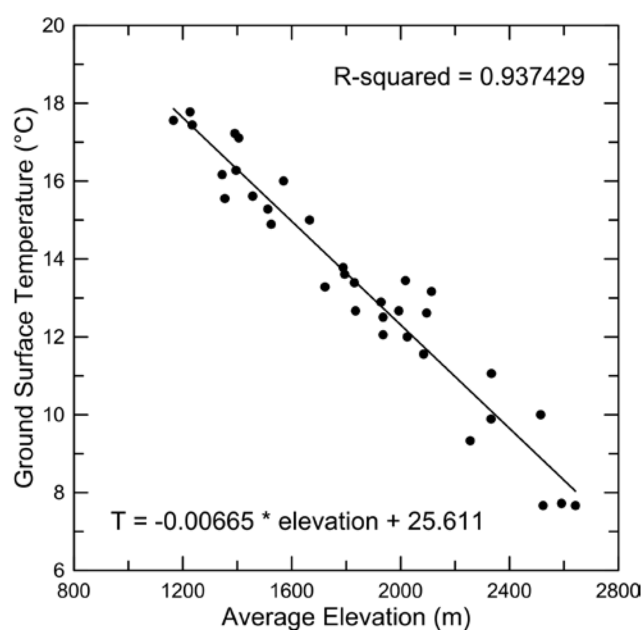


FIGURE 3. Mean annual temperature and mean elevation for 34 climate stations located in northeastern New Mexico derived from the NOAA website (http://www.ncdc.noaa.gov/cdo-web/). The line defines the lapse rate for air in this area. The mean annual ground temperature is 3°C higher (Morgan, 2009).

Calculation of corrected BHT using the formulas in Morgan (2009) and an average background gradient of 33°C/km derived from the Harrison et al. (1983) formulation yields in a large BHT correction for the deepest wells (ca. 24°C). The new (2015) BHT correction of Morgan results in a 15.5°C correction for the deepest wells; thus this correction was also investigated in this study.

Temperature data recorded during drill-stem tests (DSTs), which draw fluids directly from the formation, are closer to formation temperatures than BHT data (Morgan and Scott, 2014). An examination of scout cards in the NMBGMR Petroleum records library reveals that DST data were generally not collected in the Raton basin; only six DSTs with temperature information are available in the area of interest shown in Figure 1. The data are presented in Appendix 2.

Morgan and Scott (2011) note that many cement bond logs, which are run weeks to months after a well is drilled, commonly have BHT data recorded in the state of Colorado. Operators in New Mexico generally DO NOT record BHT data on cement bond logs; however, a set of about a dozen wells drilled in the Stubblefield and Castle Park areas drilled in early 2011 do have cement bond logs with this useful information. Those data are summarized in Table 1 and in Appendix 3.

RESULTS

Evaluation of the correction

The corrections of Morgan (2009) and Morgan (personal commun., 2015) are compared. The correction presented in Morgan (2009) produces values that are less than the measured BHT at depths <260 m in the study area. The correction proposed by Morgan in 2015 is derived from data at depths >1500 m, but the calculated BHT values using the 2015 correction are comparable to the 2009 results (<±1°C difference) at depths in the 645 to 860 m range. Below 860 m, the 2009 correction is 1–8.4°C higher than the 2015 correction. The corrected BHT values are compared to three other measures of temperature in the basins: equilibrium logs of Reiter et al. (1975) and Edwards et al. (1978), temperatures measured during drill-stem tests, and cement bond log temperatures.

Equilibrium logs

The well locations of the published heat flow data are reported to the nearest minute of latitude and longitude and commonly the real name of the oil well was not used, so the equilibrium logs were correlated to the actual wells as part of this study. Only seven wells could be tied with certainty to oil wells that were drilled in the early 1970s; the equilibrium logs, interval geothermal gradient and rock units encountered in these wells, in addition to the measured and calculated BHT values, are presented in Appendix 1. Formation tops are from Broadhead (2008) and from scout cards and well logs.

Two of the wells, the Vermejo River (likely WS Ranch 3) and Van Bremmer Creek (WS Ranch NM B5) are in the Raton basin. In both cases, the equilibrium logs appear to project to the BHT calculated using the 2015 correction.

Five wells with elevated heat flow are located in Mora County on the eastern flank of the Las Vegas basin (Fig. 1; cluster of black triangles near the center of the map). Only one of these wells could be tied to an oil well (Colmor/West = Kelly Bell 1), but that well did not have BHT data (Appendix 1). The interval geothermal gradients in the Cretaceous Pierre, Carlile, and Graneros Shales are 55–75°C/km. The remainder of these wells, which are drilled into the shaly part of the Cretaceous section just above the Dakota Sandstone, appear to be water wells. A second heat-flow well in this area, Nolan NW, is within a mile of oil well Rinehart 1 (API 30-033-20061). In the case of this shallow 280 m well, the equilibrium log projects to the value determined using the 2009 BHT correction.

The strong correlation of rock type to interval gradient in these five Las Vegas basin heat flow wells is indicative of conductive conditions. The thermal conductivity of shale is very hard to measure in the laboratory because of the tendency of clay minerals in shales to lose their isotropic orientation during removal of samples from *in situ* conditions (Blackwell and Steele, 1988, 1989). Reported measured thermal conductivity values for lower shaly interval average 2.32 W/m-K (Edwards et al., 1978), compared to the 1.2 to 1.5 W/m-K estimates of the conductivity of similar *in situ* shales in the Denver basin (Kelley and Blackwell, 2002). The heat flow values for this cluster of wells should be reduced to 65 to 75% of the reported values because the measured shale values are high compared to estimated *in situ* values.

Two wells in the southeast corner of Colfax County that lie on the broad Sierra Grande Arch, Abbott East (State FA 1) and Sauble (Sauble 1A), penetrate the Mesozoic and late Paleozoic section. The correlation of lithology and interval gradient is weak because of the 20 m spacing between the temperature readings. The "equilibrium" logs, particularly Sauble 1A, appear to be disturbed by an influx of cool water. The logs do not project to the measured BHT. Another heat flow well in southeastern San Miguel County, Chapell Spade (Frank Chappell 1), does not have BHT or lithologic information, but the rock units in nearby Hoover 2 are identifiable in the interval gradient log. This equilibrium log projects to the 2015 BHT correction.

Drill Stem Test Temperatures

Analysis of the relationship between DST temperature and bottom hole temperatures from shallow wells in the study area is relatively straightforward (Appendix 2). Three shallow wells from the Raton basin (Phelps Dodge 5 Test 1, WS Ranch NM B1 and Sedberry 2; PD5, WSR, and Sed) all have DST temperatures that are less than the measured BHT. Based on this observation, drilling fluid rather than formation fluid was sampled in these wells or the packers failed during the DST. The data from two deep wells in the Raton basin (Salman Ranch A and B; SRA and SRB) have multiple BHT and DST data measured at very different intervals (Appendix 2). The DST temperatures in these wells appear to lie between the measured and corrected BHT values, although the DST values are closest to the 2015 correction. A DST from Filly's Tooth (FT) in Quay County on the Sierra Grande arch also has a DST temperature between the measured and corrected BHT.

Morgan and Scott (2014) developed a method for correcting BHT measurements to match DST temperatures. In wells with multiple readings, geothermal gradients are calculated independently using the uncorrected BHT and the DST data. If the BHT and the DST gradients are roughly parallel, the BHT gradient is subtracted from the DST gradient, and a line is fit through the difference. The slope of the difference line can be used as a correction. We have only one well with enough points to apply this correction, Salman Ranch A1 (Appendix 2). The equations:

$$\textit{Temperature } (^\circ C) = (0.02780 * \textit{depth } (m)) + 11.06$$
$$\textit{Temperature } (^\circ C) = (0.02377 * \textit{depth } (m)) + 8.88$$

fit the DST and the uncorrected BHT data from Salman Ranch A1, respectively. Note that the 2015 corrected BHT points lie on or close to the DST gradient line. The difference between the two lines is:

$$\textit{Temperature } (^\circ C) = (0.004 * \textit{depth } (m)) + 2.18,$$

which defines the correction of the uncorrected BHT data to DST values as a function of depth in this particular well. Much more data are needed to establish a regional correction, as has been done in Colorado (Morgan and Scott, 2014).

Cement Bond Logs

BHT measured during the cementation of casing in a series of shallow (<920 m) wells drilled in 2011 in the Raton basin are compared to BHT measured shortly after circulation stopped and to the associated corrected BHT values (Appendix 3; Table 1). These shallow wells were drilled in one to two days, commonly with air or a mix of air and fluid, and thus are not highly disturbed. The temperatures derived from the cement bond logs generally lie between the measured BHT and the 2015 corrected values (Appendix 3). Deeper in the section, the cement bond temperatures overlap the measured BHT, suggesting a lack of equilibrium in these measurements in wells that take a little longer to drill. The corrected BHT calculated using the 2015 formulation of Morgan is slightly lower than the Morgan (2009) correction in this depth interval of 700–900 m. The 2015 correction of Morgan is on average 5°C higher than the measured BHT on the cement bond logs; the Morgan (2009) correction is 5.7°C higher (Table 1).

Regional Trends

Three geographically distinct groups are evident on plots of BHT versus depth (Fig. 4), which show uncorrected BHT and corrected BHT using the formulas of Morgan (2009) in order to evaluate both shallow and deep data. First, BHT data from the Las Vegas basin/ Tucumcari basin south of the Cimarron arch defines a relatively low geothermal gradient (22.0 ±1.4°C/km using uncorrected BHT; 33.3 ±1.2°C/km using 2009 corrected values). The more scattered BHT data from both shallow (<1 km) and deep wells from the Raton basin indicate a relatively high geothermal gradient (32.6 ±2.2°C/km using uncorrected BHT; 45.7 ±2.2°C/km using 2009 corrected values). Third, a group of

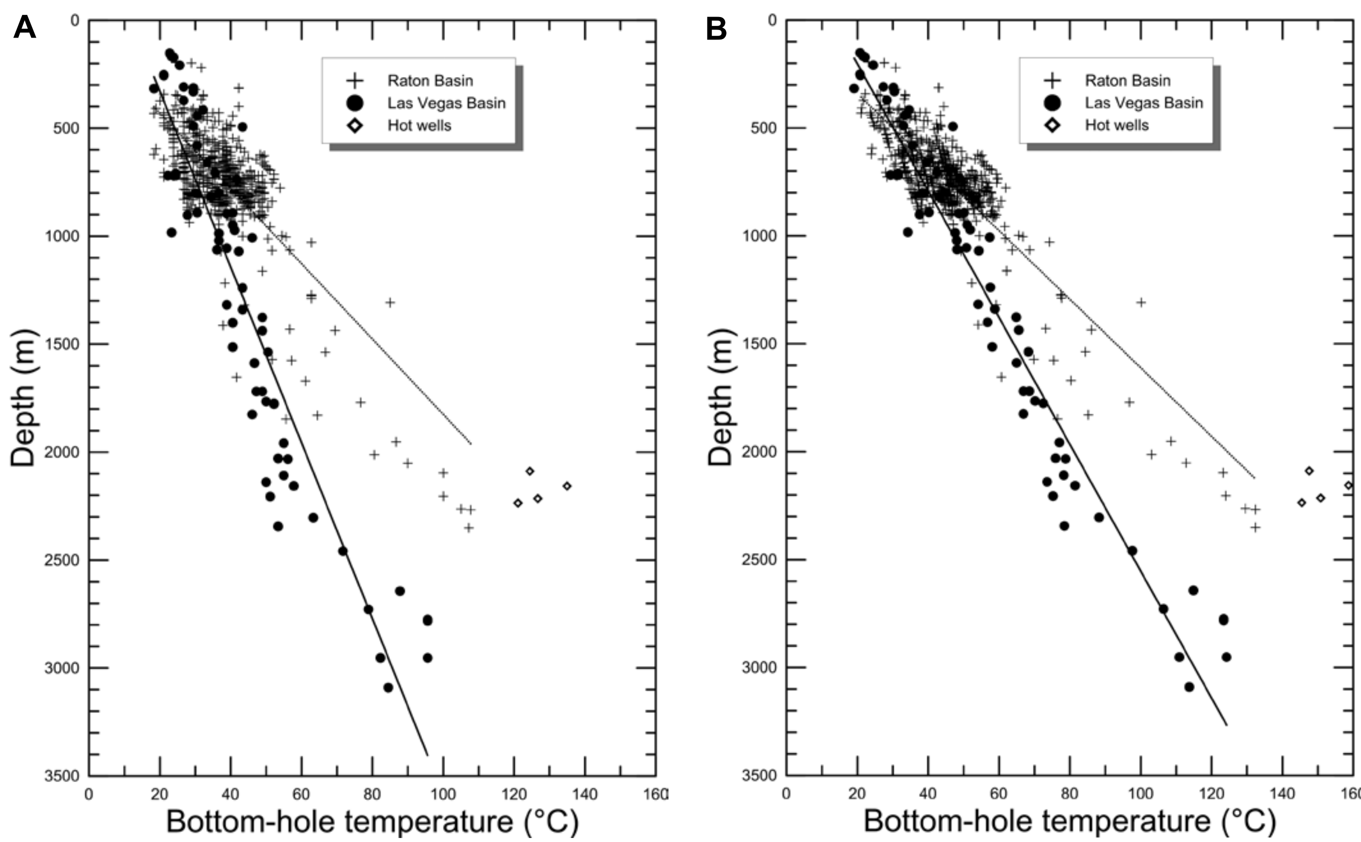


FIGURE 4. A. Average geothermal gradients and projected surface temperatures calculated from measured BHT data. B. Average geothermal gradients and projected surface temperatures calculated from BHT data corrected using the methods outlined by Morgan (2009).

three hot wells from the Stubblefield well field fall off the general trend. Linear fits to uncorrected BHT data from the Las Vegas and Raton basin groups yield projected surface temperatures of ~14 to 15°C (±1.8–2.5°C; Fig. 4), which are on the high end of the observed ground temperature data (Fig. 3). The projected surface temperatures determined from the corrected BHT data are 9 to 11°C (±1.8–2.2°C), in closer agreement with the observed data from northeastern New Mexico (Fig. 3).

The data from the shallow wells mask the nature of the deeper thermal structure of the basins. Consequently, measured BHT data and the BHTs corrected with the 2015 equation, which is more appropriate for deep wells, were analyzed in wells with depths greater than 1000 m (Figs. 5, 6). The uncorrected geothermal gradients determined from wells with a depth >1 km are slightly higher than those discussed above: 25.6 ±2.6°C/km for the Las Vegas basin/Tucumcari basin and 40.5 ±9.6°C/km for the Raton basin with low surface intercept values of 7.4 ±5.8°C and 3.0 ±3.0°C , respectively. Gradients using corrected BHT are 34.0 ±2.6°C/km for the Las Vegas basin/Tucumcari basin and 52.0 ±9.6°C/km for the Raton basin with surface intercept values of 11.9°C and 2.2°C, respectively. The hot wells are on average ca. 8.5°C cooler using the 2015 corrections, compared to the Morgan (2009) correction, yielding corrected values of 137–150.5°C at depths of 2.1–2.2 km.

Anomalously Warm Wells

Well 30-007-20540 (VPR A182) has the highest measured BHT in northeastern New Mexico (Figs. 7 and 8A). A BHT of 275°F (135°C) was measured at a depth of 7074 ft (2156 m; Fig. 8A). Multiple BHT readings at various depths (Fig. 8A) and at least two temperature logs associated with cement jobs were measured in 2005; the deeper of the cement temperature logs is shown in Figure 8A. The anomalously high BHT at ~1375 m (Fig. 8A; bad data?) was derived from a cement bond log and might be suspect data. VPR A182 has been used as a water disposal well since its completion in 2006. Water is injected into the Entrada Sandstone. Based on records on file at the OCD, injection rates were erratic in 2009, suggesting a problem with the well at that time; a wireline temperature log was measured in 2009 (Fig. 8A). Note that the temperatures measured in 2009 are significantly cooler than the measured BHTs from 2005. Injection of water is locally cooling off the well bore and the cooler water may be locally degrading the possible geothermal resource surrounding this well. The uncorrected BHT and gradient for this well are 135°C and ~57°C/km, respectively; the corrected BHT (Morgan, personal commun., 2015) and gradient are 150°C and 66°C/km, respectively.

Three other injection wells (VPR A42, A7, and A49) are located within 8 km of VPR A182. Well 30-007-20143 (VPR A42) has BHT measurements at two intervals; the closest equilibrium log at Chimney Creek is plotted for reference on Fig. 8B. The Chimney Creek log projects to the shallower of the uncorrected values, but fails to predict the high temperatures present below the low thermal conductivity Pierre Shale. The observed BHT is 121°C and the corrected BHT is 137°C at a depth of 2236 m. The gradients for VPR A42 are 50 and 57°C/km, respectively. Well 30-007-20116 (VPR A7 WDW; Fig. 8C) had a wireline temperature log that was run in 2009, about 3.5 years after injection began. In this case, the rate of injection is lower than that in VPR182 and the temperatures measured on the 2009 log are more closely aligned with the uncorrected BHT data, suggesting that cooling by injection is less important in this well. The measured BHT is 108°C at a depth of 2268 m and the corrected BHT is 124°C. The uncorrected gradient for VPR A7 is 44°C/km and the corrected gradient is 51°C/km. Well 30-007-20378 (VPR A99; Fig. 8D) had a temperature log run following a cement job but before the well was completed. This log shows possible influxes of warmer fluid in a narrow zone at ca. 800 m and at about 1050 m. The measured temperature at 2351 m is 107°C, which was corrected to 124°C. The uncorrected gradient for VPR A99 is 42°C/km and the corrected gradient is 49°C/km.

Little information is available for St. Louis Railroad 2 (API 30-007-20406; SLRR2 on Fig. 7) except that this well has the second highest BHT in northeastern New Mexico at 127°C at 2215 m. This well, drilled in 1954, was spud in the Raton Formation and reportedly bottoms in Precambrian basement. The uncorrected gradient is 53°C/km and the corrected geothermal gradient is 60°C/km.

Castle Rock Park Area

The measured BHTs from several wells in the Castle Rock Park area show a decrease of temperature with depth (Fig. 9). The temperatures are higher in the Trinidad Sandstone compared to the underlying Pierre Shale. The ellipses on Figure 9 highlight the wells with the temperature reversal between the Trinidad Sandstone and the Pierre Shale (B220, B219, B215, and B209), or wells with a higher-than-usual temperature or gradient within the Trinidad (B84). The dashed lines on Figure 9 connect BHT pairs that have a normal increase in temperature with depth. The BHT data for WS Ranch NM B2 show a sudden jump within the Trinidad. Note that the upper point of the WS Ranch NM B2 BHT pair lines up well with the ca. 40°C/km gradient of the industry wireline log for this well. The lower point on the B216A is just barely in the Trinidad and may not be in a permeable part of the Trinidad; this point is in a position equivalent to the upper point of the WS Ranch NM B2 BHT pair. A possible explanation for the unusual temperature reversals or jumps in gradient involves a plume or lateral flow of warm water through the permeable Trinidad Sandstone. Only one well in this area, B219, does not exhibit this unusual trend in the Trinidad Sandstone.

A second interesting relationship is observed in the Castle Rock Park area. As mentioned earlier, the Van Bremmer equilibrium log of Edwards et al. (1978) was likely collected in WS Ranch NM B5, which was drilled in the early 1970s. A wireline temperature log measured in a nearby coalbed methane well (30-007-20086, VPR322B H) that was drilled in 1989 closely resembles the equilibrium log, suggesting that in certain cases, particularly in wells that are drilled rapidly with air, industry

TABLE 1. BHT and corrected BHT data for wells drilled in 2011 in the Raton basin.

API	Well Name (VPR)	Well Number	Latitude (NAD83)	Longitude (NAD83)	Elevation (ft.)	Spud Date	Date Measured	Depth (ft)	Depth (m)	Temp (°C)	Temp (°F)	Uncorrected Geothermal Gradient (°C/km)	Corrected BHT (°C) Morgan (2009)	Surface Temp. (°C)	Corrected Geothermal Gradient (°C/km) Morgan (2009)	Corrected BHT (°C) Morgan (2015)	Corrected Geothermal Gradient (°C/km) Morgan (2015)	top of Raton Fm. (ft.)	top of Vermejo Fm. (ft.)
30-007-20990	A	584	36.9732	-104.8364	8231	3/31/11	4/3/11	2725	831	45.6	114	44.1	54.3	8.9	54.6	53.6	53.8	379	2165
30-007-20990	A	584	36.9732	-104.8364	8231	3/31/11	4/7/11	2676	816	43.3	110	42.2	51.9	8.9	52.7	51.3	51.9	379	2165
30-007-20989	A	583	36.9790	-104.8380	8116	3/30/11	4/1/11	1925	587	41.7	107	55.4	46.8	9.2	64.1	48.3	66.8	289	2063
30-007-20989	A	583	36.9790	-104.8380	8116	3/30/11	4/7/11	2591	790	47.8	118	48.9	55.9	9.2	59.2	55.6	58.8	289	2063
30-007-20988	A	568	36.9210	-104.8659	8275	3/28/11	3/30/11	2688	819	45.0	113	44.1	53.6	8.8	54.6	53.0	53.9	311	2105
30-007-20988	A	568	36.9210	-104.8659	8275	3/28/11	4/7/11	2635	803	46.1	115	46.4	54.5	8.8	56.8	54.0	56.2	311	2105
30-007-20987	E	065	36.9574	-104.9366	8521	3/27/11	3/28/11	2828	862	45.0	113	42.5	54.2	8.3	53.2	53.2	52.1	399	2180
30-007-20987	E	065	36.9574	-104.9366	8521	3/27/11	4/5/11	2845	867	45.6	114	42.9	54.8	8.3	53.6	53.8	52.4	399	2180
30-007-20978	A	573	36.9877	-104.9084	8375	3/25/11	3/26/11	2985	910	46.7	116	41.8	56.5	8.6	52.7	55.1	51.1	0	2326
30-007-20978	A	573	36.9877	-104.9084	8375	3/25/11	4/7/11	2995	913	48.9	120	44.1	58.8	8.6	55.0	57.4	53.4	0	2326
30-007-20967	A	574	36.9768	-104.8908	8302	3/22/11	3/24/11	2836	864	48.9	120	46.4	58.1	8.8	57.1	57.1	55.9	417	2218
30-007-20967	A	574	36.9768	-104.8908	8302	3/22/11	4/6/11	2768	844	48.3	119	46.9	57.3	8.8	57.5	56.4	56.5	417	2218
30-007-20984	A	575	36.9828	-104.9168	8490	3/21/11	3/22/11	2975	907	48.3	119	44.0	58.2	8.4	54.9	56.8	53.4	557	2362
30-007-20984	A	575	36.9828	-104.9168	8490	3/21/11	4/6/11	2951	899	48.9	120	45.0	58.6	8.4	55.8	57.3	54.4	557	2362
30-007-20968	A	577	36.9871	-104.9210	8612	3/18/11	3/20/11	2997	913	48.3	119	44.0	58.3	8.2	54.9	56.8	53.3	698	2470
30-007-20968	A	577	36.9871	-104.9210	8612	3/18/11	4/6/11	2951	899	47.8	118	44.1	57.5	8.2	54.9	56.2	53.4	698	2470
30-007-20966	A	572	36.9914	-104.9340	8537	3/16/11	3/18/11	2947	898	45.6	114	41.5	55.3	8.3	52.3	54.0	50.8	579	2339
30-007-20966	A	572	36.9914	-104.9340	8537	3/16/11	3/25/11	2907	886	48.3	119	45.2	57.9	8.3	56.0	56.7	54.6	579	2339
30-007-20970	A	581	36.9861	-104.9429	8701	3/14/11	3/16/11	2670	814	37.2	99	35.9	45.7	8.0	46.4	45.2	45.7	185	1947
30-007-20970	A	581	36.9861	-104.9429	8701	3/14/11	3/24/11	2615	797	40.0	104	40.2	48.3	8.0	50.6	47.8	50.0	185	1947
30-007-20969	A	579	36.9784	-104.9328	8449	3/12/11	3/14/11	2654	809	42.8	109	42.4	51.2	8.5	52.8	50.7	52.2	440	2206
30-007-20969	A	579	36.9784	-104.9328	8449	3/12/11	3/24/11	2615	797	47.8	118	49.3	56.1	8.5	59.7	55.6	59.1	440	2206
30-007-20986	E	068	36.9718	-104.9407	8593	3/10/11	3/12/11	2832	863	45.6	114	43.3	54.8	8.2	54.0	53.8	52.8	411	2182
30-007-20986	E	068	36.9718	-104.9407	8593	3/10/11	3/24/11	2768	844	47.8	118	46.9	56.7	8.2	57.5	55.9	56.5	411	2182
30-007-20986	E	068	36.9718	-104.9407	8593	3/10/11	4/5/11	2766	843	43.3	110	41.7	52.3	8.2	52.3	51.4	51.3	411	2182
30-007-20976	E	066	36.9518	-104.9342	8532	3/8/11	3/9/11	2831	863	43.9	111	41.2	53.1	8.3	51.9	52.1	50.7	390	2196
30-007-20976	E	066	36.9518	-104.9342	8532	3/8/11	3/24/11	2763	842	46.7	116	45.5	55.6	8.3	56.1	54.8	55.2	390	2196
30-007-20977	E	067	36.9448	-104.9341	8487	3/6/11	3/7/11	2648	807	45.0	113	45.3	53.4	8.4	55.8	52.9	55.1	no data	no data
30-007-20977	E	067	36.9448	-104.9341	8487	3/6/11	3/24/11	2613	796	48.3	119	60.7	56.6		71.1	56.2	70.5	no data	no data
30-007-20983	A	565	36.9366	-104.8727	8353	3/3/11	3/5/11	2803	854	45.0	113	42.5	54.1	8.7	53.2	53.2	52.1	411	2243
30-007-20983	A	565	36.9366	-104.8727	8353	3/3/11	3/23/11	2750	838	51.7	125	51.3	60.5	8.7	61.9	59.7	60.9	411	2243
30-007-20985	A	582	36.9462	-104.8569	8200	3/1/11	3/3/11	2622	799	43.3	110	43.0	51.6	9.0	53.4	51.2	52.8	280	2139
30-007-20985	A	582	36.9462	-104.8569	8200	3/1/11	3/23/11	2551	778	48.9	120	51.3	56.9	9.0	61.6	56.6	61.3	280	2139
30-007-20961	A	566	36.9289	-104.8782	no data	2/28/11	3/1/11	2666	813	43.9	111	-	52.4	-	-	51.8	-	no data	no data
30-007-20961	A	566	36.9289	-104.8782	no data	2/28/11	3/23/11	2631	802	49.4	121	-	57.8	-	-	57.3	-	no data	no data
30-007-20962	A	567	36.9305	-104.8721	8320	2/26/11	2/27/11	2695	821	45.0	113	44.1	53.6	8.7	54.6	53.0	53.9	no data	no data
30-007-20962	A	567	36.9305	-104.8721	8320	2/26/11	3/9/11	2615	797	49.4	121	51.1	57.7	8.7	61.4	57.3	60.9	no data	no data
30-007-20963	A	569	36.9200	-104.8778	8333	2/24/11	2/25/11	2686	819	44.4	112	43.6	53.0	8.7	54.1	52.4	53.4	no data	no data
30-007-20963	A	569	36.9200	-104.8778	8333	2/24/11	3/5/11	2618	798	48.9	120	50.3	57.2	8.7	60.7	56.7	60.2	no data	no data
30-007-20964	A	570	36.9160	-104.8726	8375	2/21/11	2/23/11	2752	839	45.0	113	43.4	53.9	8.6	53.9	53.1	53.0	no data	no data
30-007-20964	A	570	36.9160	-104.8726	8375	2/21/11	3/8/11	2710	826	49.4	121	49.4	58.1	8.6	59.9	57.4	59.1	no data	no data
30-007-20965	A	571	36.9129	-104.8784	8353	2/19/11	2/21/11	2689	820	44.4	112	43.6	53.0	8.7	54.1	52.4	53.4	no data	no data
30-007-20965	A	571	36.9129	-104.8784	8353	2/19/11	3/8/11	2526	770	47.2	117	50.1	55.1	8.7	60.3	54.9	60.1	no data	no data
30-007-20965	A	571	36.9129	-104.8784	8353	2/19/11	4/6/11	2534	772	43.9	111	45.6	51.8	8.7	55.8	51.6	55.6	no data	no data
30-007-20973	B	326	36.8073	-105.0008	7979	2/16/11	2/8/11	2581	787	40.0	104	38.9	48.1	9.4	49.2	47.8	48.7	94	2422
30-007-20973	B	326	36.8073	-105.0008	7979	2/16/11	2/24/11	2536	773	43.9	111	44.6	51.8	9.4	54.8	51.6	54.5	94	2422
30-007-20979	B	323	36.8120	-104.9796	7802	2/14/11	2/8/11	2413	735	37.8	100	38.0	45.1	9.8	48.1	45.3	48.2	0	1855
30-007-20979	B	323	36.8120	-104.9796	7802	2/14/11	2/24/11	2309	704	42.2	108	46.1	49.1	9.8	55.9	49.5	56.5	0	1855
30-007-20974	B	327	36.7997	-104.9943	8090	2/6/11	2/24/11	2736	834	43.9	111	41.6	52.7	9.2	52.1	51.9	51.2	253	2195
30-007-20980	B	328	36.7905	-104.9833	8180	1/30/11	2/22/11	2738	835	43.3	110	41.1	52.1	9.0	51.7	51.4	50.8	no data	no data
30-007-20982	B	330	36.7853	-105.5761	8287	1/27/11	1/30/11	3017	920	40.0	104	33.9	50.0	8.8	44.8	48.5	43.2	544	2416
30-007-20982	B	330	36.7853	-105.5761	8287	1/27/11	2/22/11	2867	874	43.3	110	39.5	52.7	8.8	50.2	51.6	49.0	544	2416
30-007-20981	B	329	36.7967	-105.0071	8189	1/19/11	1/20/11	2494	760	37.8	100	37.8	45.5	9.0	48.0	45.4	47.9	400	2237
30-007-20981	B	329	36.7967	-105.0071	8189	1/19/11	2/22/11	2784	849	45.0	113	42.4	54.0	9.0	53.0	53.1	52.0	400	2237

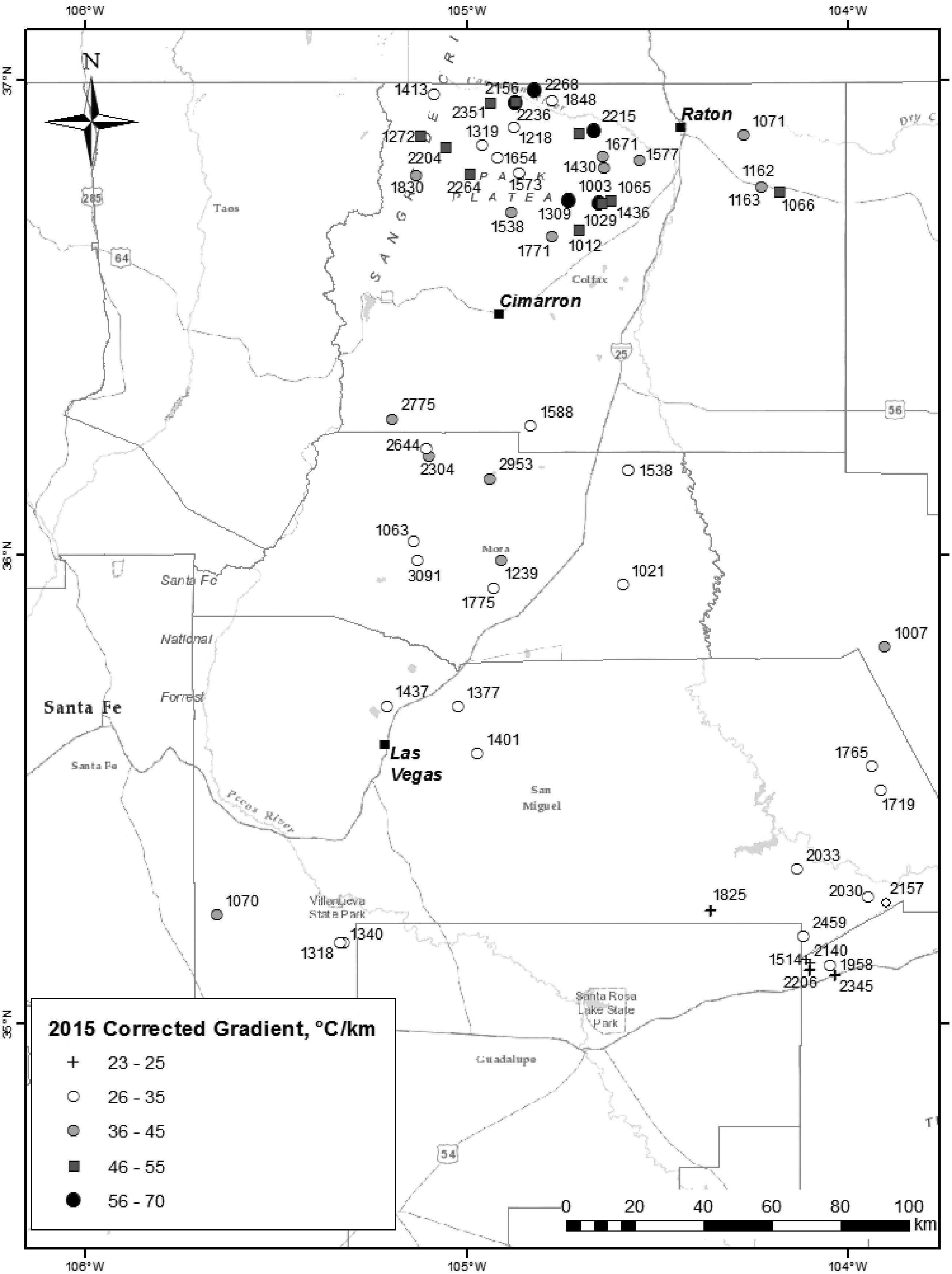


FIGURE 5. Locations of deep wells (>1000 m) in the Raton Basin. The deep wells are coded according to corrected geothermal gradient; the numbers by each well are depth in meters.

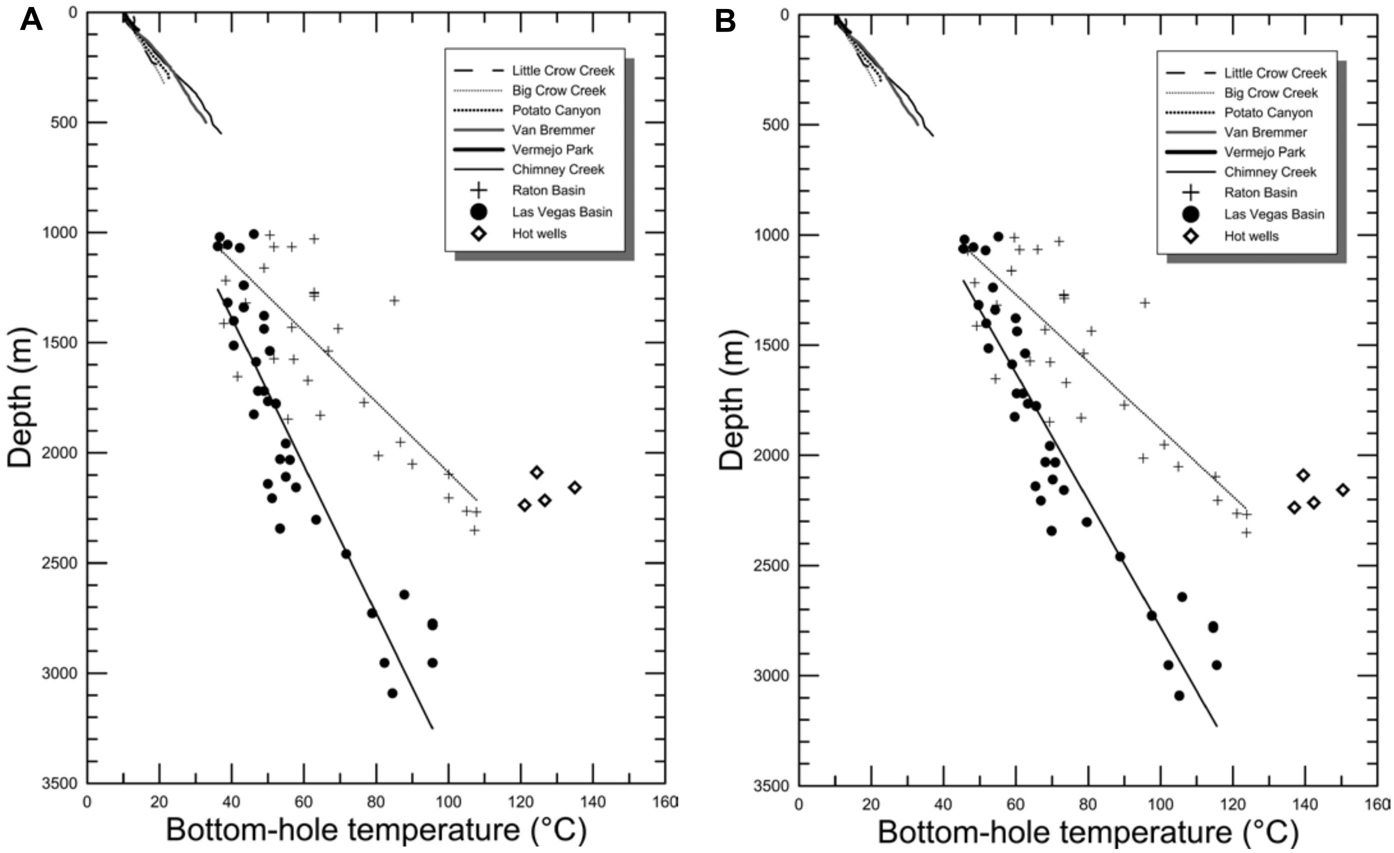


FIGURE 6. Plot of (A) corrected and (B) uncorrected BHT for wells that are deeper than 1000 m from the Raton and Las Vegas basin/Tucumcari basins compared to equibrium temperature logs associated with the heat flow data of Reiter et al. (1975) and Edwards et al. (1978).

wireline logs can provide good geothermal gradient data. This well, which is located 0.85 km SE of the WS Ranch well, was spud on June 4, 1989 and was logged on June 22, 1989.

DISCUSSION

BHT Corrections for Drill Holes in northeastern New Mexico

Two BHT corrections that have been applied to the Raton basin of Colorado (Morgan, 2009; Morgan, personal commun., 2015) were applied with variable success to petroleum wells penetrating the basins and arches of northeastern New Mexico. Neither correction matched the limited measured equilibrium or DST data or abundant measured BHT at depths <260 m; the 2009 correction tends to underestimate temperature, commonly giving values less than the measured BHT, and the 2015 correction, designed to fit data from deeper wells, is not applicable. The 2009 correction underestimates the temperature at shallow depths because this correction is derived from wells in Oklahoma where the drilling fluid, heated by solar radiation in the mud pit, actually heats the rocks surrounding the well bore. The measured BHT in these shallow holes, which usually have little drilling disturbance because of the short drill times, can provide a reasonable estimate of the true temperature at these depths. BHT values calculated using the 2015 Morgan correction are consistent with both measured temperatures and cement bond log data at depths between 520 and 1000 m. Between 645 and 860 m, both corrections yield similar values. The 2009 BHT correction values are consistently slightly higher than the 2015 correction values at depths >860 m; the 2015 correction best fits the projection of deep equilibrium logs to the depth level of the BHT measurements (Appendix 1). To summarize, correction of measured BHT in northeastern New Mexico is a two-step process: (1) use measured BHT values at depths <260 m, and (2) use the 2015 Morgan correction for depths >260 m. Further refinements of BHT corrections for this area will be the topic of future research.

Does the Raton Basin of New Mexico have Geothermal Potential?

In general, based on analysis of available regional-scale BHT data, northeastern New Mexico has limited geothermal power potential. The regional scale uncorrected geothermal gradients determined from wells with a depth >1 km are 25.6 ±2.6°C/km for the Las Vegas basin/Tucumcari basin and 40.5 ±9.6°C/km for the Raton basin with surface intercept values of 7.4 ±5.8°C and 3.0 ±3.0°C , respectively. Regional scale gradients using corrected BHT are 34.0 ±2.6°C/km for the Las Vegas basin/ Tucumcari basin and 52.0 ±9.6°C/km for the Raton with surface intercept values of 12 ±6°C and 2 ±3°C, respectively. The depth to the 150°C isotherm is more than 4 km in the Las Vegas/ Tucumcari basins and approximately 3 km in the Raton basin.

The measured BHT values for two wells (VPR 182 and A42) in the Stubblefield Canyon field lie off of the regional trend, defining a small 7 km by 8 km area in the central Raton basin just south of the New Mexico-Colorado state line that has anomalously warm temperatures (Fig. 7). The connection of this area to the high temperature measured in St. Louis Railroad 2 is not clear; the anomaly associated with SLRR2 appears to be separate. The temperatures from the warm wells are compared to temperatures in neighboring deep injection wells, equilibrium temperatures measured at heat flow sites in this area, and corrected BHT values from the Colorado portion of the Raton basin (Morgan, 2009) in Figure 10. This diagram summarizes three key points. First, background gradients calculated using only the corrected BHT values from the local injection wells indicates that the depth to the 150°C isotherm is ca. 2.6–2.7 km beneath the central Raton basin. The corrected BHT values for the hottest well is 150°C at 2156 m in the localized area around VPR 182A. Second, the equilibrium logs are too shallow to accurately predict the elevated temperatures below the Pierre Shale recorded in the measured BHT data in this part of the basin. Finally, and most importantly, the temperatures in Colorado in the 1250 to 2000 m depth range are significantly higher compared to those in a similar depth range in New Mexico. For example, at 1500 m in Colorado, temperatures are on average about 85°C, but in New Mexico at 1500 m, the temperatures are 60 to 80°C (Figs. 6, 10).

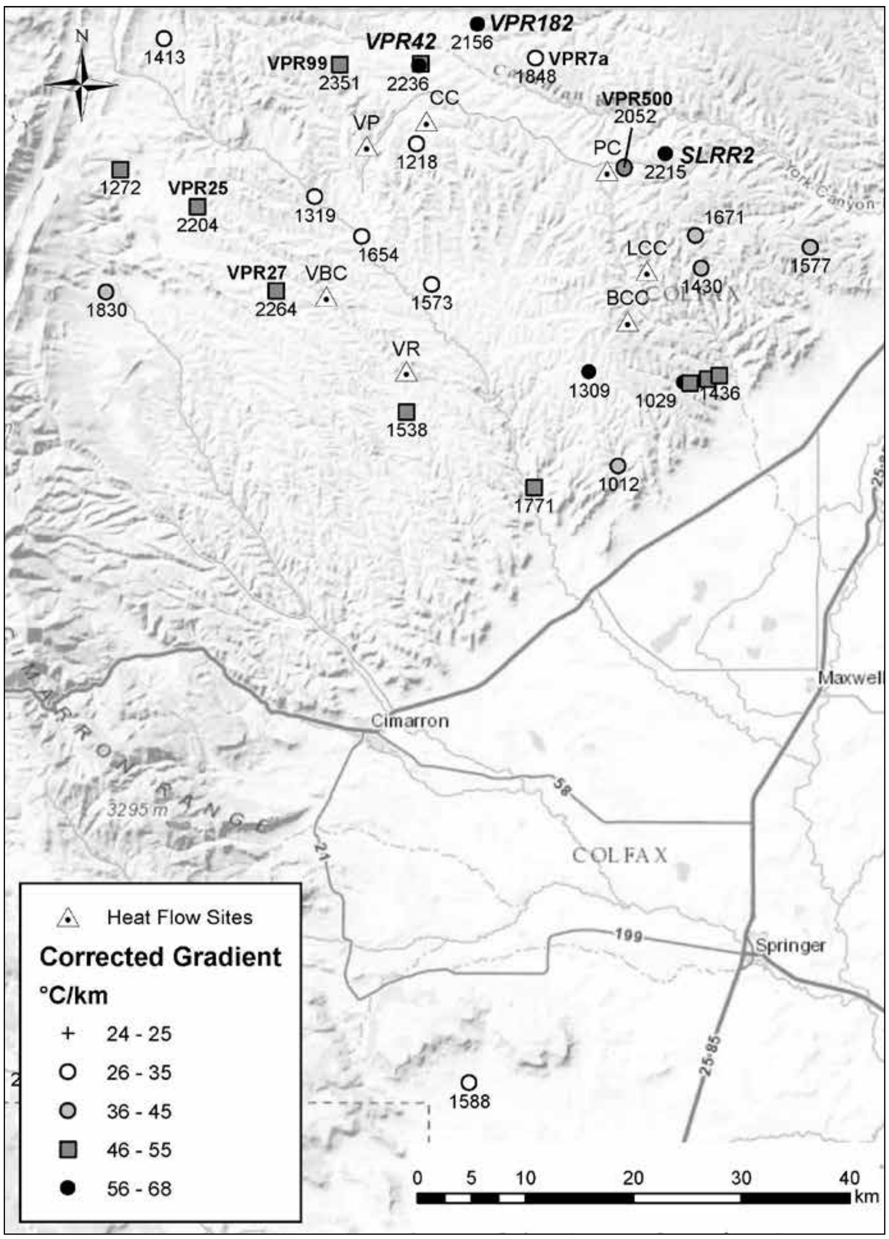


FIGURE 7. Expanded view of the Raton basin of New Mexico. The hot wells (bold italic) and injection wells are labled. The number by each well is well depth. SLRR= St. Louis Railroad 2. Heat flow sites: BCC= Big crow Canyon; CC= Chimney Creek; LCC= Little Crow Creek; PC= Potato Canyon; VBC= Van Bremmer Creek; VP=Vermejo Park; VR=Vermejo River.

Geographic Trends in Gradient

If gravity-driven fluid flow through aquifers in the Laramide and Ancestral Rockies basins of northeastern New Mexico was important in controlling the thermal regime in this area, we would expect to see cooler temperatures in the recharge area along the Sangre de Cristo Mountain front and higher temperatures in the discharge zones along the drainages on the High Plains. Instead, we observe that the highest temperatures in the Raton basin are located near the axis of the basin and warm (45°C) water is moving through the Trinidad Sandstone aquifer near the mountain front. Furthermore, BHTs in the Las Vegas basin/Tucumcari basin south of the Cimarron Arch are cooler (85°C at 3091 m) compared to those in the southern Raton basin at similar depths and the geothermal gradients are lower. The observed temperature patterns in the southern Raton basin and the Las Vegas basin may be attributed to (1) erosion of low thermal conductivity Cretaceous shales from the Las Vegas basin, (2) localized migration of warm fluid along buried basement structures or fractured middle-Cenozoic laccoliths and dike-sill complexes in the Raton basin, or (3) developing magmatism beneath the Raton basin.

Thermal conductivity structure of the basins.

As illustrated in the cross section in Figure 11, the Pierre Shale has been removed by erosion from the Las Vegas basin and the Cretaceous shale units below the Pierre Shale are thinned by erosion to the south. The isotherms

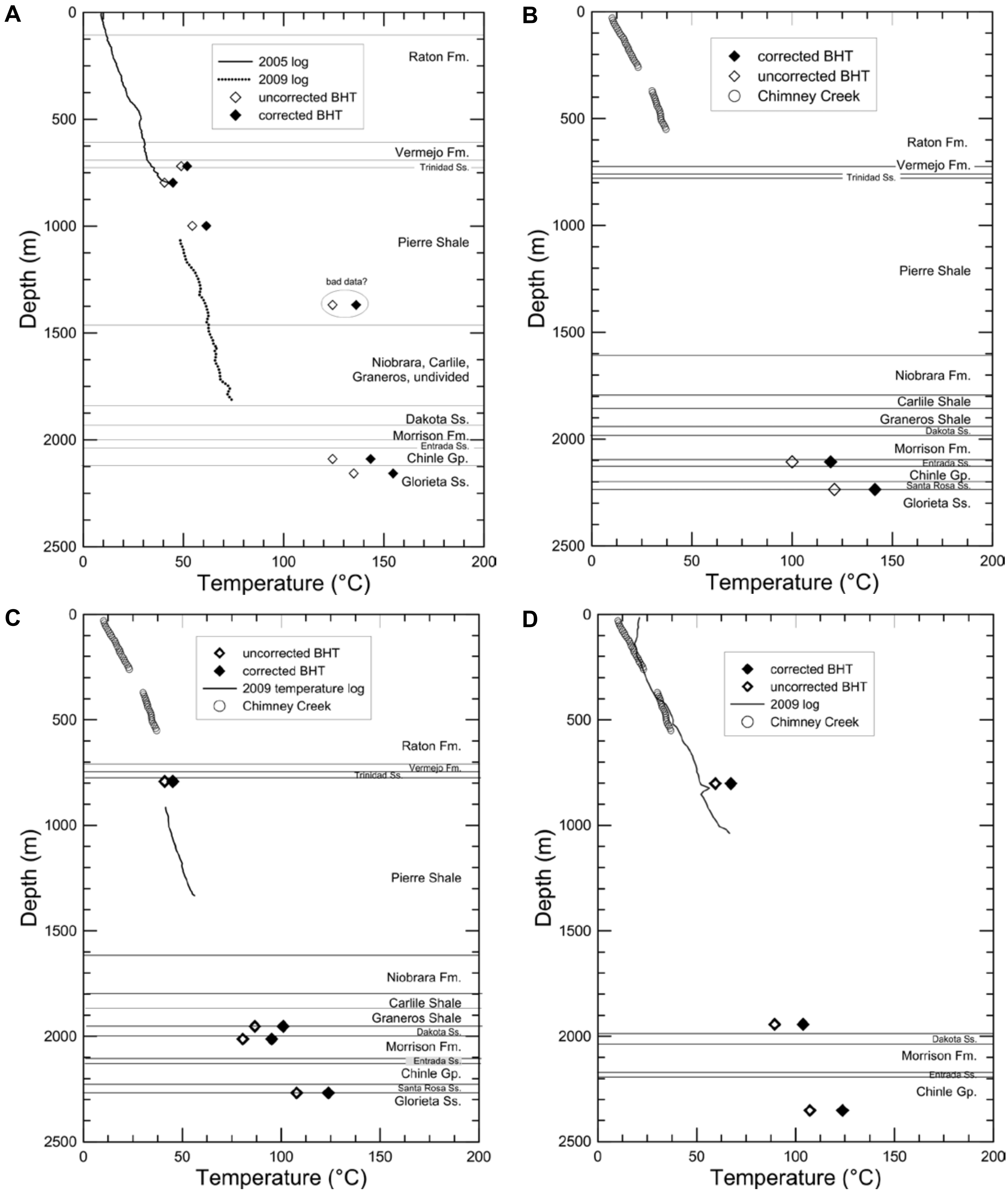
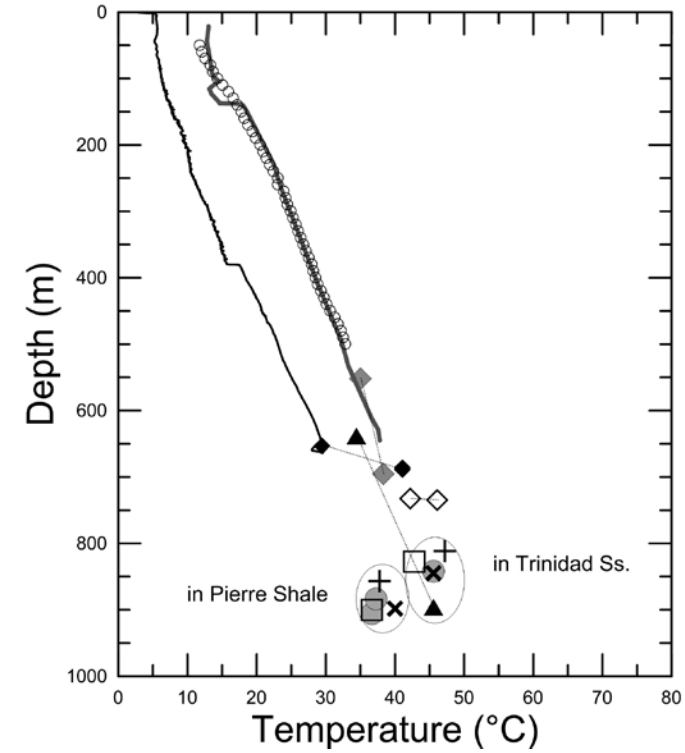


FIGURE 8. Temperature versus depth plots for four injection wells in the Stubblefield Canyon well field. Lithologic picks are from C-105 reports for these wells. The open symbols are measured BHT; the solid symbols are corrected BHT. A. Well VPR A182. The black line is a wireline temperature log run in 2005 following a cement job. A second wireline log was measured in 2009 (dotted line) after water had been injected into the well for 3.5 years. (B) Well VPR A42. Chimney Creek equilibrium log shown for reference. C. Well VPR A7. Black line is 2009 industry wireline log. D. Well VPR 99. Black line is 2009 industry wireline log.



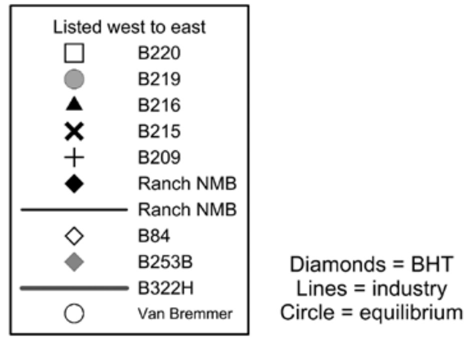


FIGURE 9. Comparison of thermal data from injection wells in the Castle Rock Park gas well field in the Raton Basin of New Mexico. The Van Bremmer well of Edwards et al. (1978) and the VPR B322H well are about 0.85 km apart and the logs overlap, indicating that, in certain cases, industry wire-logs compare favorably with equilibrium logs. The positive shift of BHT in the Trinidad Sandstone compared to the underlying Pierre Shale might be caused by lateral flow of warmer water in the sandstone.

derived from uncorrected BHT data gathered during this investigation clearly show a rise in both temperature and geothermal gradient toward the north. The effect is most dramatic beneath the low thermal conductivity Pierre Shale.

Buried structures and old intrusions

Earthquake activity in the Raton basin has been on the rise since 2001; about a dozen M>4 earthquakes have been measured between 2001 and 2013. Rubinstein et al. (2014) and Barnhart et al. (2014) tie the increased seismic activity in the Raton basin to injection associated with coalbed methane development. An interesting outcome of the recent focus on monitoring earthquakes in the Raton basin is the delineation of possible buried faults in the Precambrian basement that strike NNE (Rubinstein et al. 2014; Barnhart et al., 2014). Warm fluids may have been leaking up along these structures prior to their recent detection due to increased seismic monitoring. In addition, the presence of 24 to 35 Ma laccoliths and dike and sill complexes in the basin and in the adjacent mountains suggests the possibility that these features are also in the subsurface, but have not been recognized. If these igneous rocks have fracture permeability and if the intrusions penetrate aquitards, these features could provide avenues for the localized rise of warm fluids.

Young magmatism

Young volcanism in the vicinity of Capulin volcano is more widespread and is younger than has been previously recognized (Zimmerer et al., 2014). No deep drill holes have been drilled in this area and no data from shallow water wells are currently available, so the thermal state of the area around Capulin

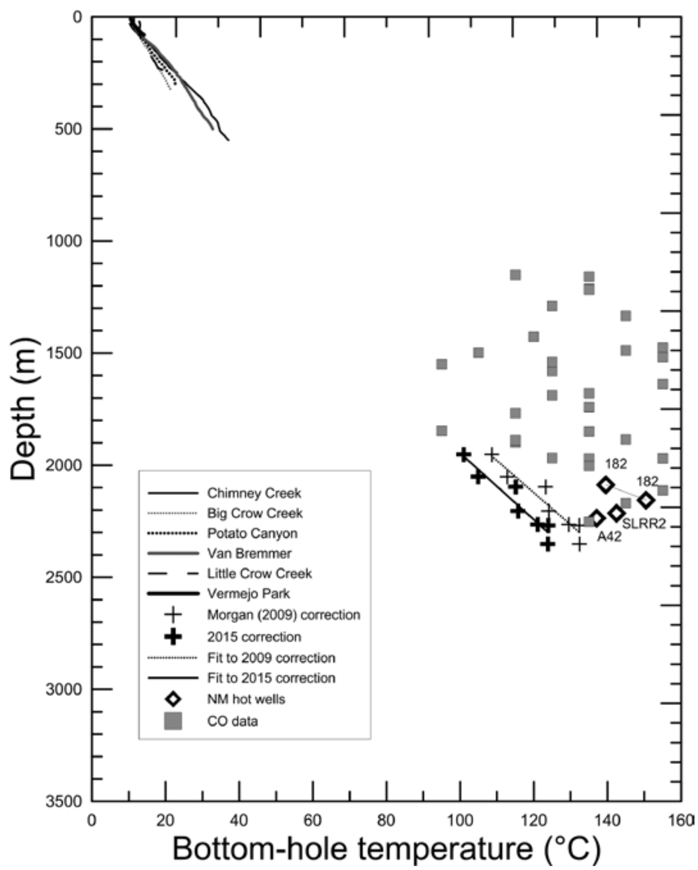


FIGURE 10. Comparison of deep well (>1850 m) BHT data from the Raton Basin of New Mexico with the Colorado Raton Basin data of Morgan (2009). Corrected BHT data and associated gradients using both the 2009 and 2015 corrections for the seven deep injection wells in New Mexico are assessed. The rest of the BHT data on the plot are corrected using Morgan (2009) to facilitate comparison to the published Colorado data. The equilibrium logs of Reiter et al. (1975) and Edwards et al. (1978) are also shown.

volcano is unknown. No earthquakes have been detected near the volcano. Focal mechanisms of the recent earthquakes beneath the Raton basin and subsidence and uplift in the basin detected by InSAR data are not indicative of present-day magmatic activity (Barnhart et al., 2014). Although Reiter et al. (2010) point out that repeated magmatic intrusions over time scales of millions of years can elevate surface heat flow above mafic intrusions, the volcanic record of surface eruptions in the Capulin area record episodic activity and the vents do not stay in a single locality over long periods of time.

SUMMARY

The potential of commercial-scale geothermal power production in northeastern New Mexico using binary technology is low, although small-scale production using a 2 MW binary plant to power pumps in the gas fields or for small community use are possibilities. Regional scale gradients using corrected BHT from drill holes deeper than one kilometer are 31.2 ±2.6°C/km for the Las Vegas basin/Tucumcari basin and 46.1 ±9.6°C/km for the Raton basin with surface intercept values of 10.8°C and 6.3°C, respectively. The southern boundary of the prospective geothermal resource identified in the Colorado portion of the Raton basin by Morgan (2009) does extend a few kilometers into New Mexico; however, the temperatures on the margin of the anomaly are significantly lower than those observed in the middle of the anomaly in Colorado. The highest measured BHT in northeastern New Mexico is 135°C (corrected to 150°C) at 2156 m. The 150°C isotherm is shallower (1500 m) in Colorado. The background gradients derived from deep injection wells in the Stubblefield Canyon gas field predict that a temperature of 150°C is reached at depths of 2.6–2.7 km. Although the temperatures and the drilling depths to 150°C in the Raton basin might be marginally prospective, the fluid production rates from underpressured the Entrada Sandstone and the Glorieta Sandstone are likely to be too low for economic development of this resource in New Mexico. In addition, geothermal development may be hindered by concerns about induced seismicity. Although the earthquakes in the Raton area have been tied to injection (Rubinstein et al. 2014; Barnhart et al., 2014), that conclusion is equivocal because of the fact that the "injection" is gravity fed and because of the difference in the great depth of earthquakes relative to the injection horizons.

The source of the heat in the center of the Raton basin remains a puzzle. The thermal structure of the basin is controlled in part by the presence of low-thermal conductivity Cretaceous shales that elevate the temperatures of the underlying section through a "thermal blanketing" effect. The relative role of elevated mantle

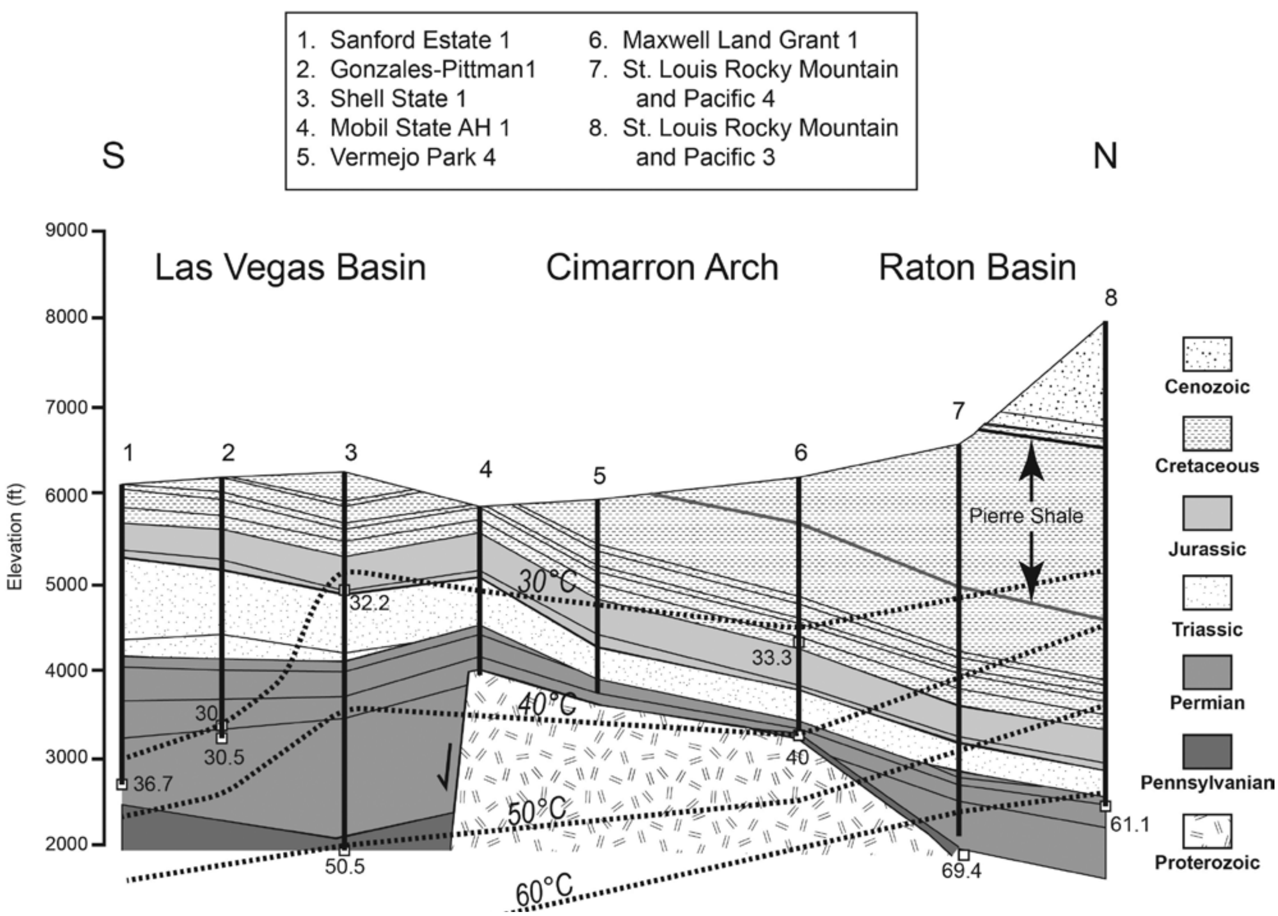


FIGURE 11. South to north cross-section through northeastern New Mexico modified from Broadhead (2008). Dashed lines are isotherms based on BHT data. Elevated geothermal gradients coincide with preserved Pierre Shale.

heat flow and hydrologic conditions in the basin needs to be evaluated in detail.

ACKNOWLEDGMENTS

Discussions with Paul Morgan, Tom Tourek, James Witcher, and Ron Broadhead helped shape this paper. Students Mussie Tewelde, Matthew Sophy, and Zeke Salez worked hard to gather the BHT and wireline temperature log data used in this investigation. Richard Kelley helped with the construction of the maps. Thanks to Paul Morgan and James Witcher for their thoughtful and constructive reviews. This project was supported by DOE grant NM-EE0002850.

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