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Dissertation for Southern Methodist University

PAPER III

THERMAL REGIME OF A LARGE MIDCONTINENT OIL FIELD (EL DORADO, KANSAS) FROM HIGH-RESOLUTION TEMPERATURE LOGS

ABSTRACT

Analyses of a suite of high-resolution temperature logs from six currently nonproducing wells of the East and West Shumway domes in the El Dorado oil field, a large, long-term producing field in south-central Kansas, illustrate generally conductive, equilibrium temperature well profiles. The results demonstrate that these types of logs can provide reliable, equilibrium-temperature measurements in an active petroleum setting. Lower temperature measured in two of the wells over the East Shumway Dome appear to be the result of a significant change in thermal gradient, perhaps from mass transport of hydrocarbons and/or in situ thermal conductivity changes related to the presence of hydrocarbons, and not inter-well lithologic variability. A preliminary analysis of high-resolution temperature logs and log-header derived bottom-hole temperature data (BHT) at the top of two productive zones (the Kansas City and Arbuckle Groups) within the West Shumway Dome suggests that the anomalously high BHT data present at the top of both horizons are close to the actual formation temperature, and encompass a much broader region of the dome than previously believed

INTRODUCTION

Thermal disturbances have been observed for many years in a variety of petroleum settings [e.g., *Roberts*, 1980]. The rapid upflow and migration of hydrocarbons, and thermal effects created by complex structure may produce strong surficial temperature anomalies centered on oil and/or natural gas deposits. Even in a static conductive setting, the presence of low thermal conductivity natural gas (0.05 Watts per meter-degree Kelvin, W/m·K), oil (0.2 W/m·K), and water (0.6 W/m·K) in the pore space may contribute to unusual thermal conditions at depth.

Thermal anomalies have been identified in both active and static hydrocarbon regimes with the aid of bottom-hole temperature (BHT) data. However, any thermal anomalies delineated in such a manner are difficult to interpret correctly because BHT data are not equilibrium temperature measurements and because the errors of BHT measurements are large and may be systematic. Furthermore, BHT data provide little if any insight into the mechanism responsible for the thermal disturbance (i.e., fluid migration versus a change in heat-flow with depth). A better method to investigate the source and spatial extent of thermal anomalies is with high-resolution temperature logs.

Recent advances in technology including fibre-optic [*Förster et. al.,* 1997] and computer tools [*Wisian et. al.,* 1998], as well as electric-line tools [*Blackwell and Spafford,* 1987] allow the routine acquisition of high-resolution (± 0.001 °C) temperature logs that record temperature as a function of depth with sub-meter resolution (0.1 m).

High-resolution temperature logs have been acquired in producing and nonproducing oil, gas, and geothermal wells and successfully used to detect upflow and interpret small-scale lithologic variations [*Blackwell and Steele,* 1989; *Blackwell et. al.*, 1999]. We use high-resolution temperature logs from the El Dorado oil and gas field (Fig. 1), Butler County, Kansas, to characterize a portion of the thermal regime of a large, long-term producing, Midcontinent oil field.

The El Dorado Field is an old field (discovered in 1915), consisting of seven fault-bounded domes striking roughly parallel to the Nemaha ridge (azimuth 020°) in south-central Kansas [*Fath,* 1921; *Reeves,* 1929]. The El Dorado field has produced steadily (~300 million bbl, cumulative) from Ordovician sands (Simpson Group) dolomites (Viola and Arbuckle Groups), Upper Pennsylvanian carbonates (the Lansing and Kansas City Groups), and Lower Permian sands (Admire Group) [*Ramondetta,* 1990]. A significant pre-Pennsylvanian unconformity is present throughout Kansas, and is particularly prominent in the El Dorado Field [*Walters,* 1958]. This unconformity represents the contact between the younger, overlying Pennsylvanian shales of the Cherokee Group and the fractured and weakly deformed lower Paleozoic formations. Below the unconformity is Precambrian granitic basement [*Ramondetta*, 1990].

We discuss in this paper six high-resolution temperature logs acquired in nonproducing wells in and around the West and East Shumway domes along the western margin of the El Dorado field. This project is the initial phase of a study to investigate the thermal regime in Midcontinent oil fields using high-resolution temperature logs. The six logs described here were collected in a period of three days in the summer of

1999. Additional logging is planned in the future to develop a detailed data set for comparison to the log-header derived BHT data that indicate a thermal anomaly of as much as 9°C associated with the field. The geologic features of the field and the sites of the logged wells are shown on the map in Figure 1. A schematic cross-section (X-X') through the fault-bounded West and East Shumway domes is shown in Figure 2 (the location of the cross-section appears as a dashed line in Figure 1). The approximate on-strike projected location of five of the wells discussed in this study along with the total depth logged in each well also are shown. Because the hydrocarbon reservoirs at El Dorado are characterized by limited connectivity, isolated oil/gas pockets are present throughout much of the field [*Ramondetta,* 1990]. These isolated hydrocarbon pockets occur as thin lenses situated above the fault contact between the West and East Shumway domes (Fig. 2). Any relief across the pre-Pennsylvanian unconformity by means of faulting or differential erosion should juxtapose units with contrasting thermal conductivity (i.e., the shales and sandstones of the Cherokee Group versus carbonates of the Arbuckle Group) and thus may generate local conductive thermal anomalies.

The effect of discrete, static, fluid bodies and contrasting thermal-conductivity units to the overall thermal regime of the field is unknown as this stage of the study, because of the wide spacing of the logged wells. However, the thermal conditions in these individual wells will be discussed in a following section.

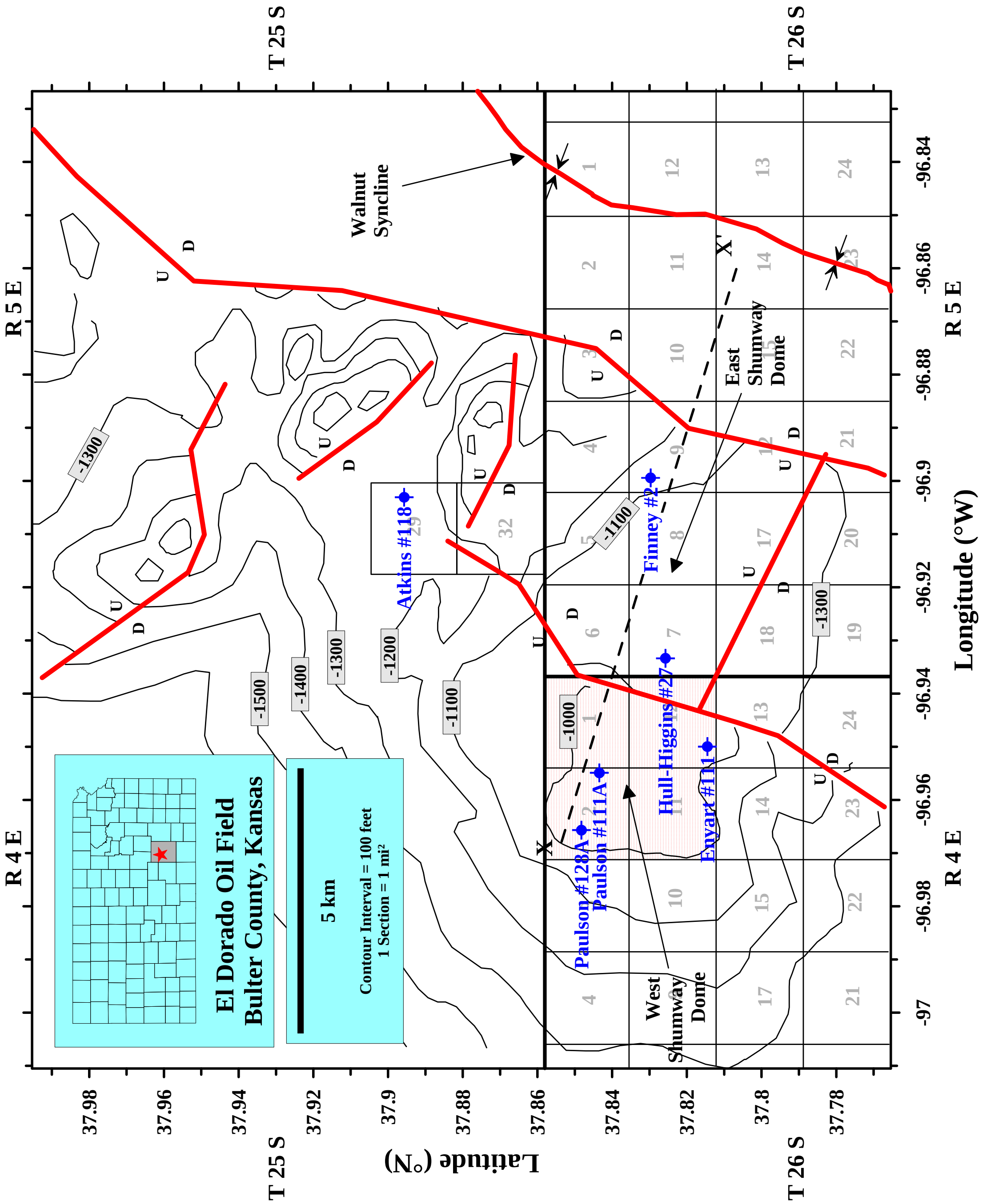

Figure 1. Location of El Dorado oil field, Kansas. The wells logged in this study appear as black dots. The stipled area represents the sections containing wells with high-resolution temperature logs and well-header bottom-hole temperature data. The dashed line labeled X-X' is the approximate location of the cross-section presented in Figure 2. One section is equal to 1 mi^2. Structural data modified from *Ramondetta* [1990].

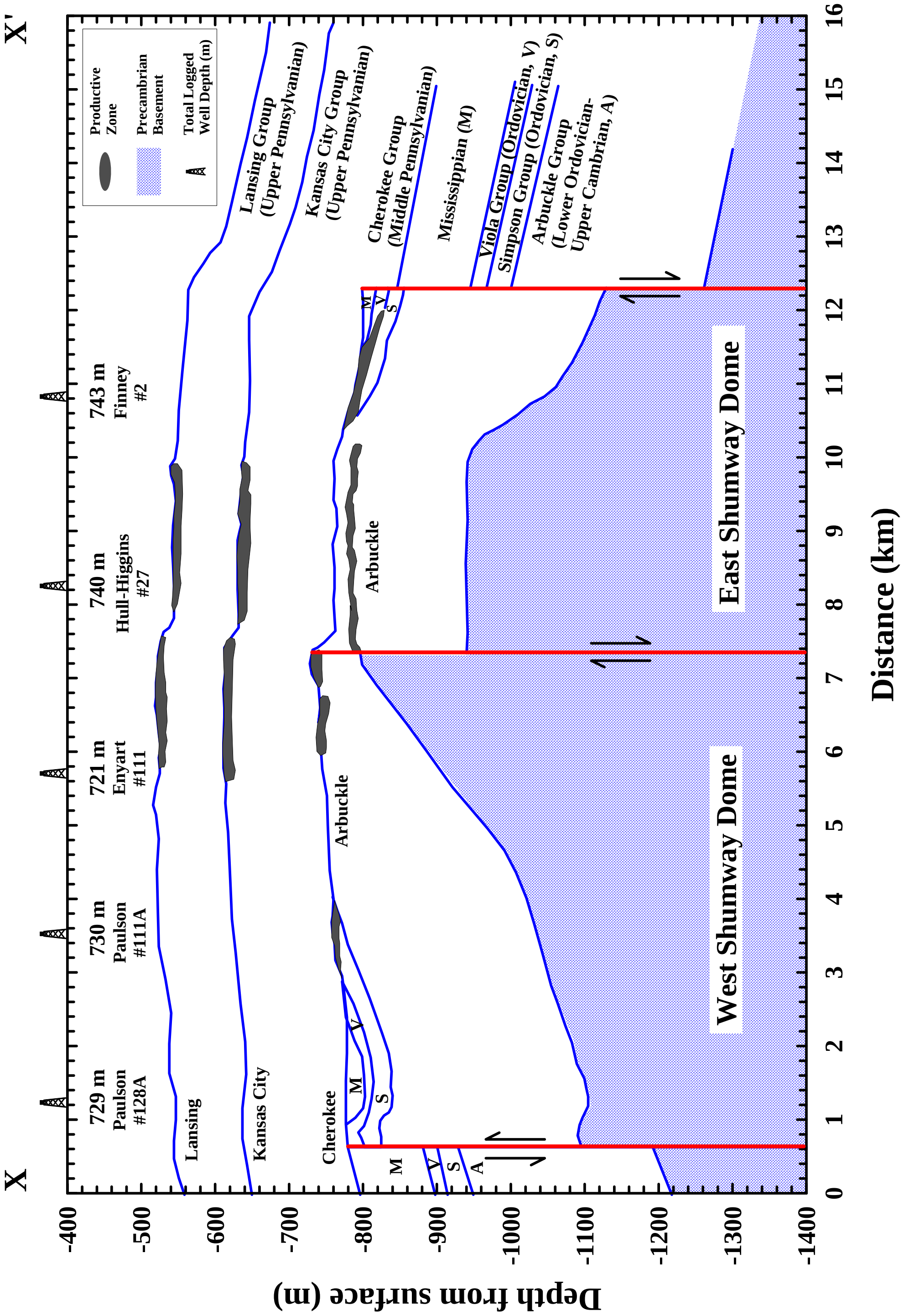

Figure 2. Schematic cross-section across the West and East Shumway domes, El Dorado. Well-locations are approximate. Note that the vertical exaggeration (28x) makes the slightly dipping normal faults bounding the Shumway domes appear vertical. Modified from *Ramondetta* [1990].

HIGH-RESOLUTION TEMPERATURE LOGS

The logged wells were drilled originally to target the Arbuckle Group at ~710-760 m depth but were either marginal or had watered out. Consequently, all the wells have been shut-in for some time, accumulating a column of oil in the borehole generally overlying water and allowing thermal equilibrium to be reached in the absence of fluid flow within the borehole. Generally, little pressure build-up occurred in each well owing to the paucity of natural gas throughout the field. The temperature-depth curves for all six wells that were logged are shown in Figure 3. The strong negative-temperature shift near 80 m depth in the Paulson #111A well (and between 80 and 120 m in three of the other wells) is the location of the air-fluid contact (i.e., water-table). This sort of a deflection is a general characteristic of temperature logs acquired in mostly fluid-filled wells and is due to the fact that the moving probe does not reach thermal equilibrium in the air column part of the well. All six wells were undisturbed for a period of months to years prior to logging and display generally conductive (linear by segments) temperature profiles. The temperature log of Enyart #111, however, displays some upflow in the borehole between 150 and 380 m (possibly as deep as 570 m), causing the measured temperatures to seem hotter for the disturbed depth interval than in all of the other wells. The main effect of this upflow within the well bore is that the upper part of the well is hotter than projected from the temperature information at the bottom part of the well. Additionally, because the holes are open for the last ~16 m, some minor upflow is present

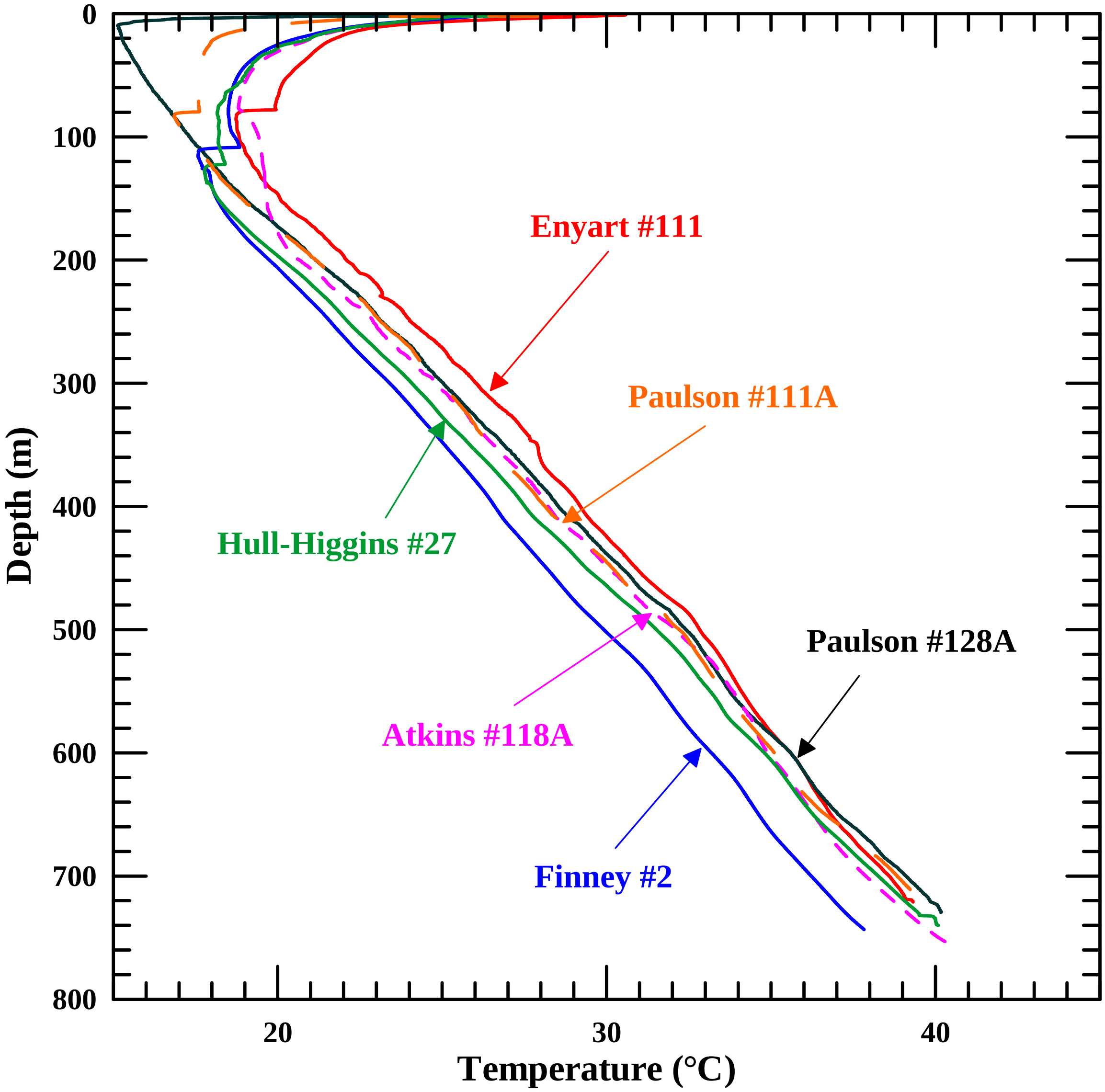

Figure 3. High-resolution temperature logs acquired in El Dorado field during the summer of 1999. All wells were logged with an electric-line temperature-probe at 8 m/min. No post-processing was performed. All the logged profiles generally seem conductive with the exception of Enyart #111 well, which is disturbed in the upper part.

in a few of the logs but is restricted to the last few meters of the log. The long production time for the field does not appear to have changed the temperatures in the Arbuckle reservoir except to a very extent.

The temperatures and the gradient patterns for five of the six wells are nearly identical-the variation in BHT is only about 1°C. However, thermal conditions in Finney #2 seem to be significantly cooler than the other wells. The temperature log BHT in Finney #2 is about 2°C less than the average temperature log BHT in wells near the crest of the West and East Shumway domes. Interestingly, the next lowest temperature-depth curve is that of Hull-Higgins #27, which also is situated within the East Shumway dome block.

It is instructive to compare temperature and thermal-gradient logs recorded in the Paulson #111A and Finney #2 wells (Fig. 4a), Finney #2 and Hull-Higgins #27 wells (Fig. 4b), and Paulson #111A and Hull-Higgins #27 wells (Fig. 4c) directly so that the salient features of high-resolution temperature logs are readily apparent. In Figure 4a-4c, the gradient log was formed by simply calculating $\Delta T/\Delta Z$, where T is temperature, and Z is depth. All the gradient logs presented in Figure 4 have been smoothed with a 7-point (0.6 m) moving-average window for clarity.

If conditions in a well are conductive, then the product of the thermal gradient and thermal conductivity is the vertical heat-flow out of the well. This is Fourier's Law: if the heat-flow is constant with depth, any decrease/increase in thermal conductivity with depth should cause the thermal gradient to increase/decrease [e.g., *Blackwell and Steele*, 1989; *Blackwell et al.*, 1999]. For example, the Finney #2 gradient log (Fig. 4a) is much less noisy than the Paulson #111A gradient log, and, therefore, is able to resolve small

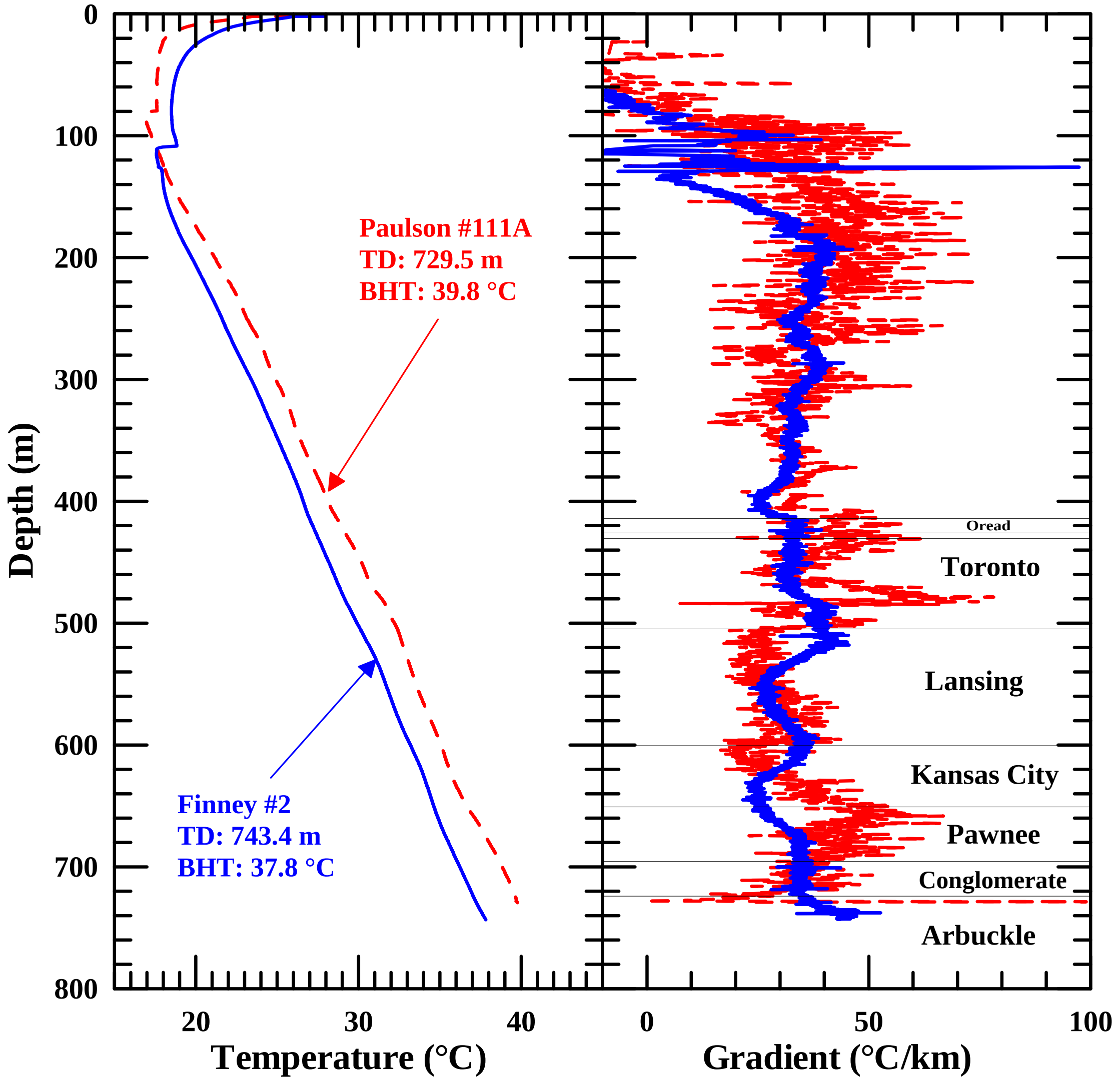

Figure 4a. A comparison of high-resolution temperature measurements logged in the Paulson #111A and Finney #2 wells, El Dorado, Kansas. Finney #2 appears cooler than Paulson #111A. Whether this is a direct result of the two wells being in the East and West Shumway dome, respectively, is unknown. The gradient logs appear different, partially because the Paulson #111 log is noisy, rendering it difficult to assess any lithologic contribution to the observed temperature differences.

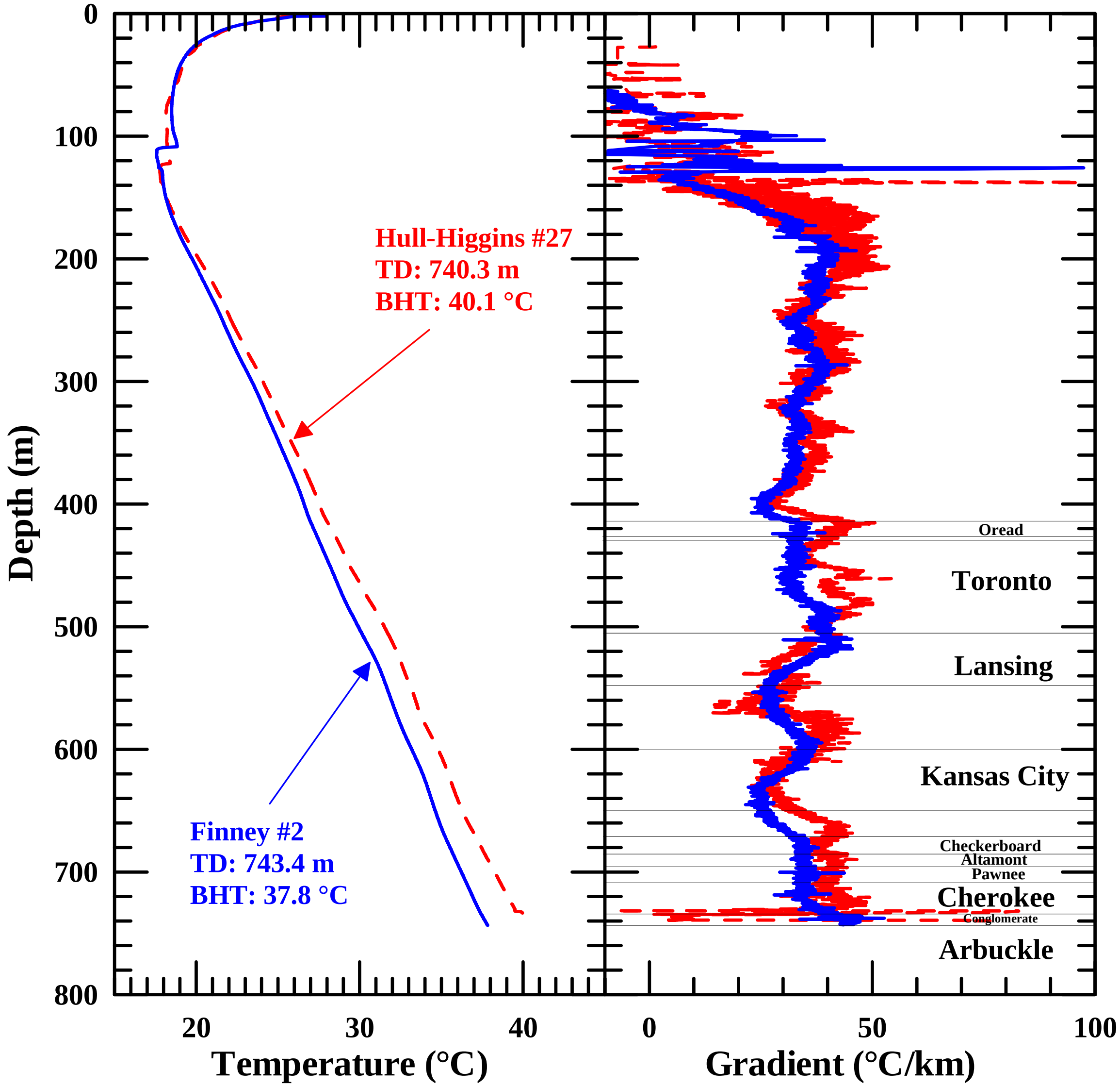

Figure 4b. Comparison of high-resolution temperature measurements in the Hull-Higgins #27 and Finney #2 wells, El Dorado, Kansas. Both gradient logs are quiet, and seem to be well-correlated as expected because both wells are situated over the East Shumway dome. The Hull-Higgins #27 gradient log is systematically higher for the entire length of the log, suggesting that the lower temperature in Finney #2 is due to a real heat flow difference and not a convective disturbance from past-production or upflow.

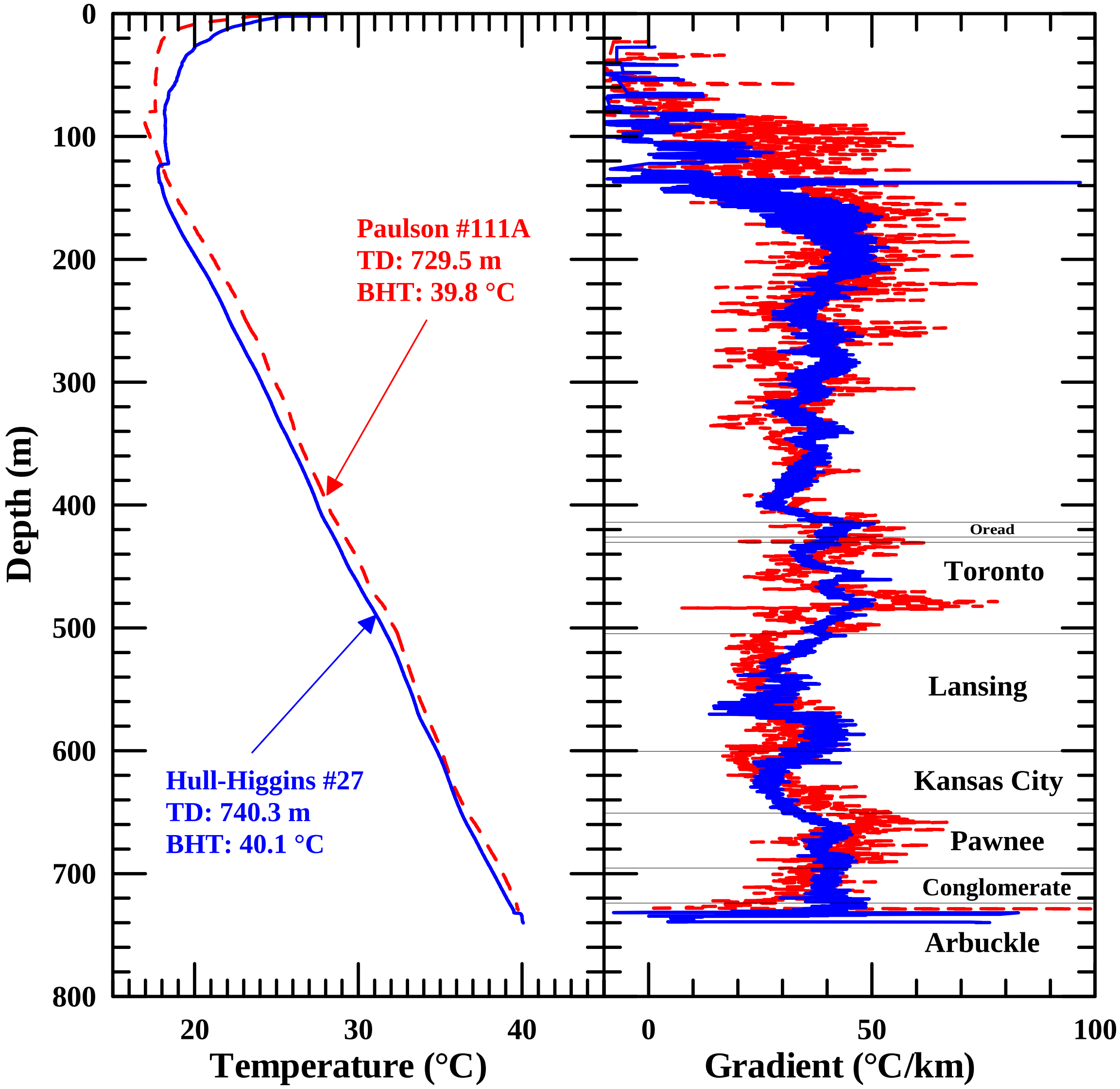

Figure 4c. A comparison of high-resolution temperature measurements logged in the Paulson #111A and Hull-Higgins #27 wells, El Dorado, Kansas. The gradient logs appear similar even though Paulson #111A is located over the West Shumway dome, whereas Hull-Higgins #27 is located close to the contact between the East and West domes. The differences in temperatures however, are probably the result of lithologic variations present in the sedimentary section at the El Dorado field.

variations in lithology. Between the top (~500 m) and bottom (~550 m) of the Lansing Group, the Finney #2 thermal gradient decreases from approximately 45°C/km to 25°C/km. Again, assuming that the heat-flow does not decrease with depth, this drop in thermal gradient implies that a corresponding increase in thermal conductivity has occurred, perhaps from a relatively low thermal conductivity shale (~1.5 W /m·K) to a higher conductivity "clean" limestone (~3 W/m·K).

Ideally, we would like to attribute the cause of the lower temperatures encountered in the Finney #2 well to systematic differences in the thermal gradient and not lithologic variability. Unfortunately, a direct comparison of the gradient logs is difficult because they differ substantially. A better comparison is available in Figure 4b, which compares the temperature measurements obtained in the Finney #2 well, which is located in the easternmost portion of the East Shumway dome (Fig. 1), with temperature measurements made in Hull-Higgins #27, which is situated over the East Shumway dome, but is close to the bounding-fault between the West and East domes.

Examining the temperature-depth curves it is apparent that Finney #2 is somewhat cooler than Hull-Higgins #27. The gradient logs are both smooth, and appear almost identical, with a minor (~35 m) offset present as a result of a thicker sequence of the Toronto Group in Finney #2. Nonetheless, it is clear that Hull-Higgins #27 is characterized by a systematically higher thermal gradient over the entire length of the log, despite possessing a stratigraphy similar to Finney #2. Because of this systematic variation we interpret that the different log characteristics are not the result of normal variations in lithology nor are they a consequence of borehole disturbances. Rather, the different log characteristics are due to distinct thermal condition in the West and East Shumway domes. This is one of the types of effects that can lead to variation in high-resolution log BHTs but cannot be uniquely determined from the BHT data alone.

Figure 4c compares the temperature measurements obtained in Paulson #111A and Hull-Higgins #27. Even though the two wells are in located in different regions of the field and the Paulson #111A log is somewhat noisy, the high-resolution temperature logs yield relatively similar temperature-depth curves. The gradient logs for these two wells are similar, but the measurable differences present seem to arise from the normal variations in lithology expected in sedimentary sections.

It is unclear what the contribution of lithologic variation in each well is to the temperature data. The Upper Pennsylvanian Lansing and Kansas City Groups are massive, relatively clean limestone units. Therefore, little variation in thermal gradient would be expected. However, the unexpected offset in thermal gradient through these units in both wells requires modeling to explain whether these observations arise from (1) conductive disturbances related to the complex structure of the field or (2) hydrocarbon accumulation and migration through the producing Arbuckle Group. We plan to investigate these affects in future work.

HIGH-RESOLUTION TEMPERATURE LOGS VS. WELL-HEADER BHT DATA

BHT data are usually used to evaluate thermal history and to constrain the timing of hydrocarbon generation in key source beds in active petroleum settings. Temperature-time histories generated utilizing BHT data can be inaccurate, however, simply because the BHT data themselves are inherently inaccurate. Before any attempt to model the thermal history of a particular source bed is made, the present-day thermal regime of the field must be accurately determined. However, because BHT data are not equilibrium temperature measurements, they must be corrected for drilling disturbances prior to use. The correction factor applied usually is empirical and specific to a particular field or lithologic unit. Only with additional log-header information, such as the time since circulation of drilling fluid and the shut-in time of the well, can an equilibrium temperature measurement be extrapolated and the "true" formation temperature determined [*Bullard*, 1947]. A better method of constraining the present-day equilibrium thermal regime in petroleum settings is with high-resolution temperature logs.

Blackwell et al. [1999] discuss several limitations inherent in utilizing BHT data to understand and model the thermal structure of sedimentary basins. They argue that the relative ease and low cost of acquiring high-resolution temperature logs, coupled with their superior information content (as described in this paper, for example), make their use preferable to BHT data in almost all instances. For example, thermal gradient estimates obtained from log-header BHT are rarely more accurate than ±10-25 %, whereas thermal gradient information derived from high-resolution temperature logs are perhaps accurate ±0.5 °C/km at 1 m resolution. Furthermore, because BHT data tend to cluster around a few depths, they cannot provide vertical depth resolution of the thermal gradient [e.g., *Jessop*, 1990].

High-resolution temperature logs, unlike BHT data, can provide sufficient resolution to assess thermal gradient fluctuations with depth and provide constraints on variations in lateral and vertical *in situ* thermal conductivity because of lithologic variations. Perhaps the most advantageous feature of high-resolution temperature logs is that appearance of the log itself (through the gradient log) affords a measure of the borehole conditions. A "noisy" gradient log suggests non-equilibrium, or even nonconductive well conditions may dominate, thereby providing a semi-qualitative indicator of the reliability of the log. BHT data cannot be similarly assessed.

To demonstrate the inaccuracies of BHT data, we present the temperature field atop two prominent horizons present in the El Dorado field: the Upper Pennsylvanian Kansas City Group (limestone), and the Upper Cambrian-Lower Ordovician Arbuckle Group (dominantly dolomite, but with some chert, shale, and sandstone). Both units have been prolific producers of hydrocarbons in Kansas and in the El Dorado field. Accordingly, both units have been the target of numerous BHT observations [e.g., *Förster and Merriam*, 1999].

Shown in Figure 5 are the contoured, uncorrected well-header BHT data sampled at the depth of the Kansas City Group (615-633 m) within the West Shumway dome.

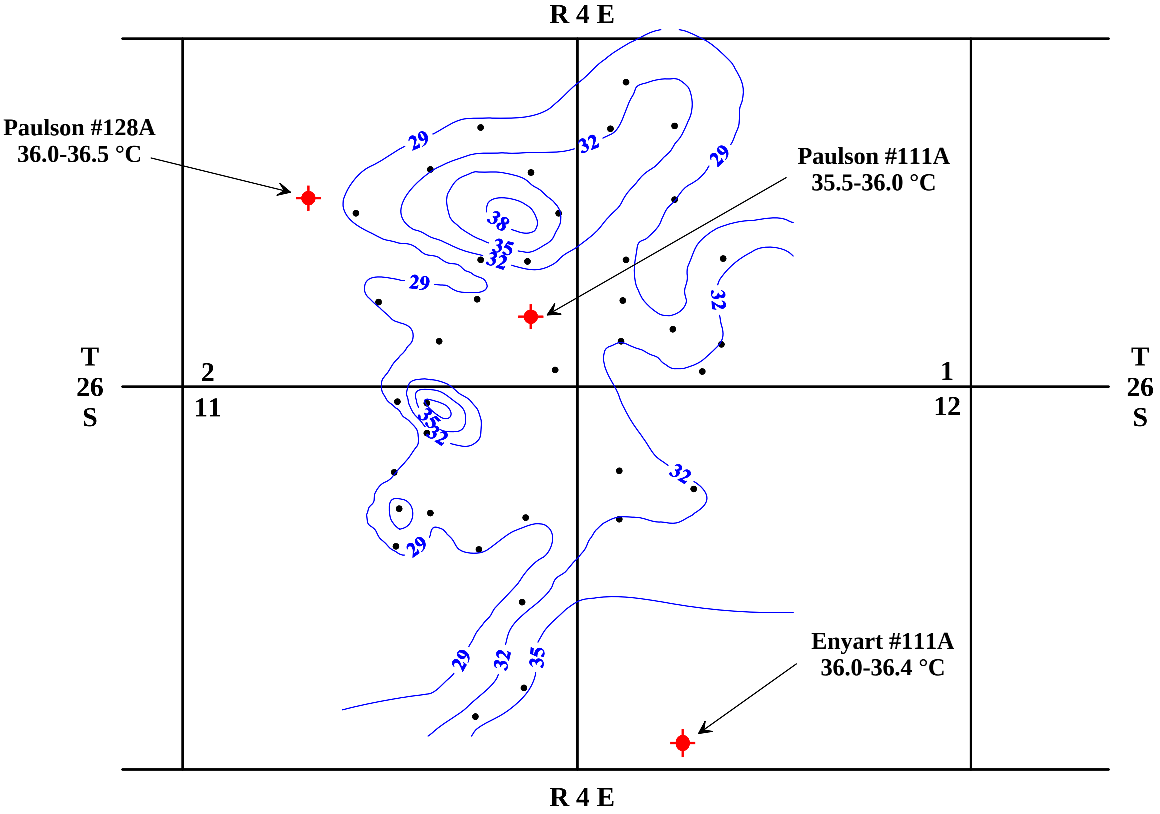

Figure 5. High-resolution temperature log and uncorrected log-header bottom-hole temperature data from the top of the Kansas City Group (615-633 m), West Shumway dome, El Dorado, Kansas. The contour interval is 3°C. One section is equal to 1 mi^2. The high-resolution measurements suggest that the ~8°C BHT anomaly actually encompasses the entire dome instead of a restricted region near the dome crest. BHT data are courtesy of Dan Merriam, Kansas Geological Survey.

Also shown are the temperature ranges from the high-resolution logs encountered in the three wells (Paulson #128A, Paulson #111A, and Enyart #111A) closest to the crest of the dome (where sections 1, 2, 11, and 12 intersect) at the same depth interval. The BHT data show a broad region of 29°C temperature centered over the dome and two smaller regions in which the temperature is in excess of 37°C. The high-resolution temperature measurements covering approximately the same area of the dome all show an average temperature of 36°C. Even though the wells are isolated from one another, the limited high-resolution data suggests that the >8°C BHT anomaly, restricted to two small areas on the dome, is in fact, not anomalous, but closer to the equilibrium temperature of the Kansas City Group.

Figure 6 is similar to Figure 5, except that the contoured, uncorrected well-header BHT data here represent estimates of the temperature field at the top of the Arbuckle Group (707-838 m). Also shown is the range of temperatures encountered from 707 m to the total logged-depth in the three wells closest to the crest of the West Shumway dome. As before, the BHT data illustrate a broad region roughly corresponding to the dome of temperature at least 32°C. In general, however, there is somewhat less complexity to the Arbuckle Group BHT delineated thermal structure at this depth interval than that of the shallower Kansas City Group (Fig. 5). The thermal structure here varies uniformly and is seen to reach a maximum of 41°C as the crest of the dome is approached from all sides. Although the amplitude of the well-header BHT anomaly for the Arbuckle Group is about 11°C, it probably is somewhat less because the depth interval at which the BHT data are recorded span the rather large depth range of about 130 m. The high-resolution temperature measurements nearest to the dome all recorded similar observations, the

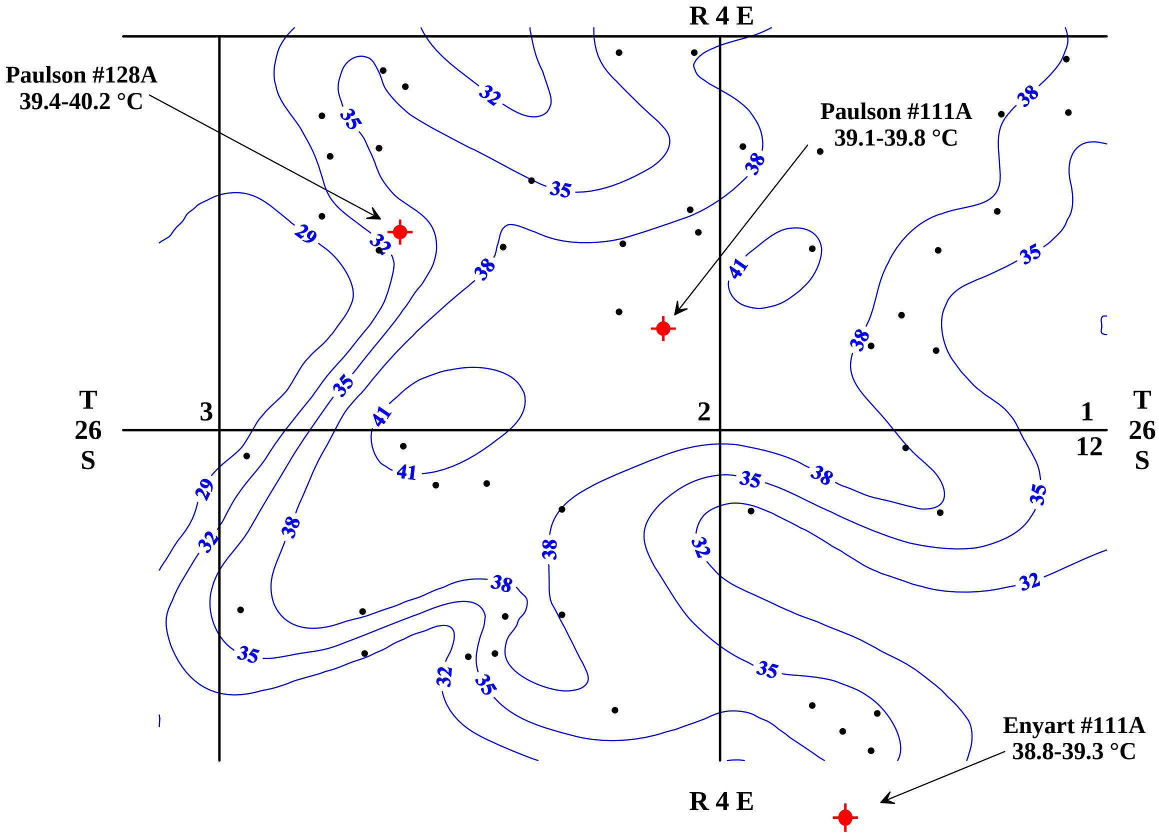

Figure 6. High-resolution temperature log and uncorrected log-header bottom-hole temperature data from the top of the Arbuckle Group (707-838 m), West Shumway dome, El Dorado, Kansas. The contour interval is 3°C. One section is equal to 1 mi^2. The high-resolution temperature measurements seem to indicate a much broader, and hotter region than the ~11°C anomaly delineated by BHT data. BHT data are courtesy of Dan Merriam, Kansas Geological Survey

mean temperature being about 39°C. Again, the results of the high-resolution temperature measurements in wells centered over the West Shumway dome suggest a broader region of high temperature at the top of the Arbuckle Group than delineated by the BHT data.

To emphasize the different interpretations of the thermal regime of the El Dorado field suggested by the log-header BHT data, and the high-resolution temperature logs, we present a composite temperature-depth plot of all available temperature measurements and uncorrected BHT data at the top of the Kansas City and Arbuckle Groups (Fig. 7). The average temperature-depth curve for the high-resolution temperature logs was constructed by sampling the temperature of all six high-resolution logs at 250, 400, 650, and 720 m depth (triangles), and averaging these measurements (stars). The resulting mean thermal gradient for the three intervals is plotted as a solid line. The individual temperature measurements appear similar until a depth of 650 m is reached. At this depth, one well (Finney #2) appears to be significantly cooler than the other wells, suggesting that distinct thermal conditions in the deeper portion of the well prevail. Ignoring the individual well-temperature differences, it is apparent that the mean thermal gradient remains relatively constant from 200 to 650 m. After this depth is reached, the thermal gradient increases by about 4°C/km, indicating that the deepest part of the wells are maintained at a higher temperature than that of the upper portion of the well. The cause for this remains unknown.

The Kansas City and Arbuckle BHT data cannot provide further insight into thermal conditions in the El Dorado field because they are not equilibrium temperature measurements (see next). However, it is interesting to compare the scatter in both types

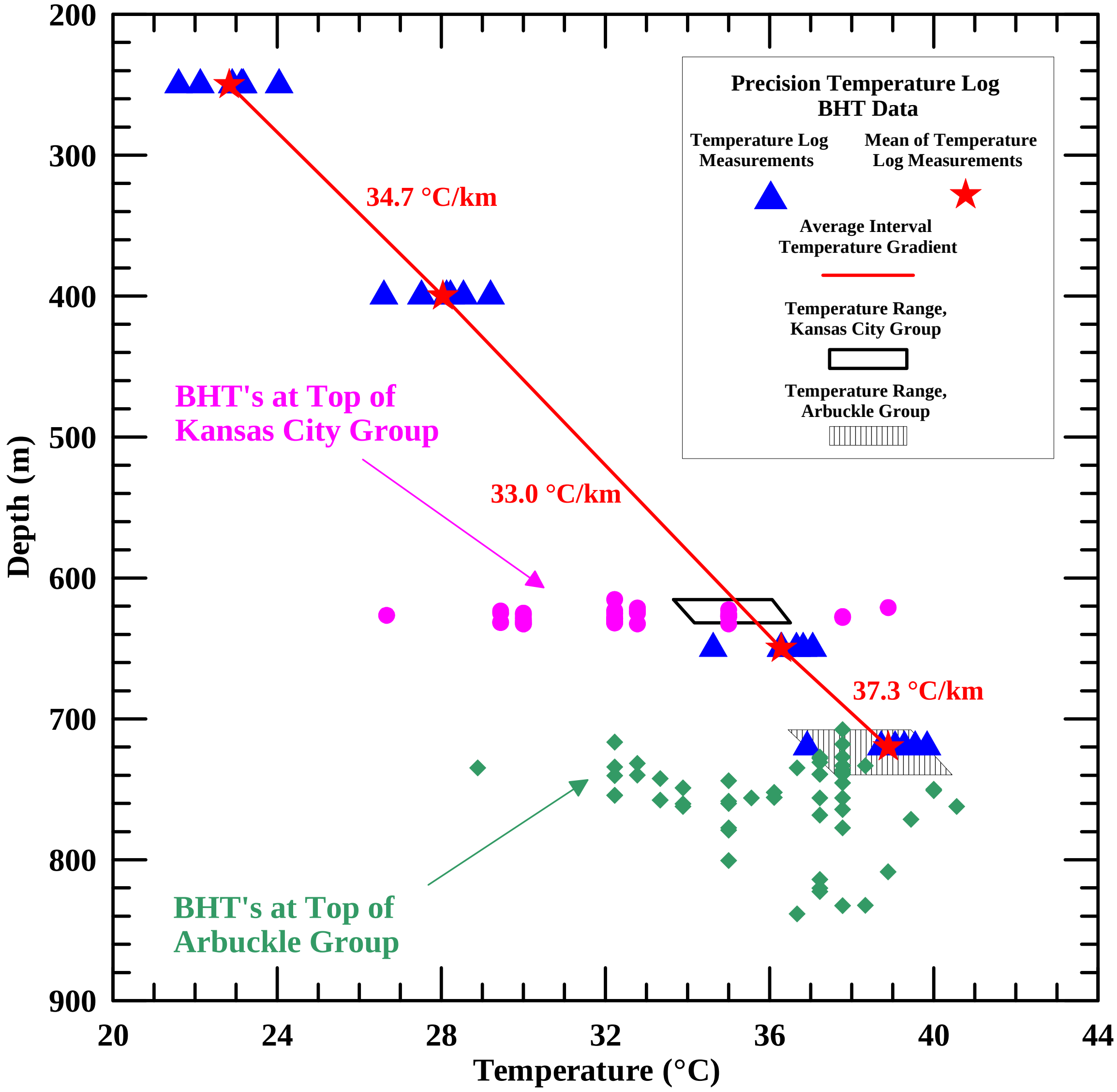

Figure 7. High-resolution temperature log and uncorrected log-header bottom-hole temperature data: El Dorado oil field, Kansas. The small scatter in the high-resolution temperature measurements (triangles) at the top of two important producing horizons, the Kansas City (open polygon) and Arbuckle Groups (vertically striped polygon), illustrates the overall consistency and reliability of the high-resolution temperature logs. The mean of the log temperature at depths 250, 400, 650, and 720 m (stars) were used to calculate the mean interval thermal gradient. BHT data are courtesy of Dan Merriam, Kansas Geological Survey.

of data at the two horizons (Fig. 7). The open and vertically striped polygons represent the range (in both temperature and depth) of the high-resolution temperature measurements at the top of the Kansas City and Arbuckle Groups, respectively. When compared to the log-header BHT data for these two lithologies, it is seen that the scatter in temperature-depth space of the high-resolution logs is less. The wide scatter in the BHT data at these two horizons emphasizes the consistency and accuracy of the high-resolution temperature logs. The other prominent feature apparent from Figure 7 is that with few exceptions, the BHT data are colder than the high-resolution temperature measurements. This pattern of colder than normal (as defined by the high-resolution temperature measurement as an equivalent depth) BHT data is consistent with either drilling disturbances (cooling at depth from circulating drilling mud) or production effects. Either interpretation emphasizes the non-equilibrium character of BHT data in general, and these data in particular which have not been corrected.

CONCLUSIONS

1) High-resolution temperature logs can provide reliable, equilibrium temperature measurements in active petroleum settings.

2) High-resolution temperature logs acquired in the producing El Dorado oil field, Kansas, illustrate generally conductive, equilibrium temperature well profiles.

3) The lower temperatures measured in the Finney #2 and Hull-Higgins #27 wells over the East Shumway dome seem to be the result of a significant change in thermal gradient, perhaps from mass transport of hydrocarbons and/or *in situ* thermal conductivity changes related to the presence of hydrocarbons, and not inter-well lithologic variability.

4) A preliminary analysis of high-resolution temperature logs and log-header derived BHT data at the top of two productive zones (the Kansas City and Arbuckle Groups) within the West Shumway dome, suggests that the anomalously high BHT data present at the top of both horizons is not only close to the actual formation temperature, but encompasses a much broader region of the dome than previously believed.

One possible explanation for the apparently broad isothermal conditions atop the Arbuckle Group in that the pre-Pennsylvanian unconformity that separates the Middle Ordovician Viola (dolomite) and Simpson (sandstone) Groups and the deformed Arbuckle Group from the younger overlying shales of the Cherokee Group is a permeable pathway for fluid migration [*Ramondetta,* 1990].

In the future, we plan to log additional wells off-axis of the West Shumway dome and wells in the East Shumway dome in order to develop a more complete data set. This data then will be modeled to determine whether the observed temperature variations are from conductive as opposed to conductive disturbances and are therefore related to hydrocarbon accumulation and migration. A more complete comparison to the BHT data, both corrected and uncorrected, also will be carried out to evaluate the real errors of using such data. This error evaluation cannot be performed using the log header BHTs themselves because of the lack of “true” data.

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